Construction and Building Materials 179 (2018) 125–137

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

3D-printed steel reinforcement for digital concrete construction – Manufacture, mechanical properties and bond behaviour

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HIGHLIGHTS

- Reinforcement approaches for digital construction are summarised.
- 3D-printing of steel reinforcement based on gas-metal arc welding is described.
- 3D-printed steel bars' mechanical performance is shown to be similar to that of conventional bars.
- Printed steel bars' failure is shown to be ductile, on both the micro- and macro-levels.
- Printed steel bars' bond to printable, fine-grained concrete is shown to be satisfactory.

ARTICLE INFO

Article history:
Received 4 February 2018
Received in revised form 1 May 2018
Accepted 24 May 2018

Keywords:
Digital concrete construction
3D-printing
3D-printed steel reinforcement
Gas-metal arc welding
Tensile behaviour
Bond behaviour

ABSTRACT

Digital concrete construction has recently become the subject of very rapidly growing research activities all over the world. Various technologies involving 3D-printing with concrete have been developed, and the number of demonstration projects and practical applications has been increasing exponentially. Most of these approaches are focused on the placement of concrete, while the suggested solutions for incorporation of reinforcement are still rudimentary, and as such they lag behind the concepts for printing concrete. Since the use of (steel) reinforcement is mandatory in most structural applications, there is an urgent need to bring the technology of reinforcing 3D-printed structural elements forward. The article starts with a brief overview of the existing approaches in using reinforcement in digital concrete construction. Then the authors' own research work is presented, namely a feasibility study on 3D-printing of steel reinforcement using gas-metal arc welding. A description of the newly developed 3D-printing process is followed by a demonstration of its feasibility in producing vertical steel reinforcement bars with and without extra ribs. The mechanical performance of the printed bars was investigated by means of uniaxial tension tests. The samples exhibited comparable mechanical properties to common steel reinforcement of the same diameter. The investigation of fracture surfaces confirmed a ductile mode of failure of the printed steel bars. Finally, the bond between printed steel bars and printable fine-grained concrete was tested by means of pull-out experiments. Here the overall performance could be rated as satisfactory, even though it could be improved by introducing extra ribs in the process of bar manufacturing.

1. Introduction

The digitalisation of planning and production processes has been developing with ever increasing speed over the last few years. In the construction practice, digital design and digital planning by means of CAD, BIM and other powerful software tools are well developed already and have been becoming ever more widespread. The step from digital planning to digital manufacturing is a logical consequence, namely a step towards a fully, or nearly so, digitalized, seamless process constituting Construction Industry 4.0. The expected benefits of digital construction are higher quality and productivity, faster construction processes, higher geometrical freedom, more efficient use of natural resources, higher cost-efficiency, universality, etc.

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https://doi.org/10.1016/j.conbuildmat.2018.05.202
0950-0618/

Since concrete is by far the world's most widely used construction material, in most applications reinforced with steel bars, the activities in the field of digital construction focus on the development of digital manufacturing techniques in applying concrete. A recent variety of methods have concentrated on the additive or generative manufacturing of construction elements and can be generally subdivided into two main categories: methods based on extrusion-like processes and methods based on selective binding, also known as powder-bed printing (an overview of further, less widespread approaches is given in [34]). In the case of "extrusion-based" additive construction, premixed material is extruded at the specified coordinates through a nozzle at the determined printing rates [1,2]. To be more precise, in most cases the mode of material flow through the nozzle of the print head does not correspond to that of the "classical" extrusion. However, since the focus of this article is on the implementation of reinforcement into digital construction, concrete 3D-printing techniques will be presented only insofar as needed to discuss the possibilities of such implementation. With respect to options of integrating reinforcement, first the fineness of deposited filament is decisive.

In the case of selective binding, dry materials are first placed as a thin layer on a platform (bed) and a binder or activator is then delivered to specified coordinates [1,2]. Then the next layer of dry material is spread and the next round of binder/activator is delivered. The process is repeated again and again while the printed element "grows", always enveloped and supported by the unbonded dry material, until it is removed after completion of the manufacturing process. While being elaborate and cost-intensive, the methods based on selective binding offer the highest degree of geometrical freedom. However, at this stage the introduction of reinforcement appears limited to one method only: In the process of printing, channels for subsequent integration of reinforcement bars are produced. Obviously, either bonded or unbonded post-tensioning cables can be used; for the latter the channel must not be filled with a grout aid. The first and, until now, the only such pedestrian bridge was built by post-tensioning several concrete segments together which were printed using the selective binding technique [3].

Researchers at the University of Loughborough [4,5] also used printed openings in structural elements for placement of steel bars which were eventually pre-stressed. They developed a concrete printing approach based on the extrusion of very thin and narrow filaments, which enabled the crafting of filigree forms including channels for reinforcement or cables.

The most widespread approach of 3D-concrete printing is the Contour Crafting method developed by Khoshnevis [6] and introduced into the construction practice by companies such as WinSun [7], TotalKustom [8] and ApisCor [9]. In this approach, the contours of mostly vertical structural elements are produced by extruding/depositing concrete filaments with a width of several, usually 2–5 cm, and a height of generally 1–3 cm. These contours establish a permanent, integrated formwork which is eventually filled with flowable concrete in most cases. Before filling the "formwork", vertical and horizontal reinforcement bars can be positioned within it, see Fig. 1a. Horizontal bars can be additionally or exclusively placed between the individual layers of concrete in the process of 3D-printing. This can be done discontinuously (bar by bar) after completion of the corresponding printed sections, or simultaneously by placing a steel wire using the printhead directly during concrete printing. Various options can be realised here, including the use of metal chain instead of wire, the latter demonstrated by TU Eindhoven [10].

Several important issues such as consideration of the "integrated formwork" in structural design, quality of corrosion protection by printed, fine-grained concrete or mortar, and classification depending on the material's having been considered in the structural design. The effect of construction joints on the transport of aggressive fluids and gases between layers, or the quality of the bond of printed concrete to the horizontal reinforcement placed between concrete layers should be mentioned here but will not be further discussed; considerable research is needed to clarify these matters.

Apart from conventional steel reinforcement, alternative reinforcement can be potentially applied in conjunction with Contour Crafting. Khoshnevis [11] suggested a novel system consisting of prefabricated steel elements assembled step-by-step by a robot in accordance with the progress of contour crafting and the filling of the "formwork" with flowable concrete. Even if the system appears very elaborate and expensive, it is at the very least sufficient to trigger engineers' fantasies toward inventing novel reinforcement approaches. Certainly, the use of technical textiles can be an option. In [12] an example of applying two-dimensional glass fibre-based, wide-mesh textile is shown, where it is placed horizontally between the printed layers, covering the entire cross-section of the structural element. The efficiency of this particular arrangement of textile reinforcement is questionable, but more productive use of textile-based systems can be easily imagined in the context of 3D-printing.

Not all extrusion-like approaches are limited to printing contours of structural elements only. At the TU Dresden the CONPrint3D technology has been developed, which enables printing of monolithic cross-sections of several decimetres in one evolution [1,13]. While the initial purpose of this approach was to replace masonry work, the integration of reinforcement is on the agenda to enhance the versatility of the technology. Again, placement of horizontal reinforcement in the form of steel bars, CRP bars or textile would not be a problem; however, suitable solutions for integrating vertical reinforcement are still under development.

An original approach to combining the manufacturing of monolithic elements with vertical and horizontal reinforcement was invented and proven feasible by the Chinese firm HuaShang Tengda Ltd. Here, steel mats are mounted initially while concrete is placed layer-by-layer, gradually enclosing the reinforcing bars from all sides, see Fig. 1b. To master this task a special design of the printhead is needed: HuaShang Tengda Ltd uses a forked nozzle that simultaneously lays concrete on both sides of the rebars, "swallowing" it up and encasing it securely within the walls [14]. This company recently "printed" an entire 400 m^2, two-story villa 'on-site' in 45 days. The approach seems to be promising; however, at this stage it exhibits some obvious limitations, such as a) the height of individual mats' being limited to the size of the forked nozzle, which is rather bulky in any case, and b) the limitation of only one or two reinforcement layers' easy integration into the middle of the wall cross-section, and c) the further limitation that only vertical walls (no inclination) can be produced.

Another very original approach has been developed at ETH Zurich under the name Mesh Mould [15]. Here an industrial robot forms steel wire by bending, cutting, and welding into complex, free-form meshes which are to act both as reinforcement and formwork all in one. Eventually fresh concrete of a specific workability is placed into this formwork, only partially 'leaking' through the mesh and so enveloping it. Very recently, the feasibility of this technology was successfully demonstrated by erecting a load-carrying wall of a very complex geometry in the framework of the NEST project [16].

To complete this brief overview (a detailed review can be found in [29]), the possibility of using dispersed-fibre reinforcement should be mentioned as seemingly capable of being most easily integrated into the 3D-printing process by using fibre-reinforced concrete instead of plain concrete. This straightforward approach is surely worth being pursued, especially taking into account tremendous advances in the field of high-performance fibre-reinforced cement-based composites, see e.g. [17–19]. However,