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Chapter 6
Structural Design and Testing of Digitally Manufactured Concrete Structures

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Abstract The form freedom enabled by digital fabrication with concrete technologies provides advantages for a wide range of concrete based objects, from architectural to structural elements. The current chapter focuses on the specifics of structural design and engineering of DFC with emphasis on those technologies based on Additive Manufacturing with extrusion. Since it is a new and innovative way to build, a clear common approach to structural engineering has not yet been developed. As a result, this chapter aims to introduce the specific challenges of structural design and engineering with the additive manufacturing technology, providing an overview of

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structural typologies that have been developed (especially concerning the reinforcement strategies, including fibre reinforcement). Furthermore, the structural principles adopted in DFC and the codified approaches used in conventional reinforced concrete is compared, and putative structural testing procedures and validation methods for DFC are reported.

Keywords Additive Manufacturing · Structural design · Reinforcement strategies · Testing

6.1 Introduction

The form freedom enabled by digital fabrication with concrete (indicates as DFC below), technologies provides advantages for a wide range of concrete based objects, varying from "sculptural" urban furniture to artificial reefs, and from sewage pits to art objects. For load-bearing elements in building structures, DFC has high potential too, particularly by introducing the possibility to materialise a topological optimisation by straightforwardly bridging the design process with the manufacture, i.e. to adjust the geometry in order to optimise structural performance for minimal material use (if necessary, customised optimisation for each individual element), without prohibitive cost increases. Indeed, a variety of construction projects for which DFC or DFC parts structurally are applied, have been presented in recent years (Labonette et al. 2016; Bos et al. 2016; Buswell et al. 2018)—and the number of examples is growing rapidly.

The current chapter focuses on the specifics of structural design and engineering of DFC with emphasis on those technologies based on Additive Manufacturing process that use extrusion.

A clear common approach to the structural engineering of DFC technologies has not yet been developed and thus bespoke procedures have been applied to obtain the required approvals, following, for instance, the indications enclosed in Annex D of the Eurocode 0, which allow individual approvals based on experimental testing. To nevertheless facilitate the development of a common understanding of structural engineering for DFC and related issues, thus moving actual applications towards achieving the full potential offered by DFC technologies, this chapter aims to:

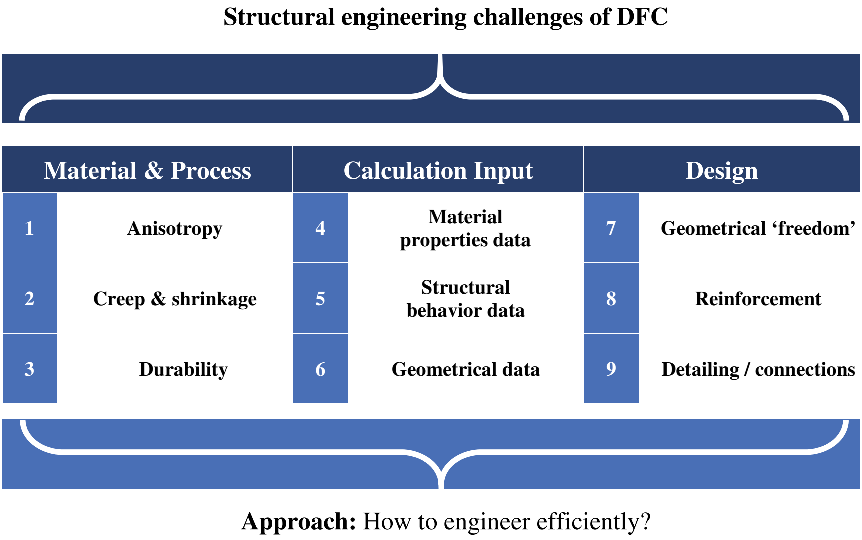
- Introduce the specific challenges of structural design and engineering with DFC, especially for the additive manufacturing technology.
- Provide an overview of structural typologies that have been developed or are under development, particularly with regard to reinforcement strategies.
- Compare the structural principles and modelling approaches of structural DFC to codified approaches used in conventional reinforced concrete.
- Discuss discrete fibre reinforcement for DFC, as one of the main strategies to obtain toughness, ductility and post-cracking tensile strength in DFC elements.
- Finally, discuss putative structural testing procedures and validation methods for DFC.

The projects that have been carried out until now are generally small in scale, use a range of different DFC processes and materials, are based on a variety of structural principles, and in terms of the consequences of an eventual structural failure are mostly minor. Due to the challenges further elaborated in this chapter, the geometrical freedom offered by DFC has hardly been capitalised upon in actual in-use projects.

As a result, the discourse in the field of structural engineering of DFC has been relatively limited. DFC projects have received plenty of popular and professional attention, but in-depth publications on the applied structural approaches have been scarce. Theo et al. (2018) has presented the design, testing and construction of a bicycle bridge. Based on the same as well as another project, (Bos et al. 2019) discussed large scale structural testing for 3D concrete printing. However, neither provided generalised discussions with regard to the structural engineering of such projects. The first endeavour to provide a holistic view on this issue, which can be found in (Salet and Nijmegen 2019), established a safety protocol for the design and testing of a 30 m multi-span pedestrian and bicycle bridge (see case study, Chap. 2 Sect. 3.1). Nonetheless, it starts from comprehensive observations regarding the structural particularities of 3D concrete printing, and thus provides a dedicated elaboration of the very generally stated requirements in Annex D of Eurocode 0.

The challenges associated with the structural engineering of DFC can be categorised into three groups (see Fig. 6.1):

- The materials and processes effects on printed products.
- Input structural design calculation.
- Aspects of design.



Structural engineering challenges of DFC

Material & Process		Calculation Input		Design	
1	**Anisotropy**	4	**Material properties data**	7	**Geometrical ‘freedom’**
2	**Creep & shrinkage**	5	**Structural behavior data**	8	**Reinforcement**
3	**Durability**	6	**Geometrical data**	9	**Detailing / connections**

Approach: How to engineer efficiently?

Fig. 6.1 Structural engineering challenges associated with DFC

These will be briefly elaborated below. Jointly, they summon the question of how a DFC structure can be efficiently designed and calculated—a topic for further research. Since existing codes have limited applicability to DFC as argued above, the validation of the structural design developed for a project is a further challenge to be addressed and which is more extensively discussed in Sect. 6.5.

6.1.1 Material & Process

The materials and processes used in DFC result in an intrinsic behaviour and properties that can be distinctively different from those commonly found on conventional cast concrete. With most DFC processes material is positioned in layers that results in anisotropic (tensile) strength (anisotropic stiffness has not been shown). Generally, the tensile strength perpendicular to the interface is lower than in the other directions. However, quantitatively this effect can vary from negligible to dramatic (<5% to >90% strength reductions) depending on material and process input parameters. This can be due to well-known or yet unrecognised influencing factors. The directional dependency of strength properties was recognised at an early stage by (Le et al. 2012), and has been the topic of a considerable number of studies (Feng et al. 2015; Nerella et al. 2016; Zareiyan and Khoshnevish 2017; Panda et al. 2017, 2018; Paul et al.; Nerella et al. 2018; Wolfs et al.; Van Der Putten et al. 2019; Panda et al. 2019; Marchment et al. 2017; Keita et al. (2019); Zahabizadeh et al. 2019), a summary of which is provided by (Timothy et al. 2018). However, because these studies have tended to be phenomenological in nature, rather than theoretical and explanatory, this has not yet resulted in a full understanding of the impact of layering and time between consecutive layers. Furthermore, with the exception of (Le et al. 2012), the focus has entirely been on the vertically stacked layers. Nevertheless, considering the scale of existing printing nozzles as well as often presented zig-zag infill structures, (local) interfaces between horizontally joining layers are also likely to occur in actual DFC projects.

The effects of creep and shrinkage are much less studied. Since printing mortars generally lack aggregates above approximately 2–3 mm grain size and the cement content is high when compared to conventional concretes, shrinkage and creep should be expected to be relatively high. The often thin-walled DFC geometries and lack of formwork increase the magnitude and rate of drying shrinkage compared to conventional concrete. In combination with restrained deformations (that may already occur due to friction of the print bed during initial stages of curing, or from uneven curing and shrinkage), this may have a significant influence on the structural integrity of the printed object, due to resulting cracking.

Several studies have pointed out that the layered structure in DFC may also result in reduced durability of the printed component. It was shown that increased interlayer interval times result in an increase in porosity (Van Der Putten et al. 2019), capillary water ingress (Schröfl et al. 2019), and chloride penetration (Bran Anleu et al. 2018).

However, it is yet unknown to what extent this impacts structural engineering considerations (e.g. with regard to strength development over the reference life span). In addition, some authors have argued that the chemicals used in some DFC processes, such as retarders and accelerators, may have a harmful on the long-term effect on the reinforcement (Lloret-Fritschi et al. 2019; Stefanoni et al. 2019).

6.1.2 Calculation Input

A structural calculation requires several types of input. Generally, a structural checking is executed by comparing a calculated structural response due to certain predetermined combination(s) of action(s), which are statistically determined, to limit values for that response. To calculate the response, geometrical and material properties data are used as an input. Material property data are also required to determine the limit values, such as the structural behaviour data. Partially due to the particularities discussed in the previous subsection, and partially due to the sheer novelty of the technology, there is a quantitative lack of data in all these three categories (i.e. material, structural, geometrical).

First of all, although some suppliers provide product data of their printable mortars obtained by mechanical behaviour studies (see previous subsection), such data are usually incomplete (i.e. do not provide values for all relevant parameters required for designing). Moreover, they are quantitatively limited (thus their statistical validity is unknown), and they are based on experimental procedures that are both not fully detailed and have not been universally agreed upon. Because the relations of material properties with manufacturing process parameters are still largely unknown, it is also unclear to what extent the provided values could be generally used. Strength classes, as the ones for concretes, fibre reinforced concretes, cements, and mortars, have not yet been developed, which makes interchangeability between materials (and suppliers) and between manufacturing systems impossible without a full reconsideration of the structural performance.

Secondly, it should be noted that a significant number of limit values provided by codes is based on empirically obtained relations (for instance for the shear resistance of reinforced concrete beams) based on testing of structural elements (rather than on materials testing). Such empirical data is practically non-existent for DFC. An important factor regarding the latter technology is that although the manufacturing method of conventional (reinforced) concrete is basically the same everywhere, the processes in DFC can vary considerably from one installation to another (see (Buswell et al. 2020) and Chap. 2). This makes it much difficult to obtain generally validated empirical relations. Nonetheless, theoretical solutions should be pursued, and/or more detailed modelling and checking should be applied (e.g. through Finite Element Modelling; FEM), as discussed further in Sect. 6.3.

Finally, a structural analysis of DFC may also be encumbered by a lack of geometrical data. For instance, in most filament-extrusion-based DFC processes, the filament height, width and density can be adjusted through adaptations to the pump pressure, nozzle speed, nozzle geometry, and layer off-set. However, more often than not, it is not exactly known which settings result in which geometrical dimensions. This issue is further complicated when stacking layers of fresh material, that may deform previously deposited layers, or by changes in nozzle speed due to the followed print paths (e.g. at corners).

6.1.3 Design Aspects

The geometrical freedom offered by DFC is enriching to the realm of structural concrete, but also introduces many challenges. Most codes are based on relatively simple, 1D (beams, columns) or 2D (flat shells, plates) mechanical schemes. In complex geometries, such the ones enabled through DFC, these approaches are no longer suitable. Thus, sophisticated modelling approaches based on FEM should be required.

Nevertheless, DFC also dictates some geometrical restrictions. In filament-extrusion technologies, this generally includes, among others, a fixed filament section dimension (i.e. a sort of print resolution), a continuous print path per layer in the object, and preferably a print path that per layer connects start to end, to achieve efficient printing of subsequent layers. In a stacked-layer process, cantilevering is often limited and 2.5D objects are obtained. Finally, it should be noted that the print path design of a globally identical shape may have a significant impact on the resistance of an object, due to the location of (vertical) interfaces and orientation of fillets—and magnitude of associated peak stresses.

A rather different, but at least equally important aspect of DFC structural design is that of reinforcement, which is required due to the fact that printable cementitious mortars, like conventional concretes, are quasi-brittle. In conventional concrete, the use of (ribbed) steel bars has long been the dominant method of reinforcement, the design of which belongs to the basic toolbox of practically any structural engineer. Besides that, reinforcement based on the application of a variety of discrete fibres, separately or in combination with steel bars, has been developed for several decades and is now entering "code-type" guidelines for structural engineering (e.g. FIB (2010)). Other reinforcement solutions include various types of meshes or bars from other materials.

Contrary to conventional concrete, no standardised reinforcement method is yet available for DFC (Asprone et al.). Instead, a solution strategy has to be designed, calculated, and tested for each case—a considerable burden on any project. The application of steel bars is incompatible or undesirable for DFC, amongst others because of geometrical difficulties, uncertainties regarding the reinforcement-to-matrix bond, and the integration of the application of reinforcement bars in the printing process. The fact that it is nevertheless sometimes applied is due to a lack of sufficiently matured alternatives, which are, however, under development as discussed in Sect. 6.2. Fibre reinforced DFC is probably the most obvious option, as well as one of the most promising, strategies and is extensively discussed in Sect. 6.3.

For detailing and connections, finally, a similar situation as for reinforcement can be discerned: there are no standardised solutions available. Including connection provisions in the casting of an element (such as starter bars), as is often done in conventional reinforced concrete, is not obvious in DFC processes. A project-specific post-processing step will generally be required. Special attention is needed for the introduction of stresses into the respective DFC elements, as here too; no standardised analysis methods are available.

Considering the shortage of data on a considerable number of relevant aspects, the question is justified whether responsible structural design with DFC is currently possible. Even though the material behaviour is not fundamentally different from conventional concrete, the answer is nevertheless affirmative—as underlined by the realised projects. On a basic level, the structural behaviour of DFC is very similar to conventional concrete. Therefore, the structural use of DFC requires specific attention throughout an integrated project approach, i.e. from the design, to the analysis, (experimental) validation, production (printing path and techniques), assembly, and demolition. The extent to which this is required is highly dependent on both the specific project requirements and the employed DFC process.

6.2 Catalogue of Digital Fabrication Processes to Manufacture Concrete Structures

6.2.1 Structural Systems

Based on their topology, structural systems might be divided in (i) framed structures, made up of linear elements (defined by either a straight or curved axis); (ii) surface structures, made up of planar (plates, slabs) or curved elements (shells); and (iii) solid structures (Buswell et al. 2018). It should be noted that most structures combine elements with different structural topologies. Given the fact that concrete is suitable to resist compressive forces, but requires reinforcement to cope with tensile forces (Asprone et al.), a relevant distinction between structural elements in the context of DFC is the load-carrying mechanism, depending on whether acting loads are carried (i) by normal forces (in the case of linear elements) and membrane forces (in the case of surface elements), or (ii) developing significant bending moments, tensile and/or shear forces. The most common standard structural elements are briefly discussed in the following paragraphs concerning this classification.

Linear elements in framed structures with general stress resultants (i.e. developing bending and shear actions as well as normal forces) are typically known as beams, which can be either straight or curved. Straight elements with external compressive loads exclusively in the axis direction are frequently referred to as columns. For a certain load state, the axis of a beam can be selected in such a way that the bending and shear actions disappear, and only compression forces occur; this element is an arch. A truss structure (i.e. straight elements connected via hinges with loads applied at the joints only) is another framed structure with elements subjected only to normal forces (compression or tension).

A shell is the most general surface structure, as it can be single or double curved and includes all general stress resultants (membrane and shear forces plus bending and out-plane twisting moments). Similarly, as for the arch, the shape of a shell can be defined to have primarily membrane forces for a certain load case; these particular shells are known as membrane shells, membranes or funicular shells. Plane structures can basically be divided in slabs, when loads are acting perpendicular to its plane (subjected to bending and twisting moments plus shear forces) and plates, when carrying in-plane loads (subjected only to membrane forces). Concrete plates can also be analysed by means of a truss analogy (Marti 1985; Schlaich et al. 1987), i.e. some areas are subjected to compression stress while others areas are in tension and, therefore, require reinforcement.

From the previous overview of structural systems, it is clear that only a very limited range of structural elements (i.e. columns, arches, compressed bars of trusses and funicular shells) might be designed (in terms of failure resistance/ultimate strength) to work as compression-only structures for permanent actions. However, tensile forces will still arise in these structures for variable loads and long-term actions, except for massive structures (as is the case of ancient structures still standing nowadays), which are out of the scope of DFC that mainly aims to minimise the material use and exploit form freedom. Consequently, modern load-bearing concrete structures unavoidably require reinforcement for resisting tensile forces in order to ensure structural code compliance (as only for very particular verifications, e.g. shear and punching shear in slabs, it is allowed to rely on the tensile strength of concrete). Moreover, besides reinforcement not been needed for strength, modern design codes for structural concrete still require providing a minimum reinforcement amount to ensure other performances such as good durability, serviceability, sufficiently ductile behaviour and robustness.

The implementation of reinforcing solutions into digital manufacturing technologies is a key aspect when fabricating load-bearing concrete structures, as reinforcement is required regardless of the structural system. The following Sect. 6.2.2 gives an overview and classification of different reinforcing strategies suitable for DFC, while Sect. 6.2.3 discusses the feasibility and potential to adopt these reinforcement strategies for the main digital concrete manufacturing processes (especially for additive manufacturing).

6.2.2 Classification of Reinforcing Strategies

Reinforcement used in concrete structures can be categorised in distinct ways, such as internal or external, metallic or non-metallic, and passive or pre-stressed (active). Metallic reinforcement products are typically used as bars, wires, welded fabric or discrete fibres for passive reinforcement, while wires, wire-strands and bars are the most frequent option for active reinforcement ones. Non-metallic reinforcement (e.g. carbon, glass, aramid or polyvinyl) is available in a very wide range of products, as bars, laminates, strips, sheets, grids, fibres or knit textiles. In conventionally built structures, passive internal reinforcement consisting of deformed steel bars with a characteristic yield strength around 450–500 MPa is by far the most used combination. This type of reinforcement is inexpensive, ductile, robust and easy to place on-site, but the use of non-conventional manufacturing technologies affects the way this reinforcement can be installed/incorporated. Therefore, other types of reinforcement, such as textile reinforcements and fibrous reinforcements, which have not yet been widely accepted and applied in current for a wide range of concrete structures, might be reinforcing solutions more suitable or compatible for DFC. Asprone and coauthors (Asprone et al.) proposed a classification (Table 6.1) of reinforcement strategies for DFC taking into account the structural principle of the reinforcing solution, as well as the digital manufacturing stage when the reinforcement is placed. It should be noted that, according this classification, hybrid solutions composed of several reinforcing strategies are possible as well. Reinforcing solutions consisting of the application of a ductile printing material will typically be applied during concrete manufacturing. In structures submitted to pure compressive loads due to the application of active reinforcement, the reinforcement can either be manufactured before (pre-tensioned reinforcement) or after concrete manufacturing (post-tensioned reinforcement). In the composite alternative, the reinforcement might be placed before, during or even after manufacturing (providing some gluing/connection system). Avoiding the use of reinforcement (compressed-only structures due to shape) has been extensively explored especially in the context of DFC (Akbarzadeh et al. 2015) because the difficulty of implementing reinforcement. However, this strategy is only applicable to a very limited range of applications, as discussed in Sect. 6.2.1.

Nerella et al. (2018) provided an alternative classification of reinforcement manufacturing processes for DFC, distinguishing between continuous and discontinuous reinforcing processes, clearly linked to the classification provided in Table 6.1. Discontinuous processes correspond to the installation of reinforcement before or after the concrete manufacturing, while continuous processes require adding reinforcement during concrete manufacturing.

6.2.3 Strategies to Fabricate Concrete Structures

Digital processes to manufacture concrete structures include a digital process for forming of concrete (discussed in Chap. 2) as well as a suitable reinforcement strategy (see classification in Sect. 6.2.2). While the reinforcement should ideally be placed automatically to allow for digital manufacturing of the entire structural elements, most reinforcing strategies suitable for DFC are not mature enough and still require a high amount of hand-labour. This is admissible at the current early age of digital fabrication of concrete structures (e.g., digital processes for forming

Table 6.1 Classification of reinforcement strategies for DFC

By structural principle	By stage of the reinforcement manufacturing
Reinforced printing material (e.g. fibre reinforced materials):	Before concrete manufacturing:
This is the case where rebar reinforcement is not needed and only the fibres are able to provide the tensile strength and the deformation capacity required for the application	Reinforcement is arranged and placed in the final configuration before concrete deposition through a digital fabrication method
DFC composite (e.g. with placement of passive reinforcement):	During concrete manufacturing:
This is the case where rebar/continuous reinforcement is needed, and it can be also installed with automated/robotised processes	Reinforcement is added during concrete manufacturing or belongs to the material itself (e.g. fibres)
Compression loaded structures (e.g. due to shape or pre-stressing):	After concrete manufacturing:
This is the case where no reinforcement or only pre-stressed reinforcement is required	Reinforcement is installed once concrete element has been manufactured through a digital fabrication method

of concrete still require considerably manual intervention in spite of being much more mature). Even the difficulty to integrate and automate reinforcing solutions for DFC, researchers should avoid facing exclusively concrete manufacturing without reinforcement, unless aiming to produce non-structural elements.

The feasibility and potential of the reinforcement strategies presented in Table 6.1 depend on the digital process used for forming concrete. Partially based on the work of Asprone et al. (2018) and Nerella et al. (2018), reinforcement strategies suitable for some of the main digital concrete manufacturing processes are discussed in the following:

- Additive manufacturing—extrusion:
  - *Enveloping reinforcement with concrete* (reinforced before concrete manufacturing; composite (concrete / steel) structure): a forked nozzle lays concrete on both sides of the reinforcement (Fig. 6.2a). This strategy allows reinforcing perpendicularly and within the printing direction, but currently, this method is limited to single curved elements with only one layer of reinforcement (see case study of the Sect. 3.8 in Chap. 2).
  - *Printable fibre reinforced concrete* (reinforced during concrete manufacturing; reinforced printing material): short fibres suitable to be pumped are added to the concrete matrix providing post-cracking tensile and stress-bridging capacity across the cracks. This solution provides strong fibrealignment in the printing direction, which could increase the fibre reinforcement effectiveness. Given the potential of this solution, it will be further discussed in Sect. 6.3.
  - *Entraining cable into the concrete filament* (reinforced during concrete manufacturing; composite structure): a flexible reinforcement cable is directly

  entrained into the extruded layer during printing (Fig. 6.2b). This concept allows reinforcing the elements in the printing direction even for complex shapes but is difficult to ensure a proper anchorage of the cables when working with smooth high strength cables (see case study of the Sect. 3.1 in Chap. 2).
  - *Placing reinforcement between 3D-printed concrete layers* (reinforced during concrete manufacturing; composite structure): reinforcement such as steel bars or textile reinforcement can be placed in between two layers, providing reinforcement in the printing direction (Fig. 6.2c). When using stiff reinforcement bars, a pre-bent in usually complex shapes is required.
  - *External reinforcement arrangement* (reinforced after concrete manufacturing; composite structure): two separate external steel reinforcing layers are post-installed on both sides of the hardened concrete element and connected through orthogonal threaded rods (Fig. 6.2d). This approach allows to reinforce complex shapes, but it is hand-labour intensive, and its durability/fire resistance should be addressed.
  - *Pre-stressed external reinforcement* (reinforced after concrete manufacturing; compression loaded structure): pre-stressing with post-placing of reinforcement in 3d-printed conduits (Fig. 6.2e). While this solution might limit the form freedom, known strategies and detail solutions from conventional externally pre-stressed structures can be directly applied.
  - *Reinforcement inside 3D-printed concrete formwork* (reinforced after concrete manufacturing; composite structure): here a 3D-printed element is used as a lost-formwork and a conventional reinforced concrete structure is produced inside the lost formwork (Fig. 6.2f and case study of the Sect. 3.3 in Chap. 2). In this approach, complex reinforced structures can be produced with the injection reinforcement technique (Fig. 6.2h). Digital manufacturing generally refers to the formwork and not to the entire manufacture of the component. The Injection reinforcement technology, on the other hand, also allows complete automation of the process.

- Additive manufacturing—spraying:
  - *Spraying around or on top of reinforcement* (reinforced before concrete manufacturing; composite structure): in this process, concrete is sprayed around (or even just on top) a pre-built mesh or textile reinforcement (Fig. 6.3a). This alternative is more promising than the equivalent extrusion process (enveloping reinforcement with concrete), as in this case the form freedom is not restricted, due to the flexibility of the spraying process. A specific implementation of such a process is the case study of Sect. 3.2 in Chap. 2, in which there are two spraying processes, i.e. before and after the reinforcement placement.
  - *Sprayed fibre reinforced concrete* (reinforced during concrete manufacturing; reinforced printing material): either short pumpable fibres can be added to the matrix or longer ones can be added sprayed together with the concrete. While fibre alignment is less controllable than when applied with extrusion production, by spraying is possible to provide fibre reinforcement in any direction of the structural element.

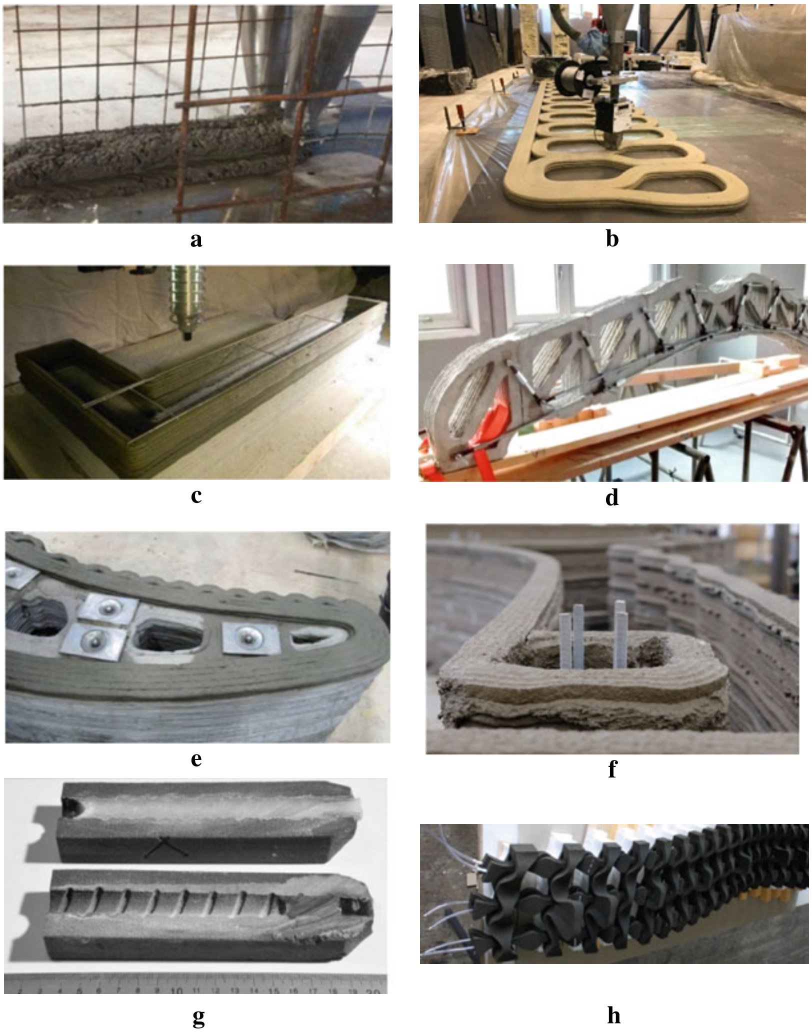


Fig. 6.2 Reinforcing strategies for extrusion based additive manufacturing: **a** enveloping reinforcement with concrete (Schlaich et al. 1987), **b** entrained cable into the concrete filament (Bos et al. 2017), **c** reinforcement placed between 3D-printed concrete layers (TotalKustom 2015), **d** external reinforcement arrangement (Asprone et al. 2018), **e** prestressed external reinforcement (Lim et al. 2012), **f** reinforcement inside 3D-printed concrete formwork (Apis-cor 2017), **g-h** injection reinforcement inside 3D-printed concrete formwork (Kreiger et al. 2019)

  - The external reinforcement arrangement and the pre-stressed external reinforcement, already presented for extrusion processes, might be applicable very similarly to sprayed concrete elements.

- Formative manufacturing:

- *Forming around existing reinforcement* (reinforced before concrete manufacturing; composite structure): in forming methods, the reinforcement integrated can be fabricated before concrete manufacturing and then the concrete is shaped around it (see the case study of Sect. 3.6 in Chap. 2, Fig. 6.3b). The complex

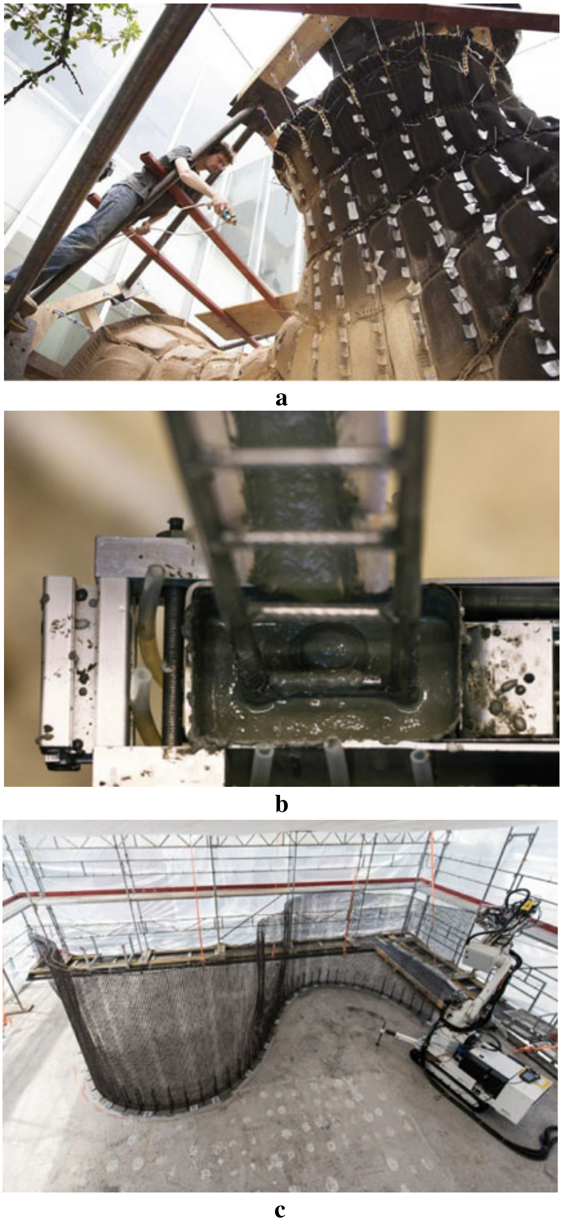


Fig. 6.3 Reinforcing strategies for spraying based additive manufacturing and for formative manufacturing: **a** spraying on top of knit textile membrane (Knitcrete et al. 2018), **b** forming around existing reinforcement (Smart Dynamic Casting 2019), **c** robotically fabricated reinforcement as permeable formwork (Mesh Mould 2019)

geometry of the vertical structural element is thus the main source of difficulty when using internal deformed steel bars, which could be solved using robotic reinforcement assemblies.

- *Reinforcement as permeable formwork* (reinforced before concrete manufacturing; composite structure): this strategy corresponds to the Mesh Mould technology in which a double side fine reinforcement mesh is robotically fabricated to serve at the same time as structural reinforcement and permeable formwork. In the first implementation of this strategy the meshes are produced by welding short reinforcement bars in one direction, therefore the mechanical capacity of the reinforcement is limited to this direction.
- The use of fibre reinforced concrete or external pre-stressing might be applied as well for formative manufacturing, but the suitability of these reinforcing strategies should be studied for each specific application.

6.3 Fibre Reinforcement in Digitally Fabricated Concrete

As highlighted in previous sections of this chapter, fibres do represent one of the key alternatives to face the need of providing adequate reinforcement in digitally fabricated concrete materials and structural components. As a matter of fact, the possibility of extruding/3D printing a fibre reinforced composite represents a straightforward solution encompassing the structural requisites highlighted above with the peculiarities of the extrusion-based digital fabrication technologies.

Fibre Reinforced Concrete (FRC) and Fibre Reinforced Cementitious Composites (FRCCs), after more than fifty-year intensive scientific investigation and structural applications pushed it from a pioneer solution to a more and more widespread solution. Nonetheless, just recently, it has been internationally recognised the full status/dignity of a structural material in the last edition of the *fib* Model Code 2010 (2010) (see also recommendations by RILEM TC 162-TDF (2003, 2002)). Structural design approaches for FRC-only and hybrid reinforced (fibres + conventional reinforcement) concrete structures are therein provided in a framework fully consistent with the one for ordinary reinforced concrete structures and complemented with guidelines and recommendations for the identification of post-cracking residual strength classes based on design material parameters from standardised material classification tests (EN 14651 2005). Similar conceptual approaches can also be found in documents recently published by TC 544-Fibre Reinforced Concrete of the American Concrete Institute (ACI).

Extrusion techniques in the manufacturing of (also fibre reinforced) cement-based composite products have been studied and applied, also at the commercial scale, since quite long before digitally fabricated concrete materials and components even came onto stage (Burke and Shah 1999; Peled et al. 2000; Peled and Shah 2003; Kuder and Shah 2003, 2010). Requisites for “extrudability” of a cement-based mix were quantified in terms of fundamental rheological properties in the domain of capillary rheology (Srinivasan et al. 1999; Zhou and Li 2005).

Like in several other cases of fibre reinforced cementitious composites with adapted rheology (including, *e.g.*, Fibre Reinforced Self-Compacting Concrete FRSCC—(Ferrara 2014)), in the case of digitally fabricated—extrusion-based fibre reinforced cement-based materials two issues of paramount importance have to be considered.

First of all, in the concept and design of the composition of the fibre reinforced composite, not only the compatibility of the fibres, in terms of size and stiffness, with the printing equipment has to be considered but also the influence of the fibres on the rheology of the composite has to be considered, through suitable models (Ferrara et al. 2007; Martinie et al. 2010), as a function of their type and dosage, geometrical and physical–mechanical characteristics. This means that producing a successfully 3D printable FRCC does not mean to merely add fibres to a successfully 3D printable plain matrix and check the maximum amount of fibres that can be added without losing the "processability" features.

Secondly, once again like in all other categories of fibre reinforced cementitious composites with adapted rheology, processing can substantially influence the fibre dispersion and orientation (Martinie and Roussel 2011; Ferrara 2015), which affect the performance of the composite both in the fresh and hardened state, with resulting outcomes on the quality and on the structural performance of the application as well as on the total cost of the production (not only due to the cost of the constituent materials, whose use can be optimized through enhanced structural efficiency of the composite but also related to the ease with which the material can be handled.

In this framework, it is henceforth evident that the relationship between processing and performance of the material represents a crucial aspect in establishing a "holistic approach" which tailors the design of the material and of the extrusion process to the anticipated structural performance and structural use and efficiency of the material under the intended service load scenarios.

Studies on the influence of flow-driven fibre alignment on the mechanical properties of fibre reinforced cementitious composites with adapted rheology have been quite abundant in the last decade or so (Ferrara et al. 2011; di Prisco et al. 2013; Abrishambaf et al. 2013), highlighting the resulting strong material anisotropy whose implications on the performance of structural applications have been also interestingly addressed (Baril et al. 2016; Ferrara et al. 2017; Abrishambaf et al. 2015a, b).

Hamback and Volkmer (2017) were among the earliest to investigate the effects of 3D-printing path on the flexural and compressive behavior of Portland cement pastes reinforced with 1% by volume of carbon fibres. The authors, confirming that an effective fibre alignment was enforced along the print path direction highlighted how the build path itself could be used to spatially control the fibre orientation within the printed structures so to optimize the structural efficiency of the material (Figs. 6.4 and 6.5). Such a "fine-tuning" the mechanical performance of a fibre reinforced cementitious composite, also through the possibility of printing "hierarchical" / functionally graded structures, which could further benefit from such an enhanced structural efficiency. The latter intrinsically calls for the development of 3D printable FRCCs featuring a strain-hardening tensile behavior (Figuereido et al. 2019)

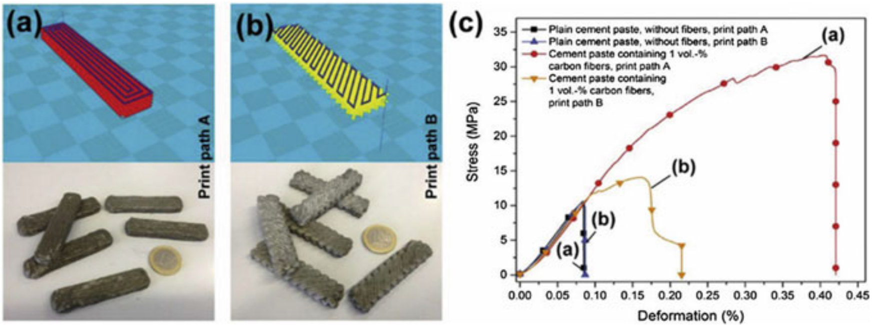


Fig. 6.4 3D-print path models in 3D-printing software and photographs of specimens fabricated via **a** print path A and **b** print path B for 3-point bending test, **c** stress-deformation plots for plain cement samples (without fibers) and carbon fiber-reinforced samples in 3-point bending test proving high flexural strength of print path A samples being reinforced with carbon fibers (Hambach and Volkmer 2017)

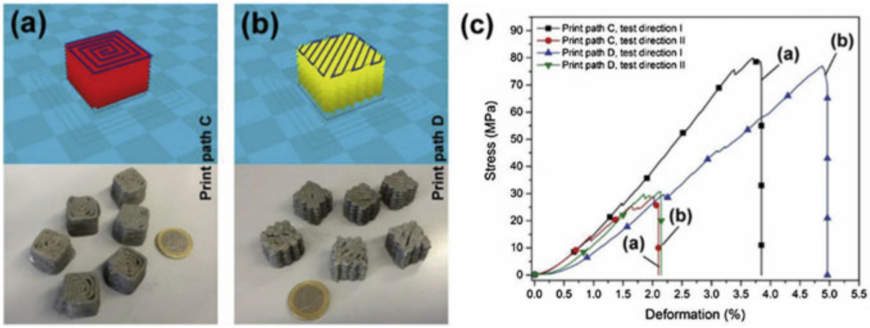


Fig. 6.5 3D-print path models in 3D-printing software and photographs of specimens printed via **a** print path C and **b** print path D for uniaxial compressive strength test, **c** Stress-deformation plots for plain cement samples (without fibers) in uniaxial compressive strength test showing high strength for test direction I and low strength for test direction II (Hambach and Volkmer 2017)

with adequate strain capacity, able to resist effectively, without the need for conventional reinforcement the tensile actions where needed, (including, e.g. tie elements in truss structures and tensile chords/meridians in two-dimensional planar or curved structural elements).

First results on the development of printable strain-hardening cementitious composite (the authors used the denomination Engineered Cementitious Composite) have been published by Soltan and Li (2018). Based on considerations of extrudability (indicating the ability of the mixture to pass through a printing system) and buildability (indicating the ability of a mixture to remain stable after deposition and during printing), that together define the printability, they developed several mixtures with 2% by volume polyvinyl alcohol (PVA) 12 mm length fibres. While investigating the influence of several ingredients on fresh state workability and processing

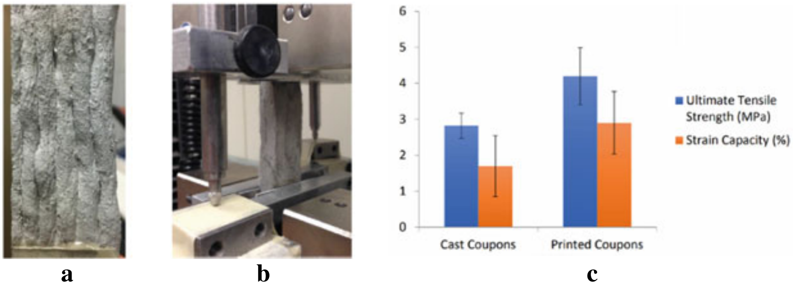


Fig. 6.6 A 3D-printed coupon specimens, **b** direct tension tests and **c** effect of the printed structure on the tensile strength and strain capacity (Soltan and Li 2018)

parameters, the authors ended up with a 3D printable mix showing strain-hardening tensile behaviour, though the assessment of fresh state properties was only based on the flow tests and not on the measurement of a fundamental rheological property. In addition, the real printability was not truly yet established as only several layers were deposited with a manual piston. Nonetheless, by 3D printing coupon specimens for direct tension tests (see Fig. 6.6) and testing them in comparison with "conventionally" fabricated ones, the authors found that the former, with highly aligned fibre orientation, outperform the latter both in terms of ultimate tensile strength and strain capacity (see Fig. 6.6c). No significant difference was detected in terms of compressive strength.

Similar results were obtained by Ogura et al. (2018), who printed 1 m long walls, 120 and 30 mm thick, employing strain-hardening cementitious composites reinforced with up to 1.5% by volume short (6 mm long) high density polyethylene fibres (Fig. 6.7). From these walls, they obtained "layered" 250 mm long, 40 mm wide and 25 mm thick coupon specimen that were tested in direct tension, also in comparison with dog-bone conventionally mould-cast ones (Fig. 6.6). A better performance of the printed specimens was confirmed preliminary in terms of strain capacity, the higher the fibre dosage the higher the performance, the extrusion-induced fibre orientation also resulting in a well-distributed multiple fine crack patterns as compared to the less regular and less "saturated" one, in terms of crack spacing, featured by mould-cast specimens. Though, the authors remarked that up to a strain of 0.3%, which largely includes the widest possible service range scenarios (it is worth here remarking that the yielding strain of conventional steel reinforcement bars is around 0.2%); the differences among the printed and mould-cast specimens and even between fibre volume ratios equal to either 1 or 1.5% were negligible. Such a consideration may play a relevant role when deciding about the most suitable mix-composition with reference to the identified values of its design parameters to be used in serviceability and ultimate limit state checks of the intended application.

While consistent structural design approaches are being developed for this category of cement-based materials, the pioneer studies reviewed above have highlighted peculiar issues related to digital fabrication technologies, which have to be addressed

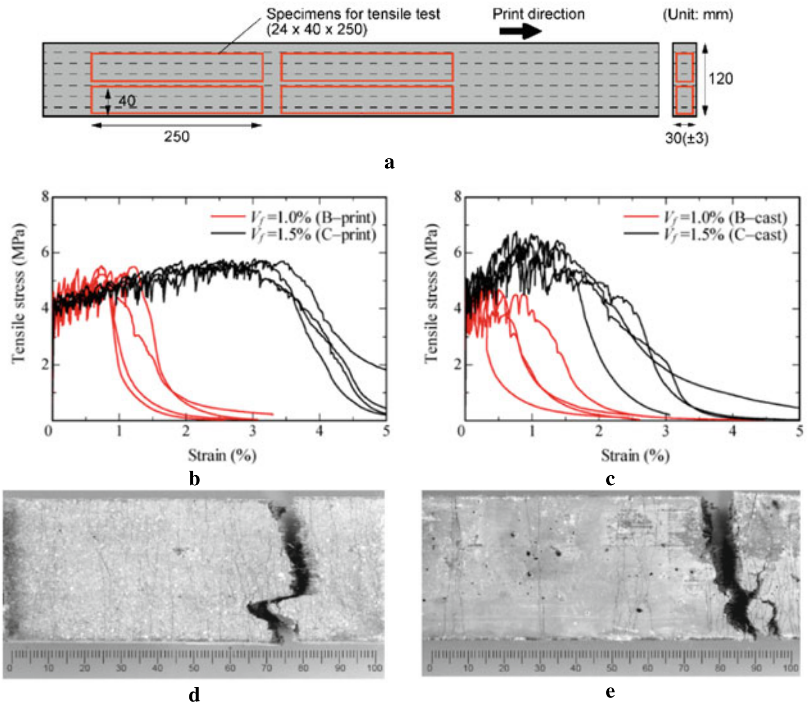


Fig. 6.7 **a** Position of the specimens for direct tension tests in the printed wall; stress–strain curves obtained from uniaxial tension tests on **b** printed and **c** mould-cast specimens and representative crack patterns of specimens after failure in uniaxial tension tests on print specimen **d** and **e** mould-cast specimen (Ogura and Mechtcherine 2018)

in order to customize the same approaches to the specific one-of-a-kind features of digitally fabricated elements and structures, including:

- The development of the tensile strain-hardening behaviour in the very early ages (fluid to solid state transition), i.e. in temporary design situations reflecting and affecting the ongoing fabrication.
- The influence of the interlayer bond on the effectiveness of the aforementioned behaviour.
- The need to develop tailored specimen fabrication and testing procedures for the identification of tensile design parameters in such a way to adequately take into account all the aforementioned issues, i.e. suitably representing the influence not only of the “extrusion”-induced orientation of the fibres (which is by now a fully design-wise acquired concept) but also, if not primarily, of the fabrication process characteristic parameters, including, e.g. layer thickness, speed of extrusion, fabrication path.

6.4 Design Principles and Modelling

The fundamental structural principles on which digitally fabricated elements (reinforced or not) are based do not differ from those of conventional cast or pre-cast RC structures; in these terms, proper design methods based on consistent mechanical models should be applied to DFC manufactured elements as well. However, available mechanical models need to be re-tuned at the material/component scale in order to account for particularities and/or specific effects induced by the novel fabrication method. Focusing on the scale of concrete material, some of these "new" effects include:

- Reduced bond strength between layers.
- Anisotropy.
- Shape-related mechanical effects.
- Printing path and sequence.
- Concrete interaction with a specific reinforcement strategy.

The thorough knowledge and understanding of the above-mentioned aspects represent a fundamental step for the design of DFC structures because they affect the macroscopic response of the fabricated elements.

6.4.1 Approach to Anisotropy

Concrete layer interfaces might represent a source of weakness for printed elements due to the formation of cold joints, which originate from the time gap between two consecutive layers. In this regard, Wolfs et al. (2019) and Le et al. (2012) investigated the bond strength of layered elements through properly designed experimental tests and found that printed element strength and stiffness are affected by the loading direction relative to layer orientation (Fig. 6.8).

However, a very limited influence of layer orientation was found for a sufficiently short interlayer time interval and when the load acted along the normal direction to the layers (Orientation I in Fig. 6.8).

In terms of structural design, this situation is different from conventional concrete for which the "bulk" properties of the element are isotropic. Therefore, a possible "new feature" for such a material design (to consider the layer configuration) might entail the evaluation of printed element compressive strength, $f^{*}_{c,d}$, as shown in Eq. 6.1:

$$f^{*}_{c,d} = \alpha_{dir} \cdot f_{c,d} \quad with\, \alpha_{dir} \leq 1 \tag{6.1}$$

where $f_{c,d}$ is the compressive strength of the equivalent cast concrete and α_{dir} is a reduction factor depending on the loading direction relative to the layer orientation (to be calibrated through specific tests).

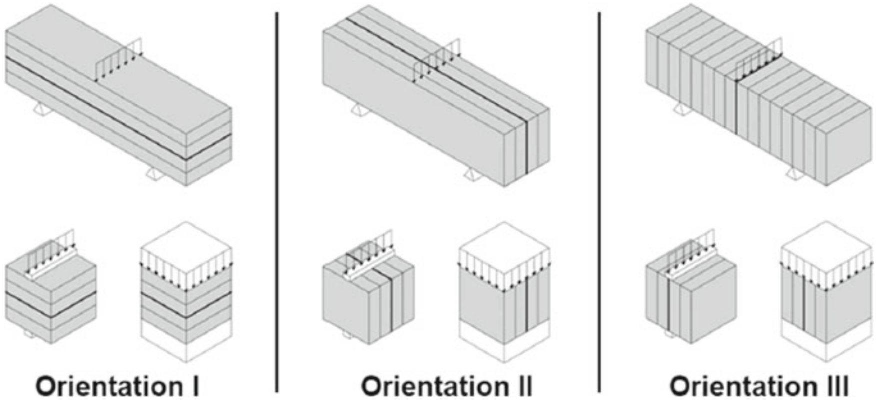


Fig. 6.8 3D Printed layer orientations in flexural tension, tensile splitting, and compression tests (Wolfs et al.)

Regarding the structural design of printed fibre reinforced composites similar challenges arise as the previous ones, since as overviewed in Sect. 6.3 the printing process will lead to a preferential fibre alignment along the printing path. The latter will be influenced by a panoply of variables, such by e.g. rheological properties of the matrix, fibre's aspect ratio, layer height, printing speed, among others. The expected anisometry of the fibre distribution / orientation within a printed element subsequently will lead to anisotropic material properties, in particular for the tensile behaviour, since it is acknowledge that the fibre reinforcement has a relatively low influence on the compressive strength (and low to moderate effect on the compressive post-peak behavior).

Approaching the anisotropic tensile behaviour of printed fibre reinforced composites will pose a bigger challenge than the one presented under compression, since the benefits of fibres mainly arise after cracking and the material behaviour is usually translated by a tensile stress—crack opening or—strain. The shape of these material laws will depend on multiple variables, by e.g. fibre type, geometry and content, fibre/ matrix bond strength and fibre distribution / orientation, in particular the fibre's orientation regarding an active crack plane (i.e. towards the principal tensile stresses). Therefore, a mere reduction factor employed to the tensile strength and/or to the residual tensile strengths may not be suffice to correctly take into account this anisotropic behavior, consequently tensile stress—crack opening or—strain relationships should be obtained for distinct layer orientations through adequate test methodologies.

Another possibility is the use of a "virtual laboratory" supported on numerical analysis through the FEM to obtain the material tensile relationship for a certain direction regarding printing direction. Fibre reinforced composites can be regarded in a simplified way as two-phase materials. Hence, FRC can be modelled in a realistic fashion by bi-phase models, respectively, by the discrete and explicit representation of fibres and plain concrete contribution, i.e. unreinforced matrix (Soetens and Matthys 2014; Radtke et al. 2010, 2011; Cunha et al. 2011, 2012; Abrishambaf et al. 2016; Zhan and Meschke 2016). In general, these models have into account the fracture process of the unreinforced matrix and the fibre reinforcement mechanisms of the discrete fibres bridging an active numerical crack. The fracture process of plain concrete, i.e. unreinforced matrix, or mortar can be modelled by smeared crack approaches, fracture-based energy interface models or damage mechanics constitutive models. On the other hand, reinforcement mechanisms of fibres being pulled out can be modelled using micro-mechanical behaviour laws (obtained through experimental, analytical or numerical techniques). These approaches rely on both the accurate knowledge of the fibre's micro-mechanical behaviour and the realistic representation of the fibres' structure, through an appropriate distribution and orientation of fibres.

Finally, another challenge regarding the structural design of printed fibre reinforced structures would be related to the modelling approaches that could be employed, since code-alike cross-sectional analysis for design would not take full advantage of the fibre reinforced composite capabilities in stress redistribution after the formation of an active crack. Hence, fully non-linear material analysis under the FEM framework would be necessary. Even though FEM methodologies have been used for a longtime to model conventional reinforced concrete as well as FRC, still nowadays they lack a consistent predictability under serviceability, namely in predicting crack patterns, crack openings and spacing. Moreover, the utilization of complex numerical models is intricate, usually not accessible to the common designer, and reliability of a certain numerical analysis is strongly dependent of the user's experience.

6.4.2 Models and Load-Bearing Capacity

From a practical point of view, it could be interesting to understand if the pre-existing models, developed for the calculation of the bearing capacity (moment, shear, torsion, etc.) of traditional RC elements, would be able to give reliable responses also for elements manufactured with DFC techniques. In this regard, to determine the capacity of a structural element (depending on the different limit states), it is first necessary to verify if the hypotheses of available models (i.e. developed so far for ordinary and pre-stressed concrete elements), are valid also in the case of digitally fabricated elements. For instance, for the evaluation of the ultimate moment capacity of reinforced or pre-stressed concrete cross-sections, the following assumptions are considered (EN 1992–1-1: 2004 par. 6.1):

- Plane sections remain plane.
- Strain in bonded reinforcement or bonded pre-stressing tendons is the same as that in the surrounding concrete.
- Tensile strength of the concrete is ignored.

- Stresses in the concrete in compression are derived from the design stress/strain relationship given in EC2.
- Stresses in the reinforcing or pre-stressing steel are derived from the design curves in EC2.
- Initial strain in pre-stressing tendons is considered when assessing the stresses in the tendons.

To put this discussion in the context of digitally fabricated concrete elements, these hypotheses could be still valid depending on the adopted printing and reinforcing technique. For example, in the case of the 3D printed RC beam (Asprone et al. 2018) in Fig. 6.21 with an external reinforcement system, the second hypothesis will not be applicable. Similarly, additional studies are needed to assess the validity of the first hypothesis, i.e. on how the planar cross-section can be guaranteed depending on the specific fabrication technique and shape of the element.

A further structural principle often applied to digitally fabricated elements, is the post-tension. There are several applications consisting of fabricating concrete segments subsequently connected by post-tensioned cables aligned with the deposition direction. Initially, this principle was applied at Loughborough University (UK) for the design and digital manufacturing of a free-shaped wall-like concrete bench using the 'Concrete Printing' approach (Lim et al. 2012), an automated extrusion-based process for concrete (see Fig. 6.9). The printed structure included a certain

Fig. 6.9 Digital manufacturing of a free-shaped wall-like concrete bench (Buswell et al. 2018)

Fig. 6.10 Printed showcase segment for the pedestrian and bicycle bridge (Bos et al. 2019)

number of conduits passing through the height of the bench. These were used for the post-printing placement of reinforcing bars that were post-tensioned and grouted to achieve a predetermined compressive stress state into the structure. A large-scale application of this principle is the pedestrian and bicycle bridge developed at the Eindhoven University of Technology (TU/e) (Fig. 6.10) (Theo et al. 2018), which was placed in Gemert, Netherlands (see the case study of the Sect. 3.1 in Chap. 2).

Thus, the application of the post-tension to the fabricated 3D printed concrete blocks could represent a valid solution to overcome the critical issues related to the assembly of several concrete segments but, at the same time, this would require particular attention to the effects produced by creep and shrinkage.

The use of totally different digital fabrication technologies impacts the way the reinforcement can be installed/incorporated and, consequently, calculated. It is well-known that the concrete tensile strength is small and so it is necessary to design an adequate reinforcement or develop suitable strategies to absorb tensile stresses. In traditional design of RC structural elements, reinforcement requirements ensure that the reinforcement is yielded in the ultimate limit state. This rule should be adapted to the available DFC technique in order to provide ductility for DFC elements. However, this aspect has not been adequately investigated so far or, for instance, has been found not to be applicable as in the case of the straight RC beam proposed by Asprone et al. (2018) in which the element failure (due to local mechanisms) preceded the yielding of the reinforcement. Quite the opposite, the compliance with reinforcement quantities provisions could be effortlessly achieved for some DFC technologies. An example is the 3D Concrete Formwork Technique through which the placement of horizontal and vertical reinforcement creates a regular reinforcing scheme in structural elements with a standard geometry. Using this technique, the US Army 3D printed complete barracks, also known as a B-Hut, within a three-year program called Automated Construction of Expeditionary Structures (ACES). The walls of the B-Hut acted as permanent formworks with a hollow core that was reinforced and backfilled with concrete after completion of the fabrication (see Fig. 6.11) (Kreiger et al. 2019).

In general, such a technique allows for the fabrication of RC structural panels or wall-like elements. To be considered a structural element it has to fulfill some code prescriptions about thickness, reinforcement percentage, ductility, seismic details

Fig. 6.11 Rendering of B Hut A

and other specifications. For instance, two major issues need to be addressed in reference to code compliance for the Mesh Mould technique; these are the use of only a certain range of reinforcement rebar diameters and the use of different stirrups spans in element height.

An even different design scenario arises when the reinforcement is placed during concrete fabrication. One of the most advanced concepts, currently under development at TU Eindhoven, is the direct entrainment of reinforcement cable into concrete layer during printing. In this case, the conventional hypothesis on concrete-reinforcement bond (nr. 2) has to be verified in relation to the strain in the bonded cable reinforcement. Indeed, in conventional RC structure, cast in-place or pre-cast technology allow for a robust bond between reinforcement and the surrounding concrete which is modeled by means of semi-empirical bond-slip models (2010), available in current regulations.

From the design point of view, connections between digitally fabricated concrete elements represent a further source of uncertainty. In several practical cases, reinforcement is used not only to absorb the tensile stresses that develop in the structural element, but also to make the connection between concrete segments effective, providing (possibly) ductility. This latter function is of uttermost importance if rotational capacity and/or dissipative capacity must be conferred to the final structural element. In some digitally fabricated RC structures (Asprone et al.), local failure mechanisms were observed in concrete-reinforcement connection, thus requiring greater attention for the purposes of design and calculation.

In general, testing and detailed modelling of concrete-reinforcement interaction still represent an issue for the effective design and implementation of DFC structures. Fundamental aspects of capacity design (e.g. avoiding premature brittle failures, ductility etc.) are strongly reliant on the DFC technique adopted and, for this reason, deserve much attention in order to create reliable predictive models. Finite Element (FE) analyses and numerical modelling certainly can help to predict the mechanical/structural behaviour of DFC structures (Wolfs et al. 2018); however, at this stage of development, there is not enough full-scale experimental evidence to support FE reliability.

From the above discussion it clearly appears that further experimental/numerical studies need to be carried out in the context of DFC structures. The common goal is to update/integrate current capacity models (developed for existing structural typologies such as steel–concrete composite elements, post-tensioned members etc.) available in national and international codes, with the final aim of creating the appropriate framework of calculation for DFC structures.

6.4.3 Structural Optimization

The geometrical freedom introduced by digital manufacturing technologies theoretically, is often expected to allow the application of structural design through optimization strategies. However, for the time being, a discrepancy remains between the underlying assumptions in existing optimization methods on the one hand, and the constraints of manufacturing on the other hand. Rippmann et al. (2018), presented the design, fabrication, and testing of a floor consisting of multiple elements, printed in sand using a powder-bed selective binding method. By using Thrust Network Analysis, the authors were able to create a purely compression-loaded floor, with a weight reduction of 70% compared to a solid floor. As the floor itself is tension-free, no reinforcement is required for the considered load case. Thus, the optimization strategy addresses an important manufacturing constraint. The applied method also allowed consideration of minimum wall thickness and maximum element size. On the other hand, directional variations in material rigidity were not incorporated in the approach. In comparison to powder-bed based selective binding methods, selective material deposition by extrusion features additional constraints, amongst which is the requirement of a continuous filament (and thus print path—although some suppliers have now presented stop-start technologies that could remove this constraint), and the fact that filament needs to be supported by previously deposited layers (or the print base plate). This further complicates the application of optimization strategies. Vantyghem et al. (2019), designed, manufactured and tested a pre-stressed beam assembled from parts made by selective material deposition by extrusion. The design was based on a 2D topology optimized beam, taken from literature, as the authors recognized the match between the particular optimization case and the manufacturing possibilities. First results of a more general topology optimization approach for extrusion-based DFC, were published by Martens et al. (2017), and Martens (2018). The model included a selection of yield failure criteria (Drucker-Prager or von Mises), the variation of stiffness in different directions, a support angle constraint (i.e. to require a layer is supported by another), and the base plate orientation. Some challenges remain, nevertheless, particularly with regard to print path determination. Thus, optimization methods need further development to better include manufacturing constraints, and/or vice versa.

6.5 Structural Testing and Validation

At increasing level of development of DFC technologies, there is a strong need to investigate the mechanical performance / response of the fabricated structural elements, focusing on different scales (at the scale of the material or element). The structures made with DFC elements are innovative to the point that there are no codes and guidelines for the testing methods and assessment of the structural performance. For this reason, the design of these structures is always followed by tests that validate their performance.

At the scale of the printed element, several authors developed proper testing procedures to investigate the mechanical particularities of DFC products. As for the study of anisotropy, recent studies conducted by Wolfs et al. (2019) have shown how flexural tensile, tensile splitting and compressive strengths change with the printing direction (Fig. 6.8). Similarly, a proper test set-up (see Fig. 6.12) was proposed by Asprone et al. [89] in order to characterize the fracture energy during shear testing of concrete layers interfaces (cold joints). The set-up was inspired by the punch-through shear test, although some modifications on the original set-up and the specimen's geometry was made due to constraints related to the printing process.

In contrast to material scale testing, the full-scale experimental behaviour of DFC structures has been rarely investigated. A complete experimental characterization was carried out for a 3D concrete printing pedestrian and bicycle bridge in Eindhoven. The structure was fabricated following the concept of 'Design by Testing' (Theo et al. 2018) and certified safe for public use. In particular, the bridge design was the result of a vast experimental campaign aimed to prove the structural integrity of the printed element. A 1:2 bridge sample was tested in a load-controlled four-point bending test, as shown in Fig. 6.13. A final full-scale flexural test (see Fig. 6.14) was

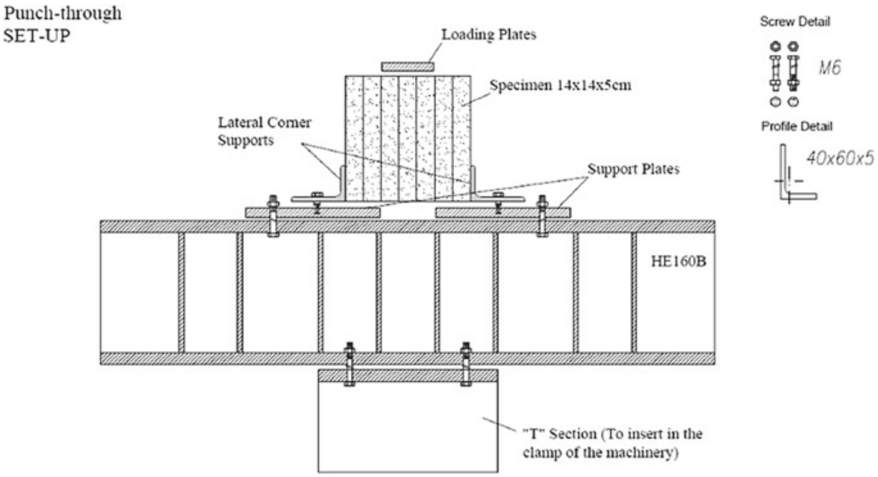


Fig. 6.12 Punch-through set-up (Asprone et al.)

Fig. 6.13 Scale model in test 4-point bending test set-up (Theo et al. 2018)

Fig. 6.14 In situ test (Theo et al. 2018)

performed in situ to guarantee that the bridge behaves as expected and be structurally safe. In situ full-scale testing is an example of a non-destructive assessment and it is used on a regular basis to verify the load-bearing capacity of older and existing infrastructures. A test phase with large-scale elements was conducted for the design of Nyborg Pavilion by (Bos et al. 2019). The Fig. 6.16 shows the cross-section of the perimeter wall of the pavilion (Fig. 6.15).

Approximately 750 mm wide straight segments of the wall section design were tested in different loading conditions.

Fig. 6.15 Wall during printing process (Theo et al. 2018)

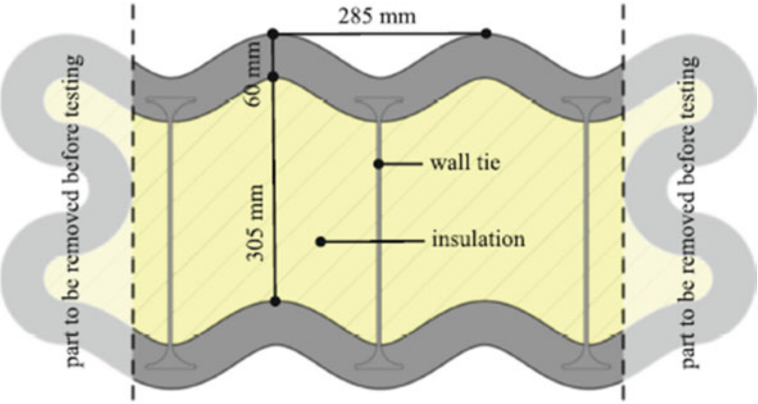


Fig. 6.16 Cross-section of the wall (Bos et al. 2019)

Compression test with the load that was applied once on each face of the tested element (see Fig. 6.17).

Vertical flexural test, as a 3-point bending test on ‘standing’ elements, with the load acting horizontally (see Fig. 6.18).

Impact test during which the element was subjected to pendulum impact loading in a set-up derived from EN 12,600 (see Fig. 6.19)

With the aim to evaluate the flexural behaviour and failure mechanisms, another example of large-scale test was carried out with a straight beam, manufactured by means of technology solution, mentioned in the previous chapters, developed at the University of Naples “Federico II” (Asprone et al. 2018). In detail, a three-point bending test was conducted on the RC straight beam. The test scheme and set-up are shown in Figs. 6.20 and 6.21.

Fig. 6.17 Compression test (Bos et al. 2019)

Fig. 6.18 Vertical flexural test (Bos et al. 2019)

The test was carried out by means of a universal servo-hydraulic testing machine. The assumed load scheme ensures that the primary failure comes from tensile or compression stress. The test was conducted under displacement control, with a velocity of 0.5 mm/min.

Strain measurements on the steel components of the beam were achieved through strain gages placed at half-length of each stainless threaded rod, as shown by Fig. 6.20. For the strain measurements of compressed concrete, always strain gages were used only at the backside of the beam. Instead, in order to measure the displacement at the mid-span of the beam, two linear variable differential transducers (LVDTs) were placed at the bottom edge in correspondence of the half of the beam.

Successively numerical simplified analyses (2D models) were to compare experimental and numerical data were carried out and presented in order to validate

Fig. 6.19 Impact test (Bos et al. 2019)

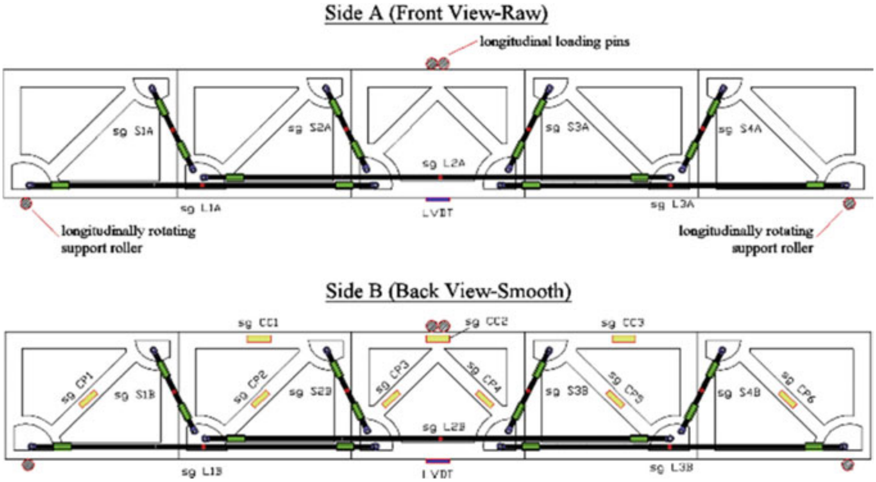


Fig. 6.20 Front view and back view of the straight beam with strain measurement devices (Asprone et al. 2018)

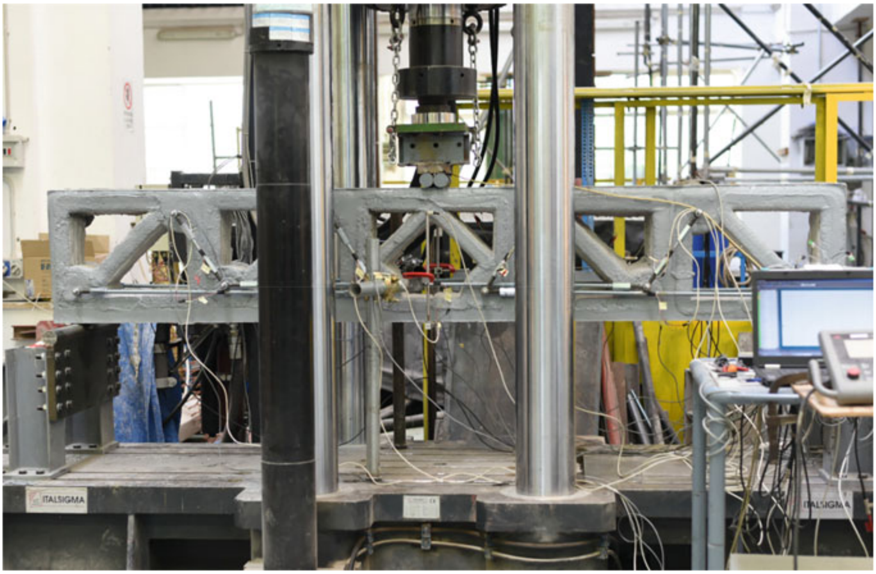


Fig. 6.21 Equipped specimen for the three points bending test (Beam UniNa) (Asprone et al. 2018)

numerical simulations as well as to obtain a better interpretation of the experimental test.

This has led to outcomes that have demonstrated that the initial flexural stiffness of the printed RC beam is comparable with an equivalent solid RC beam whereas the overall nonlinear flexural behaviour is influenced by local failure mechanisms, i.e. shear damage at the interfaces between adjacent concrete segments and steel–concrete anchoring failure. Even though several issues need to be addressed, this DFC technique can introduce a novel rational use of additive manufacturing technologies in structural engineering as it enables the fabrication of complex shapes (e.g. curved beams of variable height). The topological optimization of shapes enables harvesting innumerous advantages such the reduction of concrete volume and mass (and consequently mitigation of self-weight loadings), the elimination of complex formwork systems, and easy transportability and installation.

6.6 Conclusions

Principally, laws and codes, as well as common sense, require structures to be safe for use. To safeguard this, elaborated quality control procedures have been implemented for traditionally produced concrete structures in the construction industry, which are generally founded on regulations regarding three different target pillars:

- Construction products and materials.

- Construction processes (execution).
- Design (e.g. structural and durability).

The implementation of DFC impacts on each of these pillars. Therefore, current quality assurance systems and design codes do not adequately address DFC applications in practical cases. Considering the current state of progress of DFC as well as the time involved in design code development and subsequently its legal binding implementation, it should be expected that this situation is likely to continue for some time. Meanwhile, with ever more and more ambitious projects being proposed, the need to understand the structural engineering specifics and subsequently to develop unified approaches, is rapidly increasing; it is evident that the scientific and technical communities are aware of this need and a number of research and development projects are being developed to fill this gap.

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