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Rethinking reinforcement for digital fabrication with concrete

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ABSTRACT

The fabrication of novel reinforced concrete structures using digital technologies necessarily requires the definition of suitable strategies for reinforcement implementation. The successful integration of existing reinforcement systems, such as steel rebar, rods, wires, fibres or filaments, will indeed allow for printed concrete structures to be designed using standard structural codes. However, reinforcement integration has to be compatible with either the specific printing technique adopted for the structural element production or with its shape. This paper provides a systematic overview of a number of digital fabrication techniques using reinforced concrete that have been developed so far, proposing a possible organization by structural principle, or place in the manufacturing process.

1. Introduction

Over the last decade, developments in digital design and modelling, additive manufacturing, robotics, as well as in the engineering of cementitious materials, have allowed the introduction of new automated construction methods for these materials [1–7]. Consequently, an array of innovative fabrication technologies of concrete is now under development around the world. Most of these are identified by a range of project specific or generalized names. Although their technical differences make it hard to provide a strict classification, they generally share the following characteristics: (*i*) robotized material placement, (*ii*) lack of conventional formwork systems, (*iii*) a high degree of freedom for shapes and forms, (*iv*) introduction of new functionalities, and (*v*) bespoke fabrication.

For the purpose of discussing the new technologies or techniques having concrete as the main construction material, they are collectively identified as *Digital Fabrication with Concrete* (DFC). Generally, DFC represents an opportunity to enlarge the degree of freedom of architects and structural designers, as they can benefit from improved performances of materials, systems and structures. However, since the characteristics of DFC are quite different from those of conventional fabrication techniques, a complete rethinking of both the manufacturing and installation processes are required, including: product/concrete material design, manufacturing route, assembly in a structural system, and final product performance assessment.

Most available DFC technologies aim for structural applications of their products (to greater or lesser extent), ranging from building components to full-scale houses. In general, when dealing with concrete constructions/structures, a key point is that cementitious materials lack sufficient tensile capacity and ductility for the intended applications, and, for this reason, their implementation is made possible mainly in combination with tensile reinforcement. This mechanical aspect may represent an evident obstacle for DFC to reach maturity unless reinforcement integration is incorporated in the fabrication process itself (e.g. in [5, 8]). Reinforcement concepts and principles implemented in conventional concrete constructions (designed to overcome tensile limitations of concrete) are not generally applicable to DFC. Therefore, a paradigm change in the fundamental concepts of reinforcement technology, dimensioning and detailing – making it possible to fully benefit from digital design and fabrication– is required in order to open the way for mass market applications of digitally fabricated concrete structures.

2. Reinforcement in conventional concrete structures

Existing reinforcement technology and approaches for its dimensioning have been optimized for more than a century hand in hand with traditional construction methods. It is crucial to recognize that

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replicating existing schemes into new technologies (i.e. incorporating conventional reinforcement concepts into DFC) can be potentially detrimental for the performance and economy of the new technology. In the case of DFC, it could reduce structural performance and construction speed. It is, therefore, of paramount importance to investigate how digital fabrication can improve the performance of concrete construction and define new design criteria appropriate for each specific DFC technique. However, in order to develop the aforementioned criteria, a clear understanding of the advantages and disadvantages of current reinforcing technologies is indispensable.

The tensile strength of concrete is generally around 10% of its compressive strength, and thus relatively low. In addition, it is subject to a rather wide scatter. Furthermore, initial stresses in concrete structures, caused by restraint to impose deformations, construction stages and other factors, are largely unknown. Therefore, it is common practice to neglect the concrete tensile strength in the structural design. The use of reinforcement resisting tensile forces is essential for the load bearing capacity of structural concrete.

Reinforcement is not only required to provide strength. Rather, a substantial portion of reinforcement in real-life structures is so-called “minimum reinforcement” fulfilling one or more of the following functions: (*i*) avoid brittle failures at cracking, (*ii*) ensure a sufficiently ductile behaviour to enable stress redistribution, and (*iii*) limit deformations and crack widths. The first two functions of minimum reinforcement are related to the bearing capacity: many clauses in modern design codes for structural concrete are essentially lower-bound solutions according to limit analysis, requiring a reasonable deformation capacity to be applicable. The third function of minimum reinforcement addresses the behaviour under service conditions and durability. In many structures, minimum reinforcement for crack control is governing the overall reinforcement quantity. Rather often, the structure remains uncracked and this reinforcement remains inactive, but in the light of the uncertainties related to the initial stresses in the concrete, crack control reinforcement cannot be omitted.

Conventional reinforcement can be categorized as internal or external, metallic or non-metallic, and passive or prestressed (active). In conventionally built structures, passive internal reinforcement consisting of deformed steel bars with a 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 conventionally. The ribs or indentations of the deformed bars typically provide enough bond with concrete to transmit the force of the bars to concrete (anchorage) or to other bars (laps) following simple geometric details (e.g. anchorage length and overlapping length). Furthermore, concrete and steel reinforcement have a similar coefficient of thermal expansion, which facilitates their combination.

In spite of the fact that corrosion of steel reinforcement is the main cause for the deterioration of concrete structures, non-metallic reinforcement (e.g. composite materials) plays a minor role today, except in the strengthening of existing structures by externally applied reinforcement. This is due to their elevated cost, low stiffness, and complicated handling in conventional construction (e.g. non-metallic bars cannot be bent on site like conventional reinforcing bars), as well as lacking design provisions and experience of designers and contractors.

Prestressed (active) reinforcement is used mainly for prefabricated elements, large span structures and bridges. It is either pre-tensioned (tensioned before casting of the concrete around it) or post-tensioned (stressed against the hardened concrete). Post-tensioned reinforcement can be external (outside the concrete cross-section) or internal (in ducts inside the concrete), the latter either being unbonded or bonded by grouting of the ducts. In order to avoid disproportionate losses of the prestressing force due to shrinkage and creep of the concrete, high strength steel wires, strands or bars are typically used, with tensile strengths in the order of 1500–1800 MPa. Non-metallic active reinforcement is currently only used in exceptional cases.

Over the last decades, the use of fibres replacing or complementing conventional reinforcement has become more frequent [9]. However, compared to conventional reinforced concrete (RC), fibre reinforced concrete (FRC) is limited in terms of strength and, more importantly, of ductility [10]. Single fibre types and lengths (e.g. steel or polymeric fibres [11, 12]) as well as hybrid fibre mixes with short and deformed long fibres have been successfully adopted to achieve strain-hardening in cement-based fibre reinforced materials [13]. Ultra-high-performance fibre reinforced concretes (UHPFRC) represent the cutting edge in terms of achievable strain hardening post-cracking behaviour, but its use is so far restricted to special, typically precast applications due to the elevated costs and complex handling on site. The technological development, in terms of effective fibre embedment in the cementitious matrices, has mainly regarded the control of distribution and orientation of fibres in the fresh and hardened material [14, 15]. Given that this technological aspect might be difficult to control in many on-site situations, the use of FRC has been typically limited to applications with no primary structural function such as construction pit floors and industrial floors. In addition to the mechanical and technological limitations related to the FRC material itself, the major barrier to the widespread use of FRCs in structural applications is the limited coverage of methodology and applications in design codes, such as the *fib* Model Code 2010 [16].

In terms of reinforcement installation, available methods are coupled with conventional concrete casting processes, either for in situ or prefabricated reinforced concrete structures. In both cases, transverse reinforcement grids or longitudinal steel rebar are positioned in a wooden or metallic formwork supported by a scaffold. At casting, the concrete is filled into the formwork from top to bottom in layers, being compacted using immersion vibrators (in situ) or vibrating tables (prefabrication). In higher elements like walls, tremie placement is required to avoid segregation of the mix. In many cases, the diameter of the tremie placement hoses and vibrators defines the minimum wall thickness. This is an issue for both prefabricated elements (where weight is decisive) as well as in situ structures (where thick walls require a large amount of minimum reinforcement for crack control). Over the past decades, self-compacting concrete (SCC) requiring neither vibration nor hoses for its placement has found more widespread application, particularly in elements with high reinforcement ratios [17].

3. Reinforcement techniques in DFC

Moving from this general overview of conventional techniques typically adopted to install the reinforcement in concrete elements, it is evident that the use of totally different manufacturing technologies, such as additive manufacturing, impacts the way the reinforcement can be installed/incorporated.

Basically, the fundamental mechanical behaviour of digitally fabricated RC elements will not differ from conventionally built RC, and design methods based on consistent mechanical models are therefore applicable to additively manufactured elements as well – provided that the models are enhanced to account for fabrication method specific effects such as e.g. anisotropy, shape-related mechanical effects, weak layers and reduced bond strength in additive manufacturing. However, many current design provisions (such as shear design provisions for elements without transverse reinforcement) are semi-empirical models, based on experimental testing of traditional RC elements. Such models need to be revised and adapted to fit the mechanical performance of digitally fabricated elements, or even abandoned for some technologies since empirical models will never be able to cover the entire range of complex geometries achievable by digital fabrication.

In a final consideration, in the case of concrete elements where reinforcement is required, i.e. RC elements, the manufacturing technology must include all the processes needed to install adequate reinforcement, in whatever form it is provided, e.g. fibres, rebar, rods, filaments etc. A range of approaches is possible in the search of achieving the goal of reinforcement in DFC. They can be organized, for

Table 1
Grouping of possible approaches to address reinforcement integration in DFC.

By structural principle	By stage of the manufacturing process
Ductile printing material: e.g. *fibre reinforced materials*. This is the case where rebar reinforcement is not needed and only the fibres are able to provide the tensile strength and the ductility that are required by the application	Before manufacturing: 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*. This is the case where rebar/continuous reinforcement is needed, and it can be also installed with automated/robotized processes	During manufacturing: reinforcement is added during concrete manufacturing or belongs to the material itself (e.g. fibres)
Compression loaded structures: e.g. *due to shape or prestress*. This is the case where additional tensile reinforcement is not necessary.	After manufacturing: reinforcement is installed once concrete element has been manufactured through a digital fabrication method
Hybrid solutions: e.g. *combining any of the previous cases*.	

instance by structural principle, or place in the manufacturing process, as listed in Table 1. In any case, it is crucial to recognize that any new reinforcement concept will need to incorporate an integral approach to the development of designs, material(s) and application process.

4. Ongoing research activities

This section reports on several ongoing research activities related to DFC with integrated reinforcement.

4.1. Smart Dynamic Casting

Smart Dynamic Casting (SDC) is a robotic prefabrication technique for non-standard concrete structures developed at ETH Zurich [18] that extends the slipforming technology using either a free slipping trajectory (Fig. 1a) or flexible actuated formworks to produce variable cross-sections and geometries (Fig. 1b, c). In SDC, fresh concrete is poured into a moving formwork much shorter than the final element. The concrete has an adapted rheology in order to be workable when slipping through, but at the bottom of the formwork, concrete is in a hydration state just strong enough to be self-sustaining. The hydration process is digitally controlled by an automatic sensor and feeding system [19, 20].

SDC allows the digital fabrication of complex column structures in a continuous casting process with similar mechanical performances as conventionally built structures, even in cases where reinforcement is required. Hence, this is an example of a DFC process in which the reinforcement can be addressed by standard technologies and design processes, following similar lines as in conventional construction. The complex geometry of the vertical structural element is thus the main source of difficulty when using internal deformed steel bars, which could be solved with robotic reinforcement assemblies (as e.g. in Mesh Mould technology [8]). Currently, the reinforcement integrated in the SDC technique is fabricated before concrete casting using three-dimensional numerically controlled bending processes, which allow applying standard and inexpensive deformed steel bars to complex digitally fabricated structures. This technology has been used for the production of a large number of variable cross-section 3 m tall mullions for the DFAB HOUSE [21] in the NEST building at Empa in Dübendorf, Switzerland (Fig. 1c, d). In this application, the architectural design concept required a variable spacing between the mullions, leading to different structural requirements for each mullion, including transverse loading by wind pressure and suction. The bespoke fabrication offered by SDC allowed optimizing the geometry of each mullion to its actual

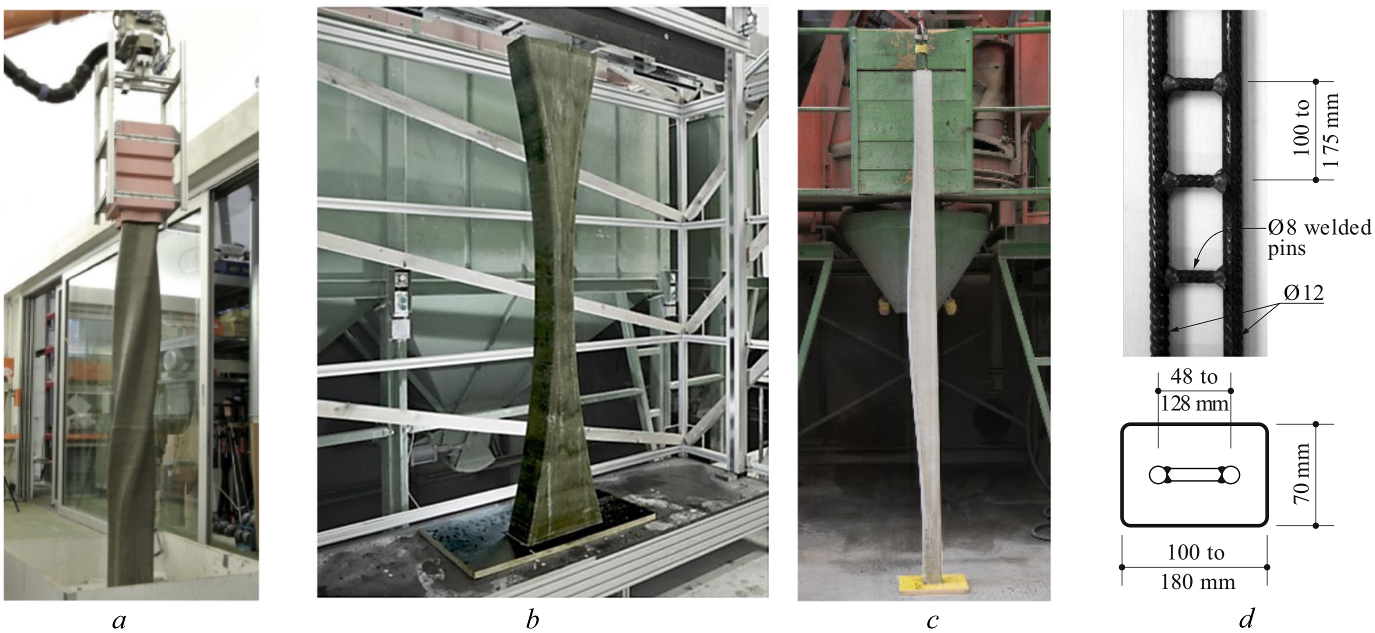

Fig. 1. Structures fabricated with Smart Dynamic Casting method [19, 20]: (a) star-shaped rigid formwork with 180° rotation over the column height; (b) 2 m tall element produced with flexible formwork; (c) 3 m tall reinforced structural mullion for the DFAB HOUSE [21] in the NEST building at Empa in Dübendorf, Switzerland; (d) geometry and reinforcement of the DFAB HOUSE mullions.

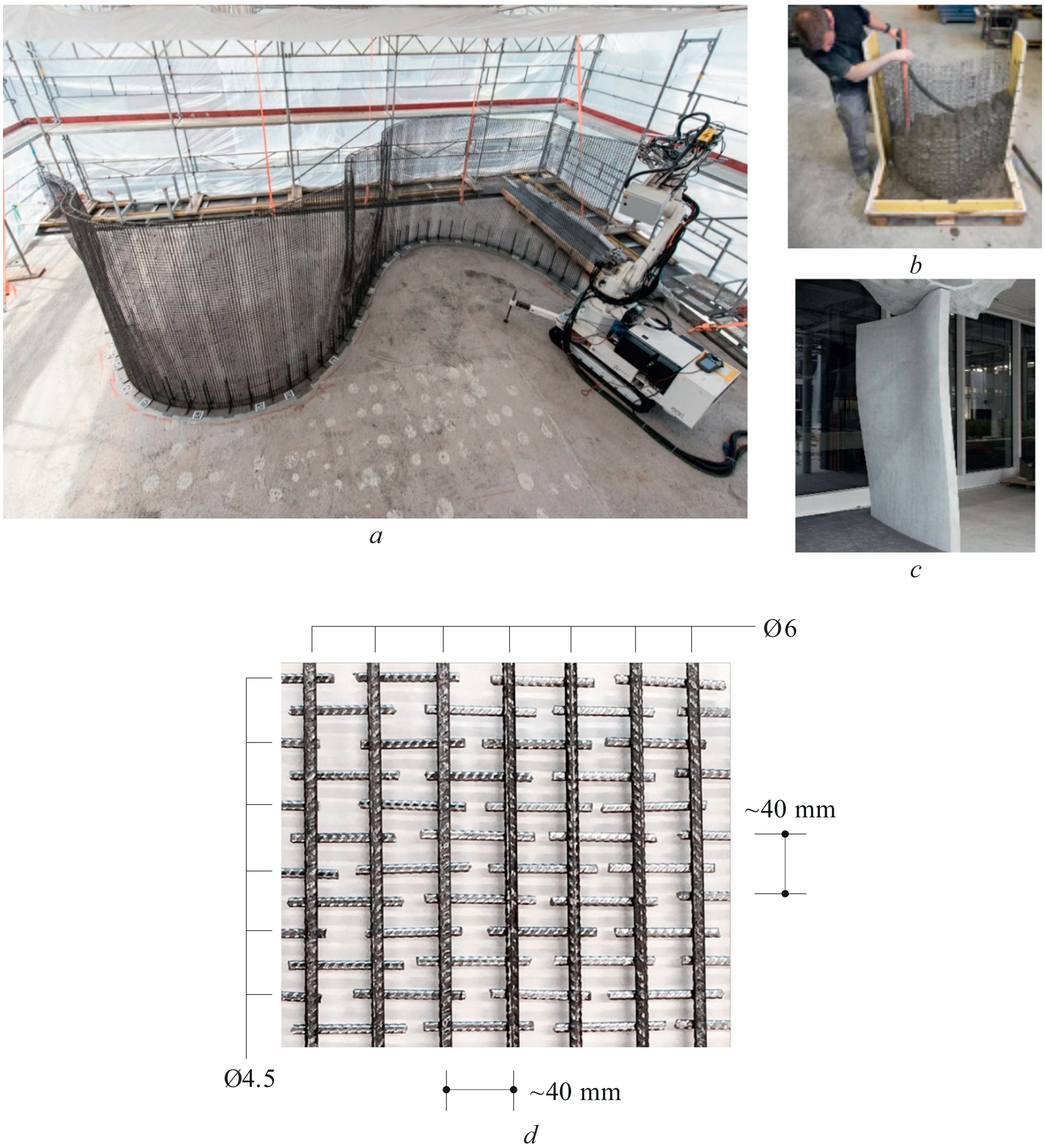

Fig. 2. Mesh Mould technology: (a) production of 14 m long mesh for a double curved load bearing wall for the DFAB HOUSE [21] in the NEST building at Empa in Dübendorf, Switzerland; (b) filling process; (c) 3 m tall double curved mockup; (d) example of reinforcement configuration.

requirements, keeping in all cases a minimum cross-section of 100 × 70 mm. While the experimental verifications showed that the tensile concrete strength was enough to develop the required shear strength, the final design included transverse reinforcement (Fig. 1d) to (*i*) improve the ductility of the elements and (*ii*) design with classic plasticity based methods – which neglect tensile concrete strength – in order to fully comply with building codes.

4.2. Mesh Mould

Mesh Mould (MM) is a digital fabrication technique developed at ETH Zurich ([8, 22, 23]) in which the reinforcement and formwork production are unified in a robotically controlled system. In MM, an industrial robot ("in-situ fabricator") equipped with a specially designed end effector [24] automatically fabricates on site a dense, three-dimensional welded reinforcement mesh (Fig. 2a), currently dimensioned using conventional structural concrete design specifications. This double side fine mesh is infilled with a special concrete mix that achieves sufficient compaction without flowing out the mesh (Fig. 2b), and is subsequently finished with a cover layer to serve as a freeform RC structural element (Fig. 2c). Hence, similarly as in Ferrocement technology conceived and promoted by Pier Luigi Nervi, optimum complex structural shapes can be produced without formwork.

As in the SDC technique, concrete is continuously cast in the core of the MM structure, reducing the potential layering issues inherent to other digital fabrication processes (e.g. layered extrusion); however, possible issues related to the adhesion of the outer concrete sprayed layer should be further analysed. MM uses conventional deformed bars in the mesh production with a grid spacing of around 40 mm, currently limited to 6 mm and 4.5 mm diameter respectively in each direction because of the bending, cutting and welding capabilities of the end effector (Fig. 2d). The mesh spacing varies depending on the mechanical requirements and the local curvature. For a thin wall application of 120 mm thickness as the DFAB HOUSE [21] in the NEST building at Empa in Dübendorf, Switzerland (Fig. 2d), the resultant reinforcement amounts (1.2% and 0.7% in the vertical and horizontal directions, respectively) provide load bearing capacity to support a 2 storey building even when considering the reduction in capacity caused by cutting and welding of the 4.5 mm reinforcement. The use of FRC to infill the mesh is a complementary reinforcement that has been proven to enhance the strength of MM elements and reduces concrete flow out of the mesh [25].

4.3. External reinforcement arrangement

The main scope of the external reinforcement arrangement approach is the manufacturing of steel rebar/tendon reinforced concrete (RC) members (beams, columns etc.) using DFC technology of concrete without interfering with reinforcement during fabrication. The implementation of this approach enables the manufacturing of structural elements characterized by complex shapes, low-weight, and functionally/mechanically optimized shapes. The approach is based on the idea that a RC member beam can be ideally cut into several "segments" which are printed separately using a specific digital fabrication technology for concrete and, in a second stage, assembled with steel reinforcing system to create the final structural element.

Each concrete segment of the structural member can be manufactured through the width direction or longitudinal axis of the member itself, i.e. in the direction orthogonal or parallel to the 2D plane of a beam, respectively. Once the number and dimensions of segments are defined (mainly depending on the digital fabrication technology used), each concrete segment can be designed to accomplish weight reduction targets and proper mechanical performances related to the internal forces acting on the structural element (shear, axial forces and bending moment). To this end, concrete segments can be topologically optimized with a number of voids, to save material while still guaranteeing the required mechanical performances. In addition, functional voids can be foreseen before the printing process. Functional voids in the concrete segments can be used as specific geometrical detail to accommodate sensors, tendons etc.

Using the above-mentioned approach, Asprone et al. [26] have fabricated two different 3D printed RC beams, being one straight and the other characterized by a curved axis with variable cross-section along the beam axis itself. The DFC technological strategy consists in printing several concrete segments, each one designed according to a specific mechanical model to resist variable bending moments and shear forces (e.g. Fig. 3a showing a single printed concrete segment). Besides the printing stage, this approach requires the beam segments to be designed in an integrated manner with the reinforcement system in order to guarantee proper tensile reinforcement (at the bottom side of the beam) and to lock the segments in a single continuous element.

The reinforcement scheme adopted in the prototypes presented by Asprone et al. [26] consists in two separate external steel reinforcing layers installed on both sides of the beams (in-plane rebar system) connected each other through orthogonal threated rods (out-of-plane system), as illustrated in Fig. 3b. The latter are positioned into the holes of each concrete segment and secured with a high strength low-viscosity cement-based mortar. The steel reinforcement of the in-plane rebar system is linked to the out-of-plane system by means of male thread connectors and hex nut rod pipes (see Fig. 3b). Asprone et al. implemented, as one of the possible mechanical optimization strategy, the classical strut-and-tie mechanical model for the design of a straight 3.0 m long RC beam characterized by a rectangular cross-section having 0,20 m and 0,45 m of width and height, respectively. The concrete segments assembled together along with the rebar system (Fig. 3c) were able to provide (*i*) a top continuous concrete chord to bear the compression forces induced by the flexural behaviour; (*ii*) a bottom steel chord to bear the tensile forces and (*iii*) diagonal compression concrete struts and opposite diagonal steel struts in the lateral segments to bear the shear forces. The same strategy was applied to print another RC beam characterized by an irregular arc profile (longitudinal profile of Vesuvius volcano) about 4,00 m long and width equal to 0.25 m (Fig. 3d).

If prestressed external reinforcement is used, strategies and detail solutions known from conventional externally prestressed structures, particularly precast segmental bridges [27], can be applied, paying specific attention to creep and shrinkage behaviour. While being similar to the external reinforcement arrangement manufacturing process investigated at the University of Naples, this approach exploits a different mechanical principle since it relies on the concrete to remain in compression at all times, rather than on activating a composite action between the concrete in compression and the reinforcement in tension. Hence, the design is based on the strategy to overcome the necessity to accommodate tensile stresses – an approach that dates back at least as far as the Roman Empire. This can be achieved by designing compression loaded structures like domes (Fig. 4a [28]; Fig. 4b [29]),

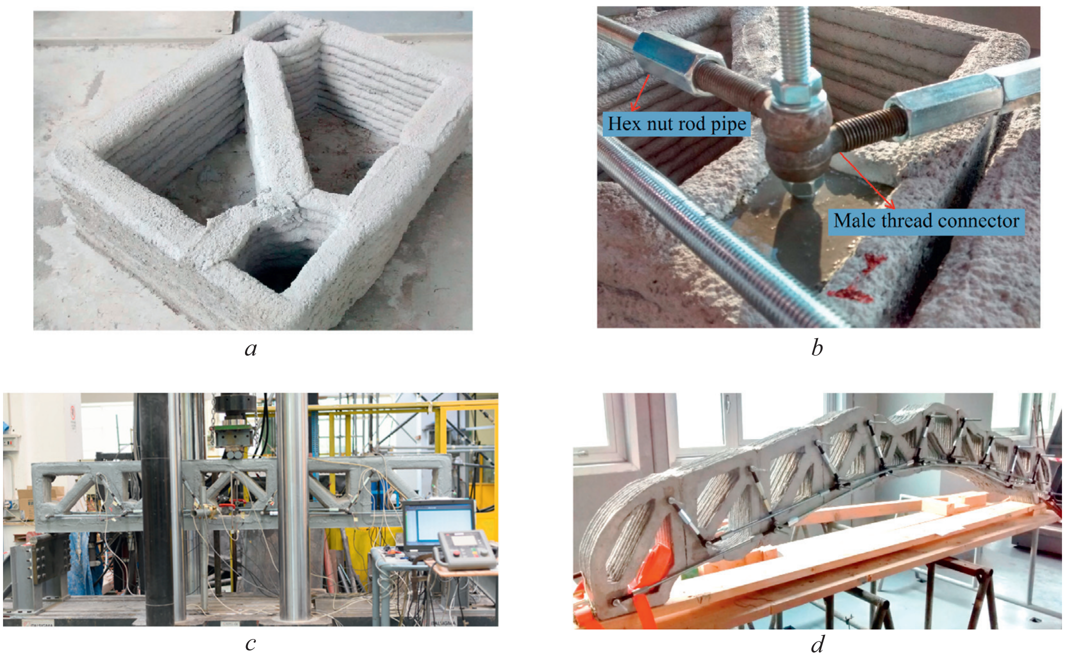

Fig. 3. External reinforcement arrangement approach [26]: (a) concrete 3D printed segment; (b) external steel reinforcement connection details; (c) straight and (d) variable cross-section RC beams obtained through the DFC technique of external reinforcement arrangement.

a *b*

Fig. 4. Compression loaded structures: (a) self-supporting shell, constructed from double curved segments printed and cast on a flexible mould; (b) thin-vaulted, unreinforced concrete floor built with digitally fabricated formworks [29].

arches, heavy walls or columns, but the application of additional amount of prestress allows expanding this strategy to elements that normally involve significant tensile stresses such as floors and beams.

This prestressing principle was firstly applied for the design and digital manufacturing of a free-shaped wall-like concrete bench using the 'Concrete Printing' approach, an automated extrusion-based process for concrete developed at the Loughborough University, UK [30, 31]. The overall size of the bench was 2.0 m by 0.9 m as footprint and 0.8 m of height. The printed structure was designed to include a certain number of conduits passing through the height of the bench; these were used for the post-printing placement of 8 mm diameter reinforcing bars which were post-tensioned and grouted to achieve a predetermined compressive stress state into the structure (Fig. 5).

Following the same structural design principle, a real scale example is the pedestrian and bicycle bridge developed at the Eindhoven University of Technology (TU/e) which was recently placed in Gemert, the Netherlands [32]. It is constructed from 6 segments, printed to a height of 99 cm each (99 layers). Fig. 6 shows a showcase segment of several layers high. After printing, the segments were rotated by 90°, positioned next to each other and connected by post-tensioned prestressing tendons that were anchored in conventional cast blocks. An epoxy adhesive was applied to the seams. A 1:2 scale model of the mentioned pedestrian and bicycle bridge was tested in 4-point bending (Figs. 7, 8). Several cracks occurred well above the design load, but the test element did not collapse. The final design also features cable reinforcement and was allowed for construction in the Netherlands.

4.4. 3D printed concrete formworks

In a limited number of projects, a different strategy has been adopted, that is the use of 3D printed concrete as lost formwork for conventional reinforced concrete. In this case, DFC is unreinforced,

Fig. 5. Digital manufacturing of a free-shaped wall-like concrete bench using the 'Concrete Printing' approach [30, 31].

typically not structurally active and the reinforcement is placed during manufacturing in a "passive" way. The inclusion of passive reinforcement using conventional steel elements represents a more straightforward approach than the above-described technologies. Placing by hand and repeatedly horizontal and vertical reinforcing steel rebar seems to be one of the easiest solution able to create a regular reinforcing scheme in structural elements with a standard geometry. This approach has been combined with several DFC techniques currently available on the market (e.g. WinSun - Fig. 9 -, ApisCore, Contour Crafting [3, 33, 34]); a typical representative example is the production of RC walls using contour crafting technique in which custom-made reinforcement ties are manually inserted between layers with a spacing of 30 cm and 13 cm in the horizontal and vertical direction, respectively [3]. Even though this approach allows for an easy and, probably, cost-effective implementation of reinforcement, some limitations appear to be not negligible from the structural design point of view. Indeed, this approach raises concern about the interface between printed and cast concrete, control of the concrete cover and structural efficiency, as well as about the flexibility in terms of shapes and possibilities of digitally producing complex reinforcement assemblies. These aspects restrict the range of structural applications to those characterized by simple loading conditions or, in general, to those not requiring complex resistant mechanisms, such as the production of vertical elements subjected to compression loads.

4.5. Printable fibre reinforced concrete

The addition of fibres to the concrete matrix is an obvious solution strategy that has been explored on a very small scale by Hambach and Volkmer [35], who added 3–6 mm basalt, glass and carbon fibres to a printable mixture, and Panda et al. [36], who compared glass fibres of different lengths (3, 6 and 8 mm) and varying the volume percentage of fibres (vol%). Both studies reported a significant increase in flexural tensile strength as well as an orientation effect of the fibres in the direction of the filament flow, but neither discussed the effects on ductility.

At the TU/e, two variants of fibre reinforcement are being investigated. Application of such concepts in large scale printing facilities, may require specific consideration and adaptations of the material mixing and/or print facility. First trials have shown that a target quantity of 150 kg/m^3 6 mm straight steel fibres (Bekaert Dramix OL 6/.16) could be printed. In a scaled-down version of the standard CMOD test, specimens showed a significant increase in tensile strength and ductility. However, the behaviour is still strongly strain-softening. As in the referenced studies, strong alignment of the fibres in the flow direction of the concrete was observed.

a *b*

Fig. 6. Printed showcase segment for the pedestrian and bicycle bridge. The bridge consists of 6 of segments of 99 cm height that have been printed, rotated 90°, stacked together and bonded with epoxy adhesive, before being further joined by post-tensioned prestressing tendons.

4.6. 3DCP with directly entrained reinforcement cable

The most advanced concept currently under development at the TU/e, is the direct in-print entrainment of reinforcement cable into the concrete filament during printing. This concept builds on an idea presented by Khoshnevis et al. [37] that included a reinforcement wire coil that would not only provide longitudinal tensile strength, but also ductility though the layer interfaces, as half of the coil sticks out of the preceding layer.

In this concept, the reinforcement cable should be sufficiently strong and ductile, but also highly flexible to allow it to follow all 3D freeform lines that can be produced with the concrete filament. High strength steel cables for synchronous belts provide such a combination of properties (Fig. 10).

Several experiments have been conducted, using 3 types of cable (A, B and C) with ultimate tensile loads of F_{uk} = 420, 1190, and 1925 N, respectively, and diameters ranging from 0.63 to 1.20 mm.

In an initial test, Bos et al. [1, 38, 39] (Fig. 11a, b), printed beams elements of 7 layers high with reinforcement in the bottom one or two layers, were subjected to 4-point bending. This showed the concept is feasible, and significant ductility can be achieved. Furthermore, the conventional methods to calculate moment resistance in RC appeared to be applicable – as long as failure was induced by cable breakage. For the stronger cables, this could not be achieved. Cable slip occurred which resulted in higher scatter and failure loads lower than those theoretically predicted.

In a more extensive subsequent study Bos et al. [39], the pull-out behaviour of the cables in cast and printed concrete was investigated (Fig. 12a, b). The bond strength in cast concrete was 1.5 to 3 times higher than in printed concrete. The bond in printed concrete was towards the lower end of what would be expected from smooth rebar. The proportion between adhesion and dilatancy in the bond resistance was also comparable (adhesion 60–90% of the overall bond strength).

From the results, anchorage lengths were calculated, and new series of beams were designed: 3 layers high, with a reinforcement cable in each layer. The beams were designed so that the ultimate failure moment should exceed the cracking moment, $M_u > M_{cr}$. However, although this approach worked for the A-type cables, failure through cable slip still occurred in the B- and C-type cables. Two possible causes were anticipated. On the one hand, the compaction of the concrete matrix around the cables may have been poorer in the printed beams than in the pull-out specimens because there were fewer layers on top

Fig. 7. 1:2 scale model of 3D concrete printed pedestrian and bicycle bridge tested in 3-point bending.

Fig. 8. The 3D concrete printed pedestrian and bicycle bridge in Gemert, the Netherlands, is hoisted into position.

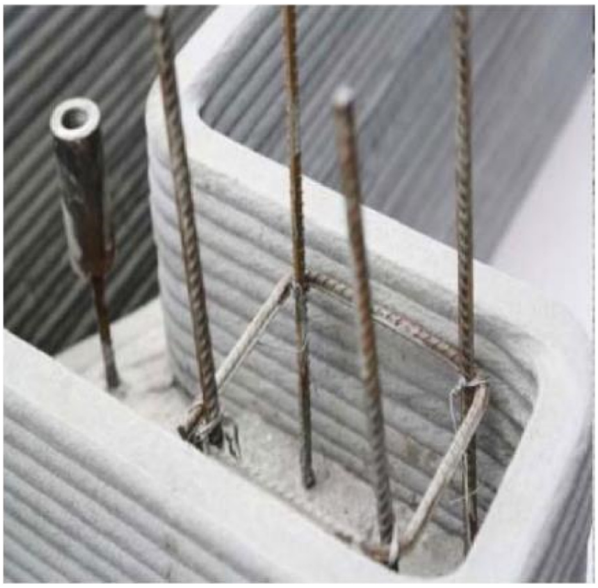

Fig. 9. Example of inclusion of passive reinforcement in a 3D printed concrete formwork (WinSun [33]).

of the reinforced layer. The lack of self-weight resulted in less bonding. On the other hand, peak stresses at the loaded side of the cables (main crack in beams) may induce gradual debonding before the cable strength is reached, regardless of the applied anchorage length. Improving the bond for B- and C-type cables will therefore be a priority, as only they are strong enough to obtain significant post-crack strength. The tests on the A-cable beams, nonetheless, confirmed the applicability of common calculation methods for RC. The variability of the bond behaviour between cables and the concrete matrix highlighted the major role of the production conditions for the effective implementation of this technique, such as contour length, drying stage, self-weight of the structural build up, concrete matrix compaction, and geometry effects [6, 40, 41]. The effective control of these process-related aspects is required to achieve the successful scale up of structural elements manufactured with 3DCP using directly entrained reinforcement cable. In addition, some specific tests need to be defined in order to develop suitable design provisions referred to the anchorage length and bond strength.

5. Discussion

The previous section showed a number of DFC techniques under development in which new approaches to the traditional application of reinforcement are incorporated. Using the categories as introduced in

Fig. 10. Printing with the Reinforcement Entraining Device (RED) to introduce a steel cable into the concrete layer.

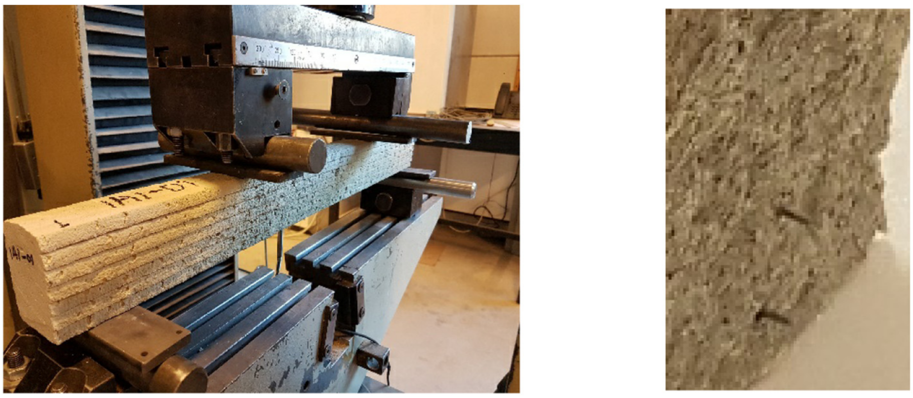

Fig. 11. Seven-layer printed beam tested in 4-point bending (a, left), and fractured section after testing (b, right). In this specimen, final failure occurred by cable breakage.

Table 1, they can be categorized in the matrix shown in Table 2.

As they are generally still in the (very) early stages of development, it is difficult to compare their performance, structurally, or in terms of efficiency and economy. Nevertheless, it is possible to discuss their potential.

With regard to the reinforcement strategy consisting in using a ductile printing material, considering the research being performed so far, it is likely that different variants of printable FRC will soon be available. They will certainly increase the (flexural) tensile strength of plain concrete, but it is yet uncertain if sufficient ductility could be achieved economically. For SFRC, it is difficult to obtain strain-hardening because of the short, straight fibres used so far in digital fabrication applications (mainly depending on technological issues arising from extrusion-like processes). On the other hand, strain-hardening behaviour has been obtained for cementitious composites with PVA fibres, initially for cast applications [11, 12] and recently for printable mixtures as well [42, 43]. Even without strain-hardening, fibre reinforced printed elements may find applications in secondary structural elements such as cladding. An alternative to address more demanding structural applications with a ductile printing material is to combine the fibres with some continuous reinforcement. This hybrid solution has been explored for the Mesh Mould technology showing promising results to overcome the limited ductility of FRC.

For those digital technologies in which the ductile material is deposited in layers (e.g. in 3DCP or layered extrusion) a major question is the mechanical performance across the layer interface. This is relevant in terms of durability and serviceability behaviour for all applications but is a critical aspect for the mechanical capacity in applications with ductile printing material whose dimensioning relies on the FRC tensile strength. When a filament with fibres is deposited, the fibres do not tend to stick out. Therefore, crack surfaces on the layered interface may perform similar to the material without fibres. Further research in this area is required to (*i*) improve the performance across the layer

Table 2
Classification matrix of reinforcement strategies under development for DFC.

Manufacturing stage → ↓ Structural principle	Before	During	After
Ductile printing material		Printable FRC	
DFC composite	Smart Dynamic Casting Mesh Mould	3DCP with reinforcement cable 3D printed concrete formworks	External reinforcement arrangement
Compression loaded structures			Prestressed external reinforcement
Hybrid solutions		FRC Mesh Mould	

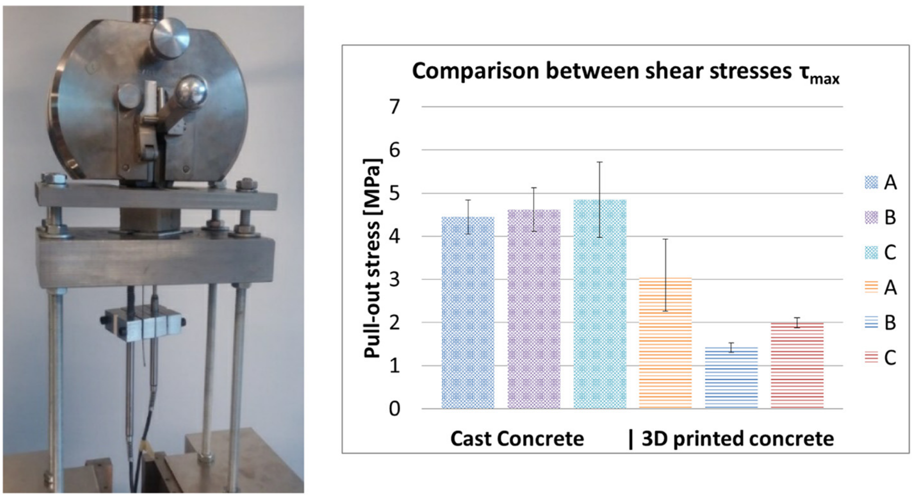

Fig. 12. Pull-out test on concrete with embedded reinforcement cable: (a, left) experimental set-up with printed specimen; (b, right) comparison of average bond strengths in cast and printed concrete for 3 types of cables.

interface and (*ii*) develop design procedures suitable for this strong material anisotropy.

Many technologies are already available to reinforce digitally fabricated elements introducing passive reinforcement besides the printing material (DFC composite structural principle as indicate in Table 1). A first possibility is to produce the reinforcement before the concrete placement. While the geometric freedom is limited in this case by the possibilities of the reinforcement manufacturing, experience with first applications in Mesh Mould and Smart Dynamic Casting technologies shows that a high geometric complexity is already possible. The use of a specialized robotic reinforcement assembly independent of the concrete placement allows placing conventional inexpensive deformed bars in multiple directions of the structure and applying similar design concepts as for conventional concrete structures already today. Further technological development of robotic rebar assembly processes is expected in the near future, increasing versatility and construction speed [24]. Another advantage of such a reinforcement strategy is that concrete layer deposition can be avoided (with a slip forming process as in Smart Dynamic Casting or with a conventional casting as in Mesh Mould), reducing potential durability and mechanical issues in the layer interface.

Passive reinforcement can also be introduced during the concrete deposition as shown by the cable reinforcement technique. This interesting development has been shown to provide considerable tensile strength and ductility, as well as a good compatibility with the print process. Like fibres, the cable reinforcement can be applied without an additional step in the manufacturing process, but the structural performance is much more comparable to conventional RC. The issue of bond and anchorage of stronger cables needs to be resolved, however, this is not expected to be an insurmountable problem. For now, a drawback remains the orientation of the reinforcement that is necessarily in the direction of the print filament. When the print path is cleverly designed, this nonetheless allows for a considerable number of applications.

A third possibility to introduce passive reinforcement is to integrate it with concrete after the DFC process. The external reinforcement arrangement makes possible to incorporate a large amount of steel reinforcement. The preliminary outcomes of the experimental activities carried out so far 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, the reduction of concrete volume and mass, the elimination of complex formwork systems, and easy transportability and installation.

For a limited number of structural applications, the necessity of tensile capacity and ductility can be over-ridden by designing structures loaded only in compression or with minimal levels of tension. Whenever feasible this solution is easy to apply as it neither requires additional manufacturing steps to insert reinforcement nor limits the form freedom (other than the requirement that the element should be compression loaded). However, as a general strategy it has significant limitations and requires considering the risk of shrinkage cracks and tensile stresses induced by imposed deformations, particularly regarding support settlements and displacements.

The application of prestress is able to overcome the need for tensile capacity, but it can be applied in a much wider spectrum of applications than the compression loaded structures strategy due to its capacity to counteract tensile stresses. Moreover, known strategies and detail solutions from conventional externally prestressed structures can be directly applied. On the other hand, applying prestress limits the form freedom and introduces an additional step in the manufacturing process. Realized projects have shown it can be a powerful solution strategy appropriate to considerable size, but its suitability is highly application dependent.

The broad range of reinforcement strategies discussed in this section has pointed out a number of issues related to the structural behaviour of the reinforced elements. So far, the structural performance and the behaviour of the reinforcement have been hardly ever studied, and the compliance of the reinforcement with building codes has been rarely considered. Of course, on the other side, also standards should evolve to adapt to the particularities of DFC.

In this context, it is important to note that in order to guarantee structural integrity and serviceability, substantial reinforcement quantities are required, being oriented in two or even three directions. Hence, just as in conventionally built structures, 60–120 kg/m^3 of reinforcing bars typically need to be provided, and fibre reinforced concrete with usual fibre contents (i.e. not affecting workability) can only replace part of this reinforcement. Unfortunately, many current DFC techniques do not cover these requirements efficiently, and their application is therefore restricted to structurally less demanding applications, such as replacing traditional unreinforced masonry walls.

6. Conclusion and outlook

Reinforced concrete is one of the world's most widely used structural materials and its implementation in digital technologies may represent a paradigm shift in the fields of construction and architecture. Being a composite material, assembling reinforcement with concrete in a digital fabrication process requires complex integration strategies involving various materials and a series of processing steps. A successful integration between concrete and reinforcement has the potential benefit of improving performances of materials, systems and structures.

In general, DFC technologies require new strategies to obtain sufficient tensile strength and ductility if its products are to be used in structural applications. Conventional reinforcement solutions are incompatible with these technologies, or impair their particular advantages, unless they are an intrinsic part of the manufacturing process. In this paper, a number of concepts that are being applied in novel DFC technologies to replace conventional reinforcement have been presented. They can be categorized according to the structural principle, the integration step in the manufacturing process or both. Although these strategies vary considerably in their approach, they all show at least the potential to generate the desired structural behaviour. However, extensive quantified characterization of their performance is generally still lacking and requires further research. Additionally, it should be noted that the applicability of most concepts is dependent on the DFC system that is used in manufacturing, and on the specific demands in terms of structural performance of the end-product. A further source of consideration is that DFC could be implemented not only as a pre-fabrication process for structural elements or building components but also in an in situ process to accomplish larger applications. Hence, issues related to the equipment mobility need to be addressed. Significant challenges are also represented by the end-product mechanical characterization (e.g. large scale testing), the quantification of design performances and design criteria suitable for structural applications; current knowledge on conventional reinforcement concrete structures should be re-thought and adapted to the particularities and new possibilities offered by digital fabrication technologies, leading to new test standards and design guidelines required to spread the use of these technologies.

As is often the case in the development of new technologies, several concepts are likely to advance simultaneously until it becomes clearer which ones are most competitive, structurally and economically effective. In any case, it is evident that the development of DFC will not be stopped by a lack of reinforcement options.

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