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3D printing of reinforced concrete elements: Technology and design approach

Domenico Asprone [a], Ferdinando Auricchio [b], Costantino Menna [a,*], Valentina Mercuri [b]

[a] Department of Structures for Engineering and Architecture, University of Naples Federico II, Italy
[b] Department of Civil Engineering and Architecture, University of Pavia, Italy

HIGHLIGHTS

- We present the fabrication of RC members based on concrete 3D printing technology.
- A straight 3.00 m long RC beam is manufactured and tested under 3-point bending.
- A second RC beam has been also 3D printed with variable cross section.
- The approach will facilitate the production of free-form structurally optimized RC structures.

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ABSTRACT

This paper deals with a novel approach to the fabrication of reinforced concrete (RC) members based on Concrete 3D printing technology. The approach consists in the partition of a RC member into different concrete segments printed separately and, then, assembled into a unique element along with the steel reinforcement system. The approach is expected to facilitate the production of free-form structurally optimized RC elements with the final aim of saving concrete material and, at the same time, fabricating lighter structures. As case study, we report on the material characterization and fabrication steps of a straight 3.00 m long RC beam together with the results of a full-scale three-point bending test performed on it. As a demonstration of the potentialities of this approach, the fabrication of a free-form variable cross-section RC beam is also presented.

1. Introduction

Additive manufacturing (AM) has been defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [1]. AM technologies are increasingly having an impact on industrial processes in many fields and numerous applications have been developed so far, ranging from, for example, automotive to medical, security and aerospace sectors [2–4]. Advocates of AM argue that this technology represents a new industrial revolution and is enabling the mass customization of industrial production, where small quantities of customized products can be built affordably [2,5].

Until a few years ago, AM technologies were mostly applied to rapid prototyping (RP), i.e. the fabrication of prototypes used for iterative design, inspection and communication tools. In fact, AM technologies were not considered to be able to process common materials with adequate mechanical and physical properties [6]. However, the emerging *digital fabrication*, defined as the application of digital modelling and technologies to the production of custom material objects, promises to revolutionize the traditional manufacturing schemes. Indeed, nowadays AM technologies are successfully implemented to fabricate objects made of ceramics [7], metals [8], and polymers [9] with adequate mechanical properties.

Recently, AM technologies are attracting a growing interest in construction industry as well, especially in the concrete technology. The interest in exploiting AM technologies in construction industry is mainly the result of the expectation of new freedom in terms of the design of shapes, elements and structures, enabling at the same time new aesthetic and functional features (often referred to as *freeform constructions*). In fact, in the construction industry, single components are in most cases unique in dimension. Standardized/traditional manufacturing processes require pieces to be cut through subtractive technologies (in which the

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* Corresponding author.
E-mail address: costantino.menna@unina.it (C. Menna).

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material is machined away to produce the final object - e.g. natural stone, ceramic pavements) or proper moulds to be created. In the latter case, moulds are utilized in combination with formative technologies (where the fresh material is cast in a mould - e.g. reinforced concrete elements) to achieve the final shape of the object [10]. Accordingly, in both cases, architectural designers are often forced to use multiple identical elements in a project to save materials and reduce costs of labour and/or moulds. By changing the approach in the way that components are produced, AM is expected to revolutionize this paradigm, allowing designers to make each component unique without incurring prohibitive costs.

Other advantages of this automated process are also expected, such as the reduction in construction time and expenses, greater worker safety, better quality and reliability, the saving of materials and, consequently, sustainability [11]. Notably, with regard the latter aspect, a recent study has demonstrated that digital fabrication is able to provide environmental benefits when applied to complex structures, for which additional complexity can be achieved without additional environmental costs.

Recently, the combination of digital fabrication techniques and cementitious materials has led to the development of innovative manufacturing processes for fabricating concrete-like products, objects and/or structures; these include Layered Extrusion (contour crafting [12], concrete printing [13], Freeform Construction), Binder Jetting (D-shape [14]), Slip-forming (smart dynamic casting [15]). The detailed review of the methods of digital fabrication with concrete (often referred to as "*digital concrete*") is reported in [11].

To date, most developments in digital fabrication of concrete-like products have been focused on layered extrusion technology (such as contour crafting, concrete printing), probably because its overall operating procedure is based on the more widespread production scheme of polymeric customized parts. However, its implementation in construction processes requires much larger printers (or, more in general, robotic machines) than those used for metal or plastic objects, due to the dimensions of the final objects to be printed. Generally, the automated machinery used for layered extrusion of concrete includes a digitally controlled moving printing head (or nozzle) which precisely lays down the concrete or mortar material layer-by-layer, enabling the opportunity to create customized structures and/or functional voids into the printed elements [16,17]. This manufacturing technology facilitates the development of on-site constructions in one single stage, reducing in this way transportation of construction equipment, assembly operations, labour costs and the risk of injuries during construction works [18].

The engineering challenges related to layered extrusion technology are manifold. Indeed, to effectively exploit the functional/mechanical properties of 3D printed concrete products, the layered extrusion of concrete elements requires the fresh printed material to have some specific rheological properties [19]:

- Pumpability: the capacity to be worked and moved to the printing head through a pumping system throughout a given time interval.
- Extrudability: the capability to be extruded properly through the printing head with a continuous material flow.
- Buildability: the capacity to both remain stacked in layers after extrusion and sustain the weight of the subsequent layers that are deposited by the printing process.

Therefore, the concrete/mortar rheology must be optimized to achieve a balance between the need for workability and extrudability on the one hand – which would require reduced yield stress – and the need for buildability on the other – which would require an increased yield stress. The printing speed is a critical parameter as well, and can have an impact on the mechanical properties of the printed elements. Printing speed must be set based on the rheology of the printed mortar, the dimensions of the objects and the dimensions of the extrusion head. In fact, the time elapsed between the deposition of two layers must be long enough to let the first layer adequately harden and become capable of sustaining the weight of the second layer, but short enough to guarantee that the first layer is still fresh enough to develop a good bond with the second layer [11,20].

Given all the issues and challenges related to the AM of concrete elements, this technology is still not mature enough to be used in the market. In addition, steel reinforcement integration into 3D printed concrete structures is characterized by lower technological progress. Available examples concern the Mesh Mould approach which consists in digitally fabricating metal wires formworks that act as permanent reinforcement during the concreting process [11] or, alternatively, the use of fibres in printable mortars. An effective approach to manufacture traditional steel reinforced concrete elements (i.e. made of concrete and steel rebar) by implementing one of available AM technologies has not been developed so far. One of the main reasons is the scarce adaptability of traditional steel reinforcing systems (in the form of stiff, straight and thick rebar or rods) to a specific/complex shape (large energies are required to bend the reinforcing steel) during the AM process. Nevertheless, researchers in this field are increasing their attention with regard to the opportunities that AM is able to provide also for steel reinforcement embedment.

This paper aims to contribute to this promising line of research, and reports on outcomes of a research program aimed to develop a novel approach to the design and fabrication of reinforced concrete (RC) beam elements, based on AM technology.

In the following sections, the scope and basic idea of the fabrication approach are firstly introduced. Accordingly, the design framework is defined, and then the experimental and numerical outcomes of the first full-scale 3D printed RC beam are discussed along with the expected advantages and critical issues arose.

2. Material and methods

2.1. A novel approach to the manufacturing of RC elements

The main objective of the fabrication approach herein presented consists in manufacturing steel RC beams using AM technology of concrete. The implementation of the proposed approach enables the manufacturing of structural elements with complex shapes. In particular, the fabrication process allows the final beam to be curved - in the plane containing the longitudinal axis - with variable cross-section heights $h(x)$ (Fig. 1). This beam configuration would require the arrangement of complex (and costly) formwork systems when using classical concrete casting technology (i.e. polystyrene moulds, multiple wooden formworks etc.). A further fundamental characteristic of this approach is that the AM allows the beam to be partially hollow (once it has been properly designed, as explained in the following section), in order to save material, provide functional uses and reduce the final weight, while still guaranteeing adequate mechanical properties related to the intended structural application.

In this study, the approach to produce a curved RC beam is implemented by the 3D printing and subsequent assembling of concrete segments (Fig. 2a). Each beam segment is printed through the thickness of the beam, i.e. in the direction orthogonal to the 2D plane of the beam (z direction in Fig. 1). This allows only cylindrical elements (with equal cross section along the z height) to be printed, with no need to shift the concrete flow layer-by-layer during the printing process to fabricate non-regular shapes through the thickness direction. This is an important point since the low