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 demonstrate a high engineering potential, mainly for tailoring the final shape while optimising the structural/functional performance, material use, overall costs, and architectural effectiveness. However, the design of structurally efficient DFC constructions or components is often faced with a lack of a common structural engineering approach that can adapt to specific DFC particularities.

In this paper, we provide a systematic overview of a number of DFC structural projects developed thus far. A comprehensive discussion about structural engineering details is provided, addressing the related fundamental structural issues and envisioning opportunities and challenges toward achieving the full potential of 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 characterised by an increasing overall complexity and a high level of digitalisation [1–5]. The growing number of irregular-shape buildings or structures recently constructed, or planned in various countries, represents the evidence of technological progress characterised by an evolution of conventional construction materials, design approaches, and manufacturing methods. In this context, digital fabrication is becoming a valuable approach to overcome the existing manufacturing limitations, as it can transform digital design into physical products [6] by adopting one or more materials (polymers, steel, wood, clay, etc.) and different automated processes (e.g. robotic assembly, extrusion, lamination, and additive manufacturing).

Different advantages are potentially offered for the specific construction project wherein digital fabrication is implemented [7–9]. Besides a higher degree of customisation, the positive performance of a digitally fabricated system can be evaluated by monitoring four main factors: time, cost, quality, and flexibility [10]. In other words, removing the formworks in favour of modularisation and prefabrication or part of the concrete/reinforcement due to material [11, 12] and shape efficiency [13] results in cost and CO_2 emission reduction [2]14], while providing additional functions [15, 16]; the resulting features represent, in practice, the key decision-making factors for the overall construction management of the project [6, 17]. However, this scenario has to deal with the slow innovation uptake of the construction industry even if estimates for future investments in infrastructure [18] have stimulated this sector toward the transformation of the way in which numerous engineering and construction firms operate [19].

A recent review by Austern *et al.* [20] classified the appearance of digital fabrication projects in the available literature, noting the implementation of approximately 15 different automated processes adopting more than 10 different materials. All of these fabrication techniques inevitably introduce feasibility and affordability issues, which often force engineers and architects to adjust the design itself according to the constraints arising from the new processes. These constraints can be grouped into the following four main categories:

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

Currently, wood, steel, polymers, and concrete are the materials mostly adopted in digital fabrication applied to construction projects [20]. Among these, polymers have the lowest prevalence and their use for the fabrication of building components is limited because of the high manufacturing cost and low stiffness [21]. In contrast, robotic systems represent a mature technology for the fabrication of non-standard timber structures, being able to obtain automatic joinery [22] as well as large-scale assembly by adopting new computational approaches [23]. A real-world case is that of the 'The Sequential Roof' project developed at ETH Zurich [24] 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. In contrast, steel-based structures are generally digitally fabricated using powder bed fusion and directed energy deposition processes [21]. Large-scale applications have been implemented, for instance, in the MX3D project [25], aimed to 3D print an 8-m stainless steel bridge (a footbridge across the Oudezijds Achterburgwal canal) with a gas metal arc welding-based six-axis industrial robot (see Figure 1b). In this case, experimental tests were needed to characterise the structural behaviour for ensuring the compliance with building regulations [26].


Figure 1: (a) 'The Sequential Roof' project developed at ETH Zurich [24] and (b) MX3D project [25].

Apart from wood and steel, concrete and cement-based materials have been increasingly used in digital fabrication techniques in the last 5–10 years. In a recent study by Tay *et al.* [14] reporting an analysis of the variants of concrete printing processes published worldwide over the last twenty years, the researchers found that topic-related research works almost doubled in the years 2013–2016 compared to in the previous 16 years. Further, automated manufacturing techniques are collectively identified as digital fabrication with concrete (DFC), allowing the construction of both structural and non-structural products (to a greater or lesser extent) without the use of traditional formworks.

The implementation of the different DFC methods is currently capable of producing architectural items, load bearing and non-load bearing building/infrastructure components, and full-scale houses/structures; an explicit mapping of the resulting digitally fabricated systems' characteristics is provided in [27], whereas the variety of available methods can be generally grouped on the basis of [14, 28, 29]:

- <u>*Process*</u>: (*i*) **extrusion process** in which concrete is automatically placed layer-by-layer through a moving nozzle, following a predefined digital path reproduced by Cartesian gantry, robotic, crane, or cable robot systems [30–33]; (*ii*) **formwork printing** in which concrete or other materials are used to fill a digitally fabricated formwork [34]; (*iii*) **use of temporary supports** which are digitally designed against applied loads, fabricated, and then, subsequently concreted [35]; (*iv*) **slipforming** consisting of a vertically moving formwork in which concrete is placed in the fluid state and allowed to harden in a controlled manner to fabricate variable cross-sectional area structures (e.g. the smart dynamic casting system developed by Lloret *et al.* [36, 37]); *(v)* **particle bed 3d printing** (also known as 'selective binding' or 'binder jetting') which is based on the selective and automated deposition of a binder onto a layer of particles (e.g. see [38]). This process is also referred to as particle bed fusion [28]; however, as it does not involve the melting of a material, the more general term of particle bed 3d printing, previously mentioned should be preferred; and (*vi*) **hybrid techniques** which aim to introduce hybrid construction concepts by using the available fabrication processes or reinforcement (e.g. sparse concrete reinforcement in meshworks which combines robot-based 3D concrete printing and textile reinforcement meshes [39] or shotcrete 3D printing which is based on an automated shotcreteing process with the ability to integrate structural reinforcement [40]).

- *Fabrication site*: (*i*) **on-site construction** is the production of full houses/structures in an open environment by means of machinery larger (e.g. the use of a gantry printer in DCP [41]) or even smaller (e.g. in-situ fabricator of mesh mould process [42]) than the structure being fabricated; and (*ii*) **prefabrication** is 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 [42, 43].

The recent successful implementation of such DFC methods demonstrates their potential in achieving concrete structures of complex geometry [45], such as thin and stable shells, arches, lightweight forms with complex topologies, advanced modular structures, custom concrete stairs [46], and even promising solutions for the construction of human settlements on other celestial bodies such as the Moon and Mars [47]. However, this revolutionary shift has introduced new possibilities and constraints for the design, dimensioning, detailing, and production of structures [48]. Indeed, it is 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 because of the considerable changes compared to the standard formative processes. In particular, the rheological and mechanical properties of the growing object give rise to new fabrication issues such as pumpability, buildability, printability, extrudability, and fluid infiltration capability into the particle bed [38, 48–50]. Moreover, the mix-design solutions adopted thus far have introduced new performances in the hardened state, making the digitally fabricated concrete objects remarkably different from those obtained using the well-established formative process. In addition, the additive nature of many DFC techniques yields layered structures with a significant anisotropy with regard to strength (occurring in both the vertical and the horizontal directions) rather than stiffness. The interfaces between adjacent layers generated by additive DFC processes are typically characterised by reduced bond strengths (in both the shear and the normal directions) and are commonly referred to as weak layer interfaces, cold joints or lift lines [40, 51]: a number of factors related to the combination of a specific DFC process and material composition (e.g. print head speed, print nozzle height, resting time, and moisture content) have been shown to have quantitative effects on the interface properties, leading, in some cases, to a 50% or higher reduction as compared to the bulk specimens [53]. Similar considerations can be drawn for other DFC processes, such as particle bed 3d printing, in which the compressive strength of the printed cylinders has been shown to depend on the penetration ratio of the binder [38].

Moving to full-scale construction projects with DFC, it is clear that all the above-mentioned mechanical aspects characterising the hardened state may represent an evident obstacle for DFC to reach maturity. In addition, unless compressed structures are considered, a key point to note is that the implementation of digitally fabricated concrete structures is made possible only in combination with reinforcement resisting tensile forces, which overcome the lack of sufficient tensile capacity and ductility of cementitious materials. Reinforcement concepts and principles are currently adapting to the different DFC processes [54]. This progressive change will affect the reinforcement technology (e.g. the various implementation techniques of fibres, rebar, rods, and filaments in DFC processes), dimensioning, and detailing in contrast to the conventional concrete constructions.

In this review paper, we aim to first provide the information collected on the existing documented DFC construction projects, bringing out the structural engineering aspects behind their design and execution. Then, a discussion is provided to address the common structural characteristics and issues associated with the DFC particularities described in the paper; in particular, being the extrusion process one of the most widely used and documented DFC technique, most of the discussion outcomes will be related to that technique. The current stage of development, in terms of the existing building regulations and full-scale validation testing, is also reported in this review, representing a key step toward the development of a common understanding of such an interdisciplinary topic.

2. AVAILABLE (DOCUMENTED) STRUCTURAL APPLICATIONS OF DFC

After an initial phase of realisation of showcase projects (e.g. [55–57]), DFC is now being introduced into general-use structures such as short-span bridges, whole buildings printed in full, 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 by the number of announced projects [58–60]. Unfortunately, thus far, publicly available documentation on structural engineering has been extremely scarce.

Asprone *et al.* [61] noted 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. Furthermore, in the domain of structural design, they identified 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 brings about new design, dimensioning, and detailing possibilities, which have considerable 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 of the engineers in consulting practice will be discussed briefly.

Table 1: Realised structural DFC projects.

Project name or description	**Location, year**	**DFC fabricator, country**	**DFC technology**	**DFC product**	**Ref.**
3D-Printed Concrete Castle	USA, 2014	TotalKustom	Extrusion	Building/house	[62]
Leward Grand Hotel, Hotel Suite	Angeles City Pampanga, The Philippines, 2015	Total Kustom, USA	Extrusion	Building/house	[63]
Office Building	Dubai, May 2016	Winsun, China	Extrusion	Building/office	[63, 64]
Krypton Post	Aix-en-Provence, France, 2016	XtreeE, France	Extrusion	Structural element	[66]
USH Sinusoidal Wall	Paris, France, 2016	XtreeE, France	Extrusion	Building component	[67]
R&Drone Laboratory	Dubai, 2017	CyBe, The Netherlands	Extrusion	Building/house	[68]
Pedestrian Bridge	Madrid, Spain, 2017	Acciona Spain with D-Shape, Italy	particle bed 3d printing	Bridge structure	[69]
Bicycle Bridge	Gemert, The Netherlands, 2017	TU/e, The Netherlands	Extrusion	Bridge structure	[69, 70]
Apis Cor Printed House, Russia	Moscow, Russia, 2017	Apis Cor, Boston, USA	Extrusion	Building/house	[64]
Maison Concept YRYS	Alençon, France, 2017	XtreeE, France	Extrusion	Building/house	[72]
Stormwater Collector	Lille, France, 2017	XtreeE, France	Extrusion	Infrastructure component	[73]
3D Housing 05	Milan, Italy, 2018	Italcementi with CyBe	Extrusion	Building/house	[74]
The BOD	Denmark, 2018	COBOD, Denmark	Extrusion	Building/house	[75]

KnitCandela	Mexico City, Mexico, 2018	NCCR Digital Fabrication, Switzerland	Hybrid techniques	Structural element	[76]
3D-Printed Concrete Pedestrian Bridge	Shanghai, China, 2019	Tsinghua University (School of Architecture)	Extrusion	Bridge structure	[77]
DFAB House	Dübendorf, Switzerland, 2019	NCCR Digital Fabrication, Switzerland	Slipforming, formwork printing, temporary supports, particle bed 3d printing	Building components	[53, 77]
Future Tree	Esslingen, Switzerland, 2019	NCCR Digital Fabrication, Switzerland	Hybrid technique	Structural element	[79]
'*De vergaderfabriek*', Meeting Room	Teuge, The Netherlands, 2019	Cybe, The Netherlands	Extrusion	Building/office	[80]
Cohesion Pavilion	Innsbruck, Austria, 2019	Incremental3D, Austria	Extrusion	Architectural structure	[81]
Building Apis Cor, Dubai	Dubai, The UAE, 2019	Apis Cor, Boston, USA	Extrusion	Building/office	[82]
3D-Printed Community	Tabasco, Mexico, 2019	ICON, USA	Extrusion	Building/house	[83]
3D-Printed Post-Tensioned Concrete Girder Designed by Topology Optimisation	Ghent, Belgium, 2019	Ghent University (Concre3DLab), Belgium With Vertico, The Netherlands	Formwork printing	Bridge structure	[34]

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 in Dübendorf, Switzerland. The project involved designing, planning, and building a three-storey house using predominantly digital processes developed within the NCCR Digital Fabrication [84]. DFAB HOUSE opened in 2019 and 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 was responsible for 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 [85] and lightweight translucent façades [86], besides the technologies used for the production of concrete structures (see Figure 2) that are presented in the following subsection. The design loads and the structural design followed the SIA 260:2013 [87], SIA 261:2014 [88], and SIA 262:2013 [89] codes, considering a five-year reference lifetime.

Figure 2. Concrete innovations on 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).

No tests of prototypes were conducted for the DFAB HOUSE, as the structural engineer merely requested material and small-scale structural tests proving that the behaviour was in accordance with conventional structural concrete principles; note that the Swiss structural design codes allow exceptions, provided that they are well founded theoretically or experimentally (SIA 260:2013 [87]). All the structural elements were monitored and inspected periodically, showing no particular issues after one year of use.

Bespoke concrete mullions (Smart Dynamic Casting)

Smart Dynamic Casting (SDC) [37, 89] 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 2, left). The architectural design concept required a variable spacing between the mullions (700 to 1400 mm), leading to different structural requirements for each mullion. Owing 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 the bottom slabs were designed to avoid the transmission of vertical loads and resist exclusively wind loads. In SDC, concrete manufacturing is continuous, and reinforcement can be easily added before the production (see Figure 3a). Hence, conventional structural design provisions were used to verify the integrity of the mullions and to limit their deflections to 1/400 of their span (because of the requirements of the glass façade). These provisions required the use of 2 × Ø12 longitudinal reinforcing steel bars and Ø6 transversal welded steel bars (see final reinforcement in Figure 3a). In all of the cases, the minimum cross section was set to 70 mm × 100 mm to ensure the required minimum concrete cover. The widest cross section of the 15 mullions varied from a minimum of 70 mm × 120 mm to 70 mm × 180 mm to strictly fulfil the deflection requirement of each mullion. In addition, to ensure the same concrete cover throughout the mullion height and during the slipforming process, the reinforcing bars were precisely pre-bent and clamped before production. In terms of the long-term monitoring of such elements, the only remarkable observations were the shrinkage cracks reported prior to the mullions' installation [37], but they did not compromise the overall structural performance because of the presence of the reinforcement.

Figure 3. Details of production of concrete structures for the DFAB HOUSE: (a) reinforcement of the mullions installed prior to concrete production [90]; (b) on-site robotic fabrication of double curved reinforcing mesh [42]; (c) 3D-printed formwork for a 7.1-m segment of the Smart Slab [91]; (d) installation of the prefabricated Smart Slab [91].

Mesh Mould double curved wall

Mesh Mould [90, 92] unifies the concrete formwork and the structural reinforcement to avoid the use of conventional formworks. This system was used on the first floor of the DFAB HOUSE to produce a 12-m-long and 120-mm-thick double curved wall (Figure 2, right) that supports the loads of the structural elements above (i.e. Smart Slab and Spatial Timber Assemblies). A double-sided welded steel reinforcement mesh was produced on site by the ‘in-situ fabricator’ robot [93] (Figure 3b) in approximately 19 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. A ready-mix concrete mix (Sika Monotop 412N) was used in the project of the load bearing wall. The concrete cover was sprayed using a ready mortar mix (Sika Monotop 352N). The surface was finished with a customised trowel, containing steel rollers with a radius of 20 mm in order to consistently ensure the required concrete cover thickness.

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 to produce a reinforcement mesh compliant with the provisions of the minimum reinforcement content (Ø6 vertical continuous bars and Ø4.5 horizontal welded segments, in both cases at an average spacing of 40 mm). The behaviour of the welded segments was studied through both material tests and structural bending tests in elements of a 400-mm span [42]. The bending tests exhibited ductile behaviour prior to the failure of the welding. The observed ductility was caused by the shear deformations induced in the perpendicular continuous reinforcement. While this deviated significantly from the conventional structural concrete, the experimentally proven high deformation capacity allowed the use of a plasticity-based design. The potential formation of weak interfaces 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.

Smart Slab

The idea behind Smart Slab was to achieve free-form shapes and high-resolution geometric features in concrete structures by using 3D-printed formworks that could 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 2 and Figure 3d) and acts as a double cantilever, carrying the two-storey Spatial Timber Units above it. The design concept for Smart Slab was to develop a highly optimised structural component embedding all the details for the façade and technical installations, such as sprinklers and lighting; then, the component was computationally designed to visualise the force flow [91]. The Smart Slab was conceived as a post-tensioned structure, with ribs parallel and perpendicular to the supporting Mesh Mould wall. Each of the 11 prefabricated concrete segments was mounted on site using scaffolding until the activation of the post-tensioning (Figure 3d). The ribs transversal to the Mesh Mould wall carry the main loads, with a maximum cantilever of 4.5 m that required a cross-sectional height between 300 mm and 600 mm. The secondary ribs (parallel to the wall) have a constant depth of 300 mm and carry post-tensioning strands used to compress the joints between the prefabricated segments. With the use of binder jetting sand-printed formworks (Figure 3c), the thickness of the concrete soffits between the ribs was reduced to only 20 mm in thickness. This allowed the reduction of 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 [91] working over the same spans for the same service loads. 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, and conventional procedures were followed to install the reinforcement and guarantee its location and cover. Besides the post-tensioning tendons carrying the main forces, the ribs included conventional shear reinforcement.

2.1.2. Future Tree

The Future Tree [94] is a permanent outdoor pavilion (Figure 4a) 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 supported a permeable timber roof of around 100 m^2. The geometry of the concrete column reflected the timber roof morphology with eight outer ribs serving as a support for the timber profiles (Figure 4).

In the Eggshell method, an ultra-thin 3D-printed formwork (Figure 4b, 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 [89, 95]. This technology is similar to the smart dynamic casting process, but the use of an ultra-thin formwork allows for more complex geometries. 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. The 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 these applications where a reinforcing bar cage can be fit to the formwork geometry (as for the Future Tree column, see Figure 4a, centre), the structural design can be addressed by essentially conventional procedures. In this particular application, the design loads and the structural design followed the SIA 261:2014 and SIA 262:2013 codes [87, 88].

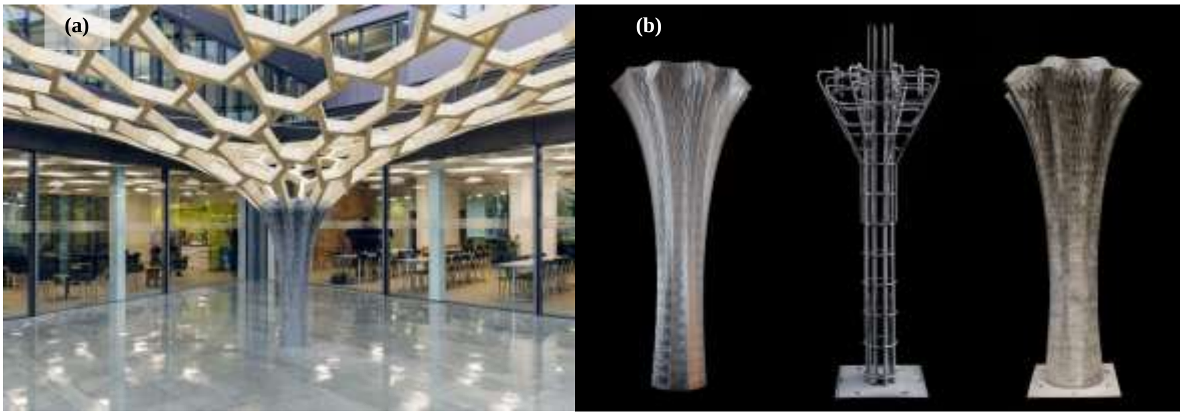


Figure 4. Future Tree pavilion in Esslingen, Zurich: (a) completed pavilion (Image: Basler & Hofmann AG, Stefan Kubli); (b) Eggshell column, from left to right, printed ultrathin formwork, reinforcement cage, and finished concrete element (Image: Gramazio Kohler Research, Joris Burger).

The core of the column was dimensioned to resist the global loads of the timber roof, which required eight Ø14 longitudinal bars and Ø10 stirrups at a spacing of 150 mm. The eight ribs were reinforced to contain the minimum reinforcement to guarantee the crack width control and to avoid brittle failures at cracking (i.e. a reinforcement ratio of more than 0.6% for the longitudinal reinforcement and more than 0.1% for the shear reinforcement). The minimum reinforcement of the whole rib was calculated for its largest section (200 mm × 70 mm), resulting in 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 the tests of prototypes, as the dimensioning was possible by following essentially conventional methods.

2.1.3. KnitCandela

KnitCandela (Figure 5) is a thin, undulating, 50-m^2 concrete shell built in 2018 at the *Museo Universitario Arte Contemporáneo* (MUAC) in Mexico City. The shell was designed in collaboration between Zaha Hadid Architects and the researchers of the NCCR Digital Fabrication as a homage to the Spanish–Mexican shell builder Félix Candela. The concept was to explore how the range of buildable concrete shell geometries can be expanded by the use of novel computational design methods and a custom-knit textile as a lightweight stay-in-place formwork that allows the generation of a ribbed structure. In KnitCrete, the formwork is coated with a thin layer of fast-setting cement paste [96] that serves as a first stiffening layer for the textile, minimising formwork deformations during the application of further concrete layers.

Figure 5. Finished KnitCandela concrete shell showing the soft textile interior and the smooth concrete exterior [96].

KnitCandela was located inside a museum and classified as an artwork. Hence, the conducted structural verifications [96] (limitation of concrete stresses and deflections) had to prove the safety of the shell but without having to strictly follow any particular building code. The shell was considered unreinforced for these verifications (the contribution of the textile was neglected), but a small amount of glass fibres was added to the concrete mix provided by Holcim Mexico in order to ensure crack distribution and predefined capacity redistribution.

2.1.4. Bicycle bridge Gemert

In 2017, at the initiative of contractor BAM, a bicycle bridge mainly consisting of six extrusion-based 3D concrete printed parts was realised in Gemert, the Netherlands (Figure 6). The project is extensively described by Salet *et al.* [42, 97]. Structural engineering was performed by Witteveen+Bos consulting engineers, in close collaboration with Eindhoven University of Technology (TU/e), which also provided all the experimental testing. The parts were printed at the TU/e 3DCP facility and moved to the site, where they were joined to the bridge element.

Figure 6: 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 pre-stressing.
The design of the single segments was purposefully kept relatively simple, bearing the characteristics of the 3DCP facility in mind. The segments had two straight sides, acting as the top and the bottom of the bridge. In between, a 'bottle-shaped' pattern of the filament was designed to transfer shear forces (Figure 7). 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 the structural requirements. In contrast to the default 40-mm width of the facility, a 60-mm filament width was applied to increase robustness.

To avoid any unforeseen structural behaviour, a full 3D non-linear finite element model (FEM) was developed for the structural calculations. The design loads were taken from EN 1991 [98,99], 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 [100]. This provided directionally dependent compressive and tensile strength data, as well as the data on stiffness, shrinkage, and creep. However, despite a rather extensive experimental campaign, note that because of the large number of parameters to be tested, the average sample size is still limited and not all of the process variables could be taken into account. Moreover, the applied experimental methodologies were in the early stages of development and are still evolving.

Figure 7: Printing of one of the parts of the bicycle bridge at the 3DCP facility of the TU/e

In the direction of the main span, the pre-stressing 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 (as clearly visible in the mock-up structure of Figure 16, which is discussed in Section 4.1); this concept did not disrupt the printing process. In the perpendicular direction, an innovative concept of the entrained high-strength steel cable reinforcement was applied over a part of the height [101, 102] as an experimental addition. These cables were intended as compatibility torsion reinforcement in case of misalignment in the abutments (hence, they provide an additional precaution, but the structural safety of the bridge does not rely on them). As the cables were galvanised, the considerations of the concrete cover were omitted.

The building permit was obtained from the local authorities on the basis of 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 four-point bending test on a 1:2 scale mock-up of the bridge was performed to verify the failure resistance and the failure behaviour. 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. This was suspected to be the cause of some of the cracks that appeared after installation. Besides, the impact of shrinkage differences caused by both drying shrinkage and temperature gradients induced longitudinal cracks in the printed segments over time. Neither crack was critical, but they were a consequence of the slender dimensions of the printed filaments compared to the massive traditional structures (which is a serious issue to consider).

2.1.5. 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 8). 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, characterised by a multitude of developing and merging double curved surfaces, consists of 47 radially positioned, unique parts. The outer surface of each part was dictated by the architectural design, while the infill was to be designed according to the structural needs. The parts were produced by Incremental3D using extrusion-based 3D concrete printing, with the two-stage material supplied by Baumit. The on-site construction was performed by contractor PORR. A detailed description of the project was provided by Grasser *et al.* [81].

Figure 8: 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 selected. 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' (see Figure 8). Reinforcement was only applied to ensure structural safety, not to act in tension under the in-service conditions.

To determine the design loads, the pavilion was considered a Consequence Class 1 (CC1), Reliability Class 1 (RC1)-type structure as defined by the EN 1990-1, with a five-year reference lifetime. Determining the location and magnitude of loads that should be considered to act on the structure was difficult because of 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 analysed. A simple linear elastic 2D FEM approach in one or more radial planes of the part was adopted. For the larger parts, a model with linear geometries was initially used to gain insight into the order of the magnitude of stresses and develop a principal 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 value and an estimate of shrinkage. However, because of a lack of standardised testing methods, these had to be treated as global indicators because details such as sample size, testing direction, and printing conditions were unreported. Globally, a material safety factor of $\gamma_M = 2.0$ 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 30 mm. The internal structures were mostly designed in an orthogonal manner (vertical and horizontal), as this was expected to be the easiest way to control shrinkage cracks in printing, leading to parts that would be less susceptible to shrinkage stresses than parts with diagonal infills. Figure 9 shows the pavilion during construction, with some insides of the parts on display.

Figure 9: Details of Cohesion pavilion, celebrating the 350th anniversary of the University of Innsbruck (Photo: Freek Bos)

In general, reinforcement in the form of either woven carbon fibre-reinforced polymer, CFRP, or steel bars was applied twice in each printed 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 corresponding section. Considering the short reference life span, the nominal concrete cover of 27 mm on most steel bars was considered sufficient. In some cases, the reinforcement was embedded in only one filament. This reduced the cover to 12 mm, but in these areas, the reinforcement was heavily over-dimensioned and therefore accepted. Because of the size and location of the pavilion on the university grounds, no separate approval for the structural design was required by the authorities. All of the CFRP elements formed continuous (semi-rectangular) geometries so that their reinforcing performance would not depend on the bond with the concrete, as this was expected to be limited because of the strand smoothness. Because of the time constraints, these innovative CFRP reinforcements were only applied to a selection of the higher parts in the outer ring, while conventional reinforcement bars with a diameter of 6 mm were manually applied to reinforce critical sections of the remaining 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.

During construction, one part was severely damaged by collision from a fork-lift truck, to which these parts are more sensitive than conventional concrete parts because of 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.

2.1.6. 3D-printed concrete girder designed by topology optimisation

The lab-scale footbridge project shown in Figure 10 and Figure *11* and thoroughly discussed in [34] is a post-tensioned DFC girder (4-m span) that was constructed at Ghent University in 2019. The 2D shape of this girder was optimised using topology optimisation techniques developed at Technion-Israel Institute of Technology. With advanced algorithms, not only the concrete distribution was optimised, but the optimal shape and curvature of the post-tension cable were also determined. The objective was to minimise the displacements at the top surface of the beam, because of the combined action of the external loads and the post-tensioning tendon [103]. As the implementation of the optimisation procedure was until then developed in 2D, some post-processing was necessary for the final design, and a 3D finite element analysis was performed to determine the design values and limits. Similar to the bridge project in Gemert, the final structure was made from multiple concrete segments that were printed independently and then compressed together with the tendons. However, in this project, the internal cavity was grouted to create a solid shape. 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, note that the FE model of the girder did not include the complex interaction between the 3D-printed formwork and the solid infill. Instead, a homogenised Young's modulus value and the associated concrete grade (C30/37) were used in the simulation. The production of the 3D-printed segments was realised in collaboration with Vertico, and the printing setup was made of the following: (i) a six-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 were 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 were slightly pre-stressed 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 that used 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 10**Errore. L'origine riferimento non è stata trovata.**). With respect to the reinforcement cover, the tendons were enclosed by the post-tensioning duct and kept in the middle of the concrete volume by plastic point spacers. The steel rebars in the struts were connected to the tendons and run through the mid-section.

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 the numerical results. No destructive testing has thus far been performed on this case study. In the referenced paper, a comparison was also made to a T-section girder with the same total deflection, presenting material savings of roughly 20%.

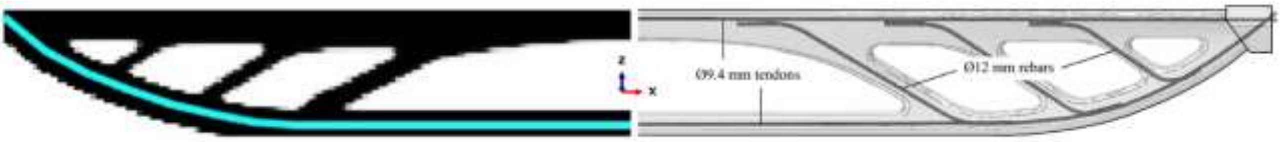


Figure 10: Results of (a) the topology optimisation procedure, for a single-span beam subjected to a uniform load and (b) the dimensioning procedure, showing the 12-mm rebars in the struts and 9.4-mm tendons in the top and the bottom chords [34].

(a) *(b)*

Figure 11: Completed optimised girder - Source: (a) Vertico 3D concrete printing and (b) the individual DFC elements before assembly [34].

2.2 Structural engineers' perspective

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

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

To deal with this, an approach that significantly deviates from the conventional way of working is needed. First of all, it should require 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 customised material properties. For instance, the density may have to be increased artificially to account for the possible increases in 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 the unexpected deviations from the actual structure to the modelled one, as well as for effects that are not explicitly covered in these analyses. As such experience-based rules are unavailable for 3DCP, significantly more explicit consideration and testing of the possible failure mechanisms and 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 deviations from those of conventional concrete. Local stability and strength effects such as local and plate buckling have become highly relevant and possibly governing. Because of the filigree nature of 3DCP structures, the thermal storage capacity is considerably less, which may result in cracking due to thermal expansion. To identify all of these possible failure mechanisms, Witteveen+Bos performs extensive 3D non-linear finite element analyses (FEA) on its 3DCP projects, for both 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 and properties as well as price. Often, element manufacturers only work with one material supplier. Structural property data are often not easily shared by material suppliers because of the competition in material development. This makes an economical, fit-for-purpose selection of material and structural design very difficult. Furthermore, the lack of certified ancillary products, such as anchors, is a practical but significant obstacle in the general structural use of DFC. Nevertheless, the experience of Witteveen+Bos in acquiring building permits for DFC structures is fairly positive. In Europe, Annexure D of the EN 1990 provides a global basis to approve structures that fall outside the scope of the other parts of the Eurocode. It has turned out to be workable in practice. When given the appropriate attention, e.g. by showing production facilities, the authorities in both Dubai and the Netherlands have shown willingness to give this new technology the required reasonable amount of testing to prove its structural safety. The testing sequence, generally, consists of four steps. Material tests are initially needed to determine the properties required for the 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 is confirmed, the design can be constructed and tested in-situ to ensure that 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 the possible unknown long-term effects.

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

3. OPPORTUNITIES

3.1. Specialised computational methods

Terms such as ‘design complexity’ and ‘freeform architecture’ are often cited as the primary advantage of DFC. 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. This is mainly attributed to the fact that appropriate tools to fully exploit them, also in terms of a commonly agreed ‘tailored’ design and code-regulation framework, may not yet be fully available.

Many recent projects mention structural optimisation theories, often referring to topology optimisation and generative design, in an attempt to optimise the structural efficiency. Topology optimisation (TO) is a mathematical method that is generally used to optimise 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 optimisation 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 minimises the strain energy of a structure (equivalent to maximising its stiffness), as depicted in Figure 12. 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 optimisation 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 behaviour of the material (i.e. concrete having different strengths in traction and compression). In response, several extensions to the original formulation have been proposed thus far [104–107] and for the simultaneous optimisation of concrete and rebars [108–110].

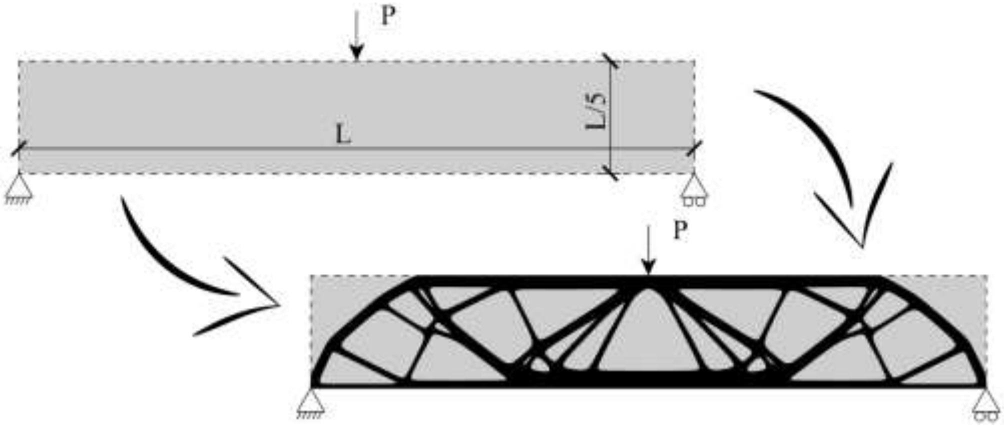


Figure 12: Result of a topology optimisation study of a rectangular design domain subjected to a concentrated load [15].

However, only few of these algorithms have found their way into mainstream use; the common methodology involves using minimum compliance designs in the conceptual design stage; thereafter, several more design iterations are performed using traditional finite element modelling for studying the buckling behaviour of local members, fatigue constraints, vibrations, fire safety, robustness, etc.

Additionally, in order to not restrict the practical cases to formulations specifically made for the design of concrete structures, recent approaches have also been developed for linking TO to additive manufacturing in general, e.g. overhang limitation for TO [111, 112], minimisation of support structures [113], and optimisation with anisotropic materials and infills [107, 114, 115]. Moreover, several multi-disciplinary aspects could be included in the optimisation process as well, e.g. the optimisations of the thermal resistance of wall structures, fire safety, and acoustics are all very important and often make use of multi-material optimisation techniques where the positioning of the materials is crucial; in this latter case, a link can also be made to multi-material 3D printing [116, 117].

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. Designs that are optimised according to specific TO algorithms (in their current implementation) may behave unexpectedly or even suffer from damage because of the 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, TO awaits fundamental investigation about time, location, and fabrication path-dependent material characteristics. Moreover, 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, the first structural design opportunity therefore lies in the investigation of these advanced physical–mechanical characteristics.

Furthermore, an additional opportunity is not focused on optimising the design in the hardened material state, but rather on optimising (or simulating) the finalised design for the manufacturing phase. The reason for this is that many optimised designs are just ‘not ready’ to be digitally fabricated with the current technology capabilities. In other words, models (both analytical and numerical) that can determine and predict how a DFC element behaves while the concrete is still fresh following a topology-optimised fabrication path, are currently desired. Firstly, such models can offer direct improvements in reducing costs and labour-intensive printing experiments, and limit the number of failed printing attempts. Secondly, these models can offer the potential to further tune the existing structural optimisation strategies and help to solve key challenges in the future.

To this end, different analytical models already exist and have been developed for concrete printing applications (mainly layered extrusion DFC processes). For example, Suiker [118] proposed a mechanistic model to analyse and optimise the mechanical performance of straight unreinforced wall structures in 3D printing processes. The model investigates the influence of the printing speed, curing of the material, and geometrical features on failure mechanisms such as elastic buckling and plastic collapse. In contrast, Roussel [50] presented a set of analytical equations studying the rheological requirements for the printable concrete structures needed to control the final geometrical dimensions of a structure. Among others, the 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 (free-form) shapes. In response, Wolfs *et al.* [52, 119, 120] first proposed a numerical model using 3D finite element analysis to investigate the fresh early-age mechanical behaviour 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 to simulate complex geometries. A different approach is taken by Kruger [121] and Reinold [122], where the rheological material properties form the basis for the prediction analysis. Reinold [122] developed a numerical model based on the particle finite element method that can assist with the understanding of the complex interaction between the printing process and the evolution of structural parameters throughout the manufacturing process.

The potential for all of these simulation techniques is to provide quick preliminary data and enable improved production processes for DFC. Basic implementations can help construct design rules and link digital design information with the physical production processes (e.g. as in the process shown in Figure 13). Secondly, a coupling between the existing topology optimisation algorithms can be made and foster reliable design opportunities.

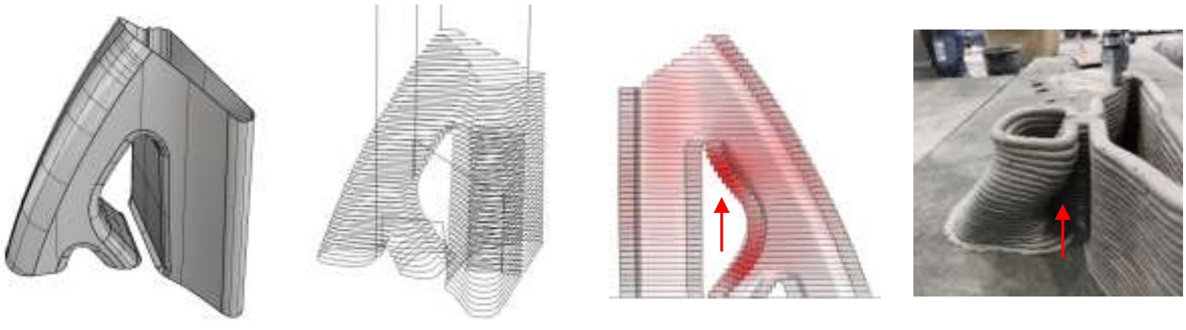

(a) *(b)* *(c)* *(d)*

Figure 13: Complete digital design-to-manufacture process of a segment of the optimised design presented in [34]: (a) 3D poly-surface (b) slicing and tool-path generation, (c) process simulation, and (d) actual fabrication

Note that the simulation techniques described above focus primarily on the fabrication process. To date, much less work has been carried out on the structural design of the final product of the fabrication process. Here, these methods need to combine the intrinsic properties of 3D printed concrete with the structural integrity requirements and the related mechanical models for conventional reinforced concrete structures. Therefore, it is possible to find new structural design concepts, such as weak interface design, which will be discussed in the next section.

3.2 Structural design concepts

Over the past few years, the digital fabrication research community has developed diverse digital fabrication technologies. The researchers have placed a strong emphasis on material and geometrical aspects, whereby the structural aspects have been 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 behaviour has been extensively discussed but not solved. Further, note that digital fabrication 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 has already been extensively explored. 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 optimised shapes (reducing material consumption). However, this advantage is limited in many cases, particularly in buildings, because of the existence of the requirements for geometric simplicity that are independent of the construction technology [123]. Despite the fact that geometric flexibility has already been explored, most of the 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 in geometrically simple structures and to solve the current issues of high costs and lack of compliance with structural integrity requirements. One possibility to comply with the requirements of geometric simplicity while taking advantage of the geometric freedom and the possibilities of multi-material printing is the use of complex cross sections, in which the materials are selectively placed to optimally fulfil several functions (e.g. insulation).

Mata-Falcón *et al.* [48] formulated additional opportunities related to the saving of structural reinforcing steel. For example, reinforcement quantities required for the ultimate limit state can be significantly reduced by using a robotic placement of the reinforcement [93], which allows the provision of 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 the minimum reinforcement, which often makes up for more than 50% of the total reinforcement content [48]. 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 may reduce the minimum reinforcement very significantly. One possibility in this direction is to tailor the concrete grade locally to the actual needs (e.g. reducing the cement content where a low concrete strength is sufficient) [48]. While the 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 the amount of reinforcement required. Besides reducing the tensile strength of concrete everywhere, a further option to reduce the cracking load and to ensure appropriate serviceability behaviour is to produce weak sections in the structure. This corresponds to the concept of crack initiators that digital fabrication technologies can introduce by means of geometric or material discontinuities [48]. One example of intrinsic crack initiators caused by material discontinuities is the weak interface between concrete layers generated in many additive manufacturing processes (e.g. 3D concrete printing). A simple mechanical model [48] shows that a reduction in the tensile strength at the weak interface allows the proportional reductions of the cracking load, crack spacing, and crack widths for a given applied load. The results of this model agree with the experimental observations of crack widths shown in Figure 14 [125]: for the same load, the layered specimen with the reduced tensile strength (by 30%) leads to average crack widths of around 30%–40% lower than in the reference specimen without layers. In this sense, the reduction of crack widths introduced by a weak interface can be used in elements where the serviceability design is critical to reduce the content of the minimum reinforcement and/or improve the durability. In spite of these advances, most of the discussed opportunities for improving the efficiency of structural designs remain unexplored today. Moreover, there will still be a plenty of unforeseen opportunities. One of these could be the development of more structurally efficient or more environmentally friendly reinforcing strategies, which would be possible only because of 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 economical concrete structures.

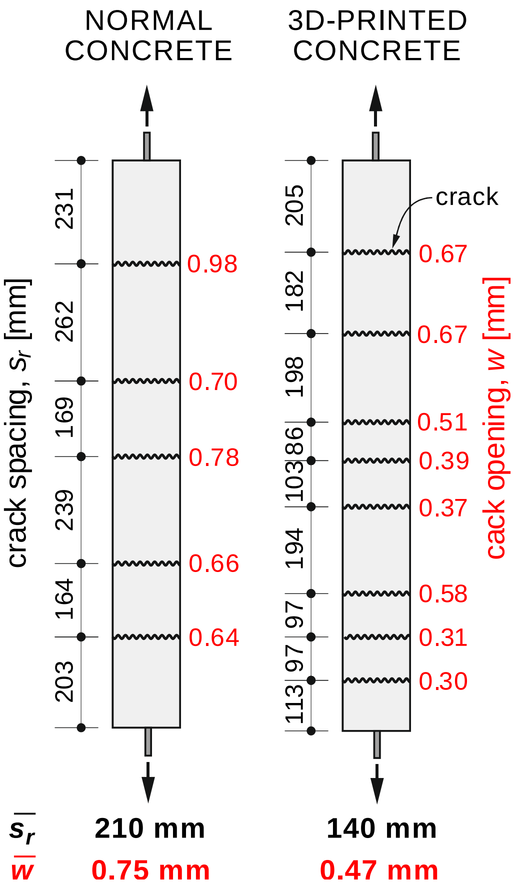


Figure 14. Potential of 3D printing weak interfaces as crack initiators: direct tension tests on tension chords fabricated with weak interfaces (70% of the concrete tensile strength) show a reduction of 30%–40% in the mean crack spacing and crack width at the onset of yielding with respect to the reference conventionally cast specimens [124].

4. STANDARDS AND GUIDELINES FOR DFC STRUCTURES: ON-GOING INITIATIVES

In the highly stimulating and dynamic framework of increasing DFC 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 of setting up adequate transnational initiatives. The latter aim to point out, 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 in highlighting the research needs and fostering the development and technology transfer in a coordinated manner, along with paving the way toward the development of material and product standards as well as established design approaches. The final goal is to achieve consistency and harmonisation with the approaches currently governing the design of conventionally cast reinforced concrete structures.

As a matter of fact, RILEM launched in May 2016 at the 8th International RILEM Symposium on Self-Compacting Concrete held in Washington, DC, 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, not only has started to organise a successful series of International Conferences, now in its second edition, but is also en route to releasing the first international state-of-the-art report on the topic. The report, moving from the materials 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 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, by defining the preliminary structural code prescriptions, e.g. in the form of annexes to the current codes, such as *fib* Model Code 2010, valid for conventionally cast reinforced concrete structures, as well as by complying with the recently reapproved ISO - ISO 22966:2009 - Execution of concrete structures [125].

In the same framework, and fruitfully exploiting its signature healthy interaction between the academia and the industry, as well as the synergy with the existing technical committees dealing with the related specialty topics, from materials science to workability to fibre-reinforced concrete, ACI has also recently formed *ACI Committee 564: 3D printing with cementitious materials*. The Committee held its first meeting 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. Moreover, it has also been regularly organising dissemination and educational events on topics related to 3D printing, which have been instrumental in 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.

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

4.1 Example of DFC structural design protocol

An example of the need for providing an internationally harmonised structural design and material acceptance framework for DFC structures (or even a pathway which has to be followed for implementing such a task) is represented by the case study of the 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 the essential performance requirements to protect the citizen. With a focus on Europe, this means that the safety in the construction industry needs to be ensured at three different stages: building preparation or design (EN-1992-1-1 [126]), building construction (EN 13670 [127]), and materials supply (EN 206 [128]). Unfortunately, the pre-stressed bridges at issue do not comply with any of these regulations. In terms of design, the minimum amount of reinforcement is lacking, particularly in the cross section. Moreover, the flow of forces is considerably more constrained in the printed segments by the tool-path, leaving less room for the redistribution of forces in combination with the plastic deformations of the reinforcing steel. Furthermore, the material properties of printed concrete are not known from the regulations and cannot be tested accordingly to them; this is attributed to the fact that testing cannot be done using standard cylinders without applying intense vibrations. Besides, the impact of the typical layered structures most likely needs to be tested as well, taking into account the printer settings and ambient conditions. One can even question whether the mortars that are printed, without coarse aggregates, can be considered 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 anticipated such a situation. Annex D of EN-1990 [100] describes a procedure for supporting the design by testing. A special protocol has been developed to embed the idea in the design and realisation of the post-tension bridges, as shown schematically in Figure 15.

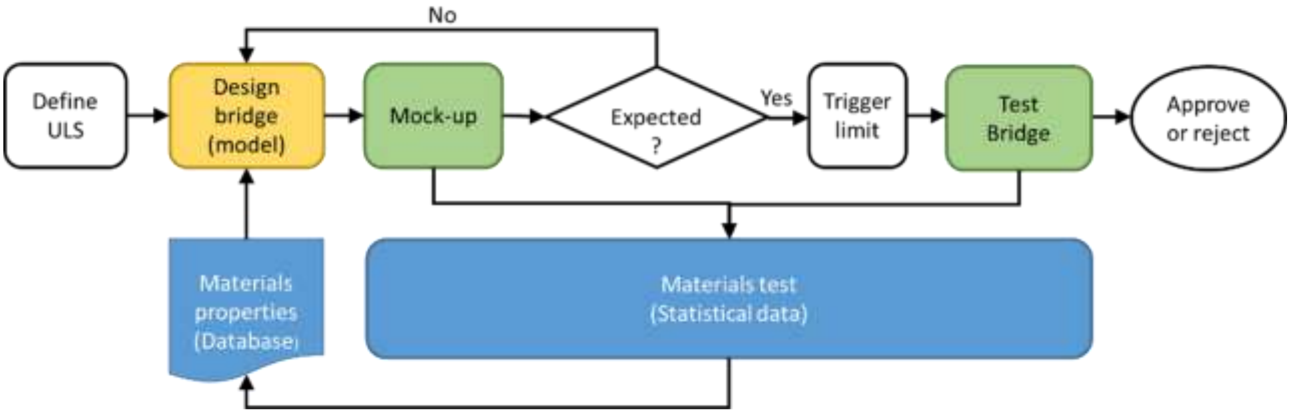


Figure 15: Protocol followed in the design of the post-tensioned bridges

The protocol starts by defining the ultimate limit state and approaches the design of the bridge, accordingly, using standard tools and the available design code. The material properties of the printed concrete still have to be assumed at this stage on the basis of the 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 16).

Figure 16: Large-scale testing, as part of the protocol at TU/e

The predictions must be updated prior to the comparison with the material 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 Annex D of EN-1990. Note that the designer in-charge also needs to define the type of structural behaviour that needs to be compared between the design and the tests upfront and thus, the need for appropriate measuring devices.

In case of an unexpected behaviour, a re-design may 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 in terms of its structural integrity before being used. The reason for the additional tests is the difference in the manufacturer and the manufacturing circumstances between the mock-up and the full bridge and the simple fact that the real bridge is considerably larger than the part tested in the mock-up; this leaves higher chances for imperfections. Obviously, the on-site testing of the bridge is not conducted up to failure. Instead, a type of diagnostic test is performed, which can also be coupled with continuous monitoring to check for deviations, if any, from the predictions along the time, because of different causes, including material and structure aging, accidental events, change in loads, and environmental actions. The load test should be sufficiently high to measure any structural response, but not so high as to avoid unnecessary damage. This trigger limit is defined on the basis of the mock-up definition. Finally, the material properties of the bridge are again tested as a measure of quality control.

It is realised that the protocol 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 the single components of the bridge, such as shear strength (including the size effect), embedded anchor blocks as previously discussed, and anchors, to mount a parapet to the printed concrete.

5. Discussion

The information presented in Table 1 points out that the number of realised large-scale construction projects using digital fabrication techniques has surprisingly increased in the last two years. The growing number and ambition of the DFC construction projects to be delivered in the near future points out the urgent need for new, unified, and effective design-to-fabrication approaches [129, 28], including the testing methods and regulations. Indeed, at the current stage of development, DFC cannot sufficiently guarantee the 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 for their safe use. However, when evaluating the potential of structural engineering in DFC, a highly inter-linked scenario must be taken into account, as depicted in Figure 17. In particular, for a given project, determining the relationships between material performance (in either the fresh or the hardened state), DFC process adopted, pre-defined function, reinforcement typology, and design aspects represents the major challenge thus far.

The examination of the projects reported in this review paper revealed that DFC by means of an extrusion process is by a large margin the most widely used technique thus 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 considerably larger research and development effort put into this technology with respect to other DFC processes.

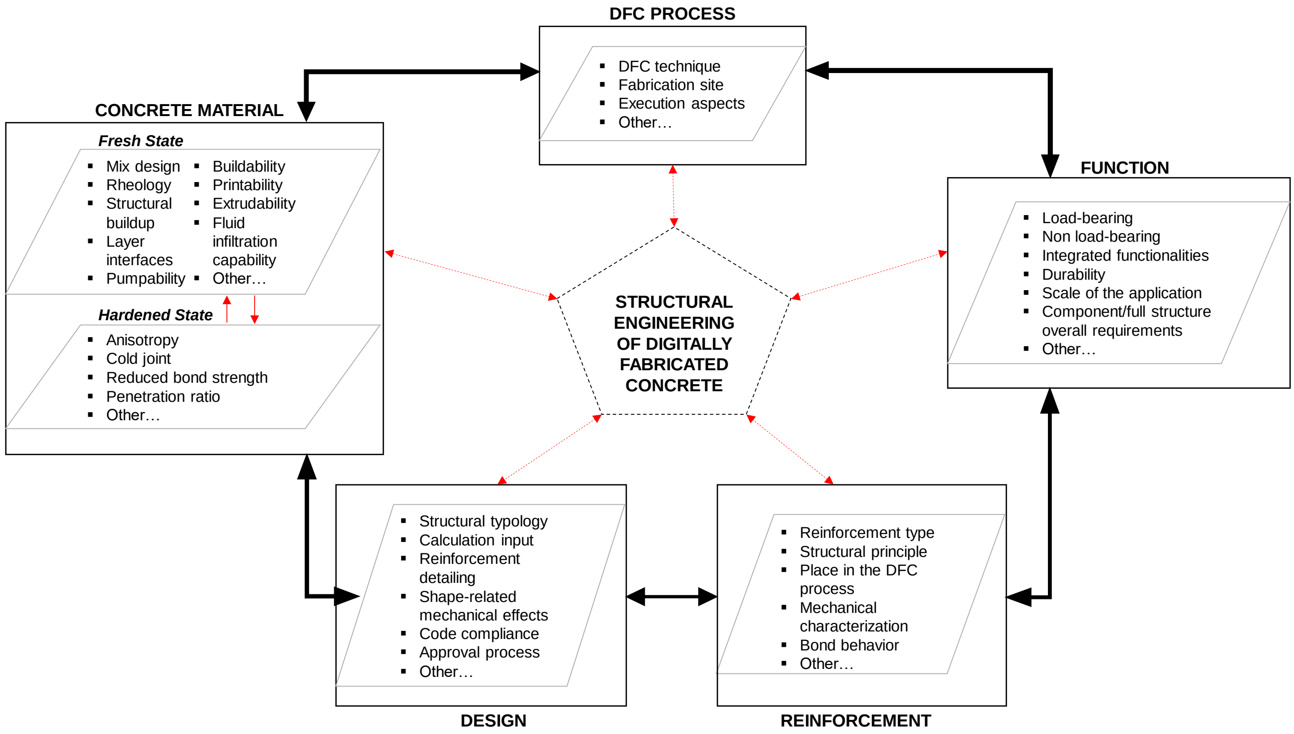
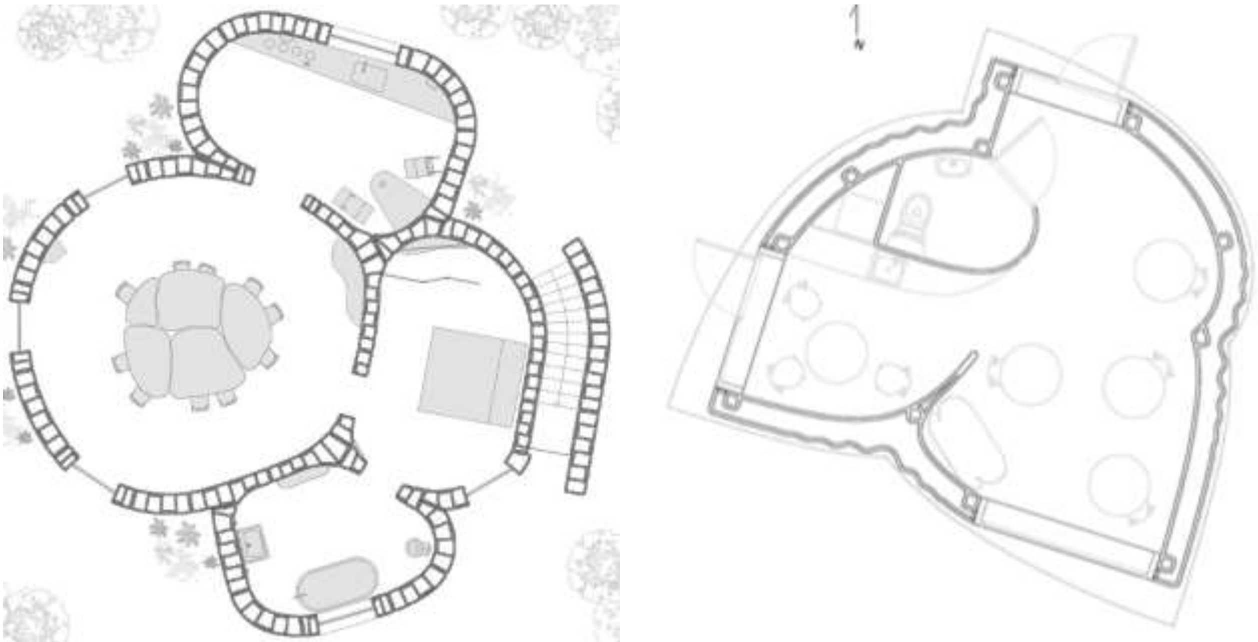


Figure 17: Inter-linked aspects for the structural engineering of DFC structures.

In terms of the 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 18). From the structural point of view and for the design of these construction solutions, the realised houses resemble the behaviour of (unreinforced) masonry structures or that of an assembly of load-bearing walls subjected to vertical loads. Indeed, for a limited number of situations (e.g. based on the in-service conditions or the type of applied load), the requirement of tensile capacity and ductility can be over-ridden by designing structures loaded only in compression or with minimal levels of traction. This solution is reasonably feasible and easy to apply, as it does not require additional manufacturing steps to insert reinforcement while guaranteeing form freedom; however, note that unreinforced single curved walls (the standard case in the listed applications) could have been built cheaper by using other conventional techniques. Moreover, the fully structural characterisation of such types of structures is yet to be determined (e.g. in-plane/out-of-plane behaviour), particularly focusing on the mechanical role of the layer interfaces/bonds in such possible design approaches.

Design limitations and requirements should be carefully considered in reference to the risk of shrinkage cracks and tensile stresses induced by the imposed deformations, particularly involving support settlements and displacements. In this regard, the existing 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, can represent a possible inspiration for adapting the current available design. However, as these types of structures are dependent on new material 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.



(a) (b)

Figure 18: Plan view of assembled DFC panels for housing: (a) 3D Housing 05 [74] and (b) ‘the BOD’ [75]

As far as infrastructure objects are concerned, the available literature reports that the most common method to produce bridge structures involves digitally fabricating concrete segments by using an extrusion process (with an almost free-form in the cross section) and then assembling them on-site by means of post-tensioning in the direction of the stacked layers of concrete. This is somehow similar to the already available technology on precast segmental bridges [130] regulated by the post-tensioning design principles. The evaluation of the structural integrity of these types of structures should be complemented by experimental validation (as described in *Subsection 4.1*) 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 3d printing fabricated by D-shape in eight segments using a micro-reinforced concrete), there was not enough documentation to be discussed in this paper.

On 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. [45, 94, 131, 132]), temporary projects have normally been classified as artworks (e.g. KnitCandela) and, for this reason, did not require strict structural design regulations.

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

- The reference lifetime for structural design input is relatively short, probably because of the insufficient knowledge on the durability behaviour of innovative DFC products (e.g. five-year reference lifetime).
- The structural design is frequently reliant on experimental inputs from the researchers from academia (particularly for DFC material property inputs).
- The fact that different available structural design codes allow exceptions in reference to innovative construction products/systems (provided that they are well founded theoretically or experimentally) is exploited. 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 can be derived from experimental testing; the corresponding design values can be determined, for instance, according to EN 1990, Annex D. Moreover, note that the safety factor commonly used to calculate the design concrete compressive strength has been increased in some cases to account for the larger scatter in the mechanical properties of digitally fabricated concrete.
- Even though EN 1990 Annex D adequately covers the engineering issues for construction and first service, for cyclic loading in brittle DFC objects/components (particularly in the cases of weak layer interfaces), long-term performance needs to be evaluated with respect to the crack propagation phenomena over time.
- Ensuring of the concrete cover dimensions depends on the specific DFC technique adopted and can be achieved within the printed layer itself, by appropriately filling the hollow-printed objects/components or by covering a pre-arranged steel reinforcing system.
- In unreinforced DFC products, structural design provisions are mostly used to verify the structural integrity in terms of the maximum and minimum concrete stresses as well as the maximum allowable deflections. For DFC structures containing reinforcement, all the design provisions concerning the composite action of the concrete and the reinforcement should be considered as well.
- Unreinforced digitally fabricated products are dimensioned in a way that they do not exceed the design concrete tensile strength. Therefore, they are typically restricted to applications with very low structural demands, such as the vertical walls of a single-storey building.
- The mechanical issues of component joining from prefabricated components are still mostly not yet addressed, particularly with respect to the print inaccuracy, roughness, and stress concentrations.
- Classical approaches for the simulation of the behaviour of structural elements are only suitable for simple 1D or 2D geometries. The simulation of all the 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 the envisioned opportunities to exploit the benefits of DFC, topology optimisation procedures certainly represent the most promising approach because of 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 the applied loads and/or the allowable deformations. However, it is clear that the design conceived in this way is currently too demanding for topology optimisation procedures, as their level of development is still not sufficient to deal with the particularities of DFC techniques or reinforcing strategies. In some cases, DFC can also be used to control concrete cracking as well as to provide additional opportunities related to the saving of structural reinforcing steel.

6. CONCLUSIONS

In this paper, we discussed the recent construction projects carried out by means of DFC technologies. The focus was on the aspects of structural design and engineering of DFC with a major emphasis on extrusion-based concrete 3D printing, as it is one of the most widely used and documented DFC technologies thus far.

Depending on the specific DFC process adopted, the structural use of DFC products requires appropriate attention throughout the project, from the design, to the analysis, production, execution, assembly, experimental validation, and in-service use. Progress has been made in this sense, particularly for the general approval of construction projects as well as for the code compliance of DFC products; this has been possible mainly because of the fact that different available structural design codes allow exceptions on the condition that appropriate 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 a considerable amount of research needs to be performed to consider DFC as a standard construction method. One of the priorities is represented by the definition of appropriate parameters for the extensive concrete material characterisation to be used as input in the structural design. The development of suitable numerical modelling approaches is also desired in order to achieve further improvements on the topology/functional/structural optimisation 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 a considerable amount of research effort on this topic.

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