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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