

Reinforcing 3D printed concrete – challenges and current developments

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Abstract

In recent years, 3D printing in the construction industry has gained significant interest due to its ability to create complex structural forms with notable savings in both time and cost. Despite this growing interest, it continues to face various technical and operational difficulties. In order for 3D printed concrete to have a meaningful, long-term influence on construction practices it is essential to develop strategy for integrating reinforcement without contradicting the advantages that the 3D printing process delivers. This paper seeks to give a comprehensive review of the current developments on reinforcement strategies for 3D printed structures.

Key words: 3D printed concrete, additive manufacturing, layered-extrusion, reinforcement, fibers

Armiranje 3D printanog betona – izazovi i trenutna postignuća

Sažetak

U posljednjih nekoliko godina, 3D printanje u građevinskoj industriji izazvalo je značajan interes zbog svoje sposobnosti stvaranja složenih oblika konstrukcije uz znatne uštede vremena i troškova. Unatoč rastućem interesu, tehnologija i dalje nailazi na razne tehničke i operativne poteškoće. Kako bi konstrukcije od 3D printanog betona imale značajan i dugoročan utjecaj na građevinsku struku nužno je osmisliti načine integriranja armature koji ne kontriraju prednostima koje proces 3D printanja omogućuje. Cilj ovog rada je pružiti sveobuhvatan pregled trenutnog razvoja u području armiranja 3D printanih konstrukcija

Gljučne riječi: 3D printani beton, aditivna proizvodnja, slojevito istiskivanje, armatura, vlakna

1 Introduction

The fundamental concept behind 3D printing involves fabricating structures layer by layer, where three-dimensional components are created using computer-aided-design. Among the available 3D printing technologies, the ones that have attracted the most interest in the construction industry are binder jetting and layered extrusion. In binder jetting, a bed of dry powder is selectively bound by spraying water, applying a liquid binder, or injecting cement paste into layers of aggregate. In the layered extrusion method, pre-mixed concrete is extruded through a nozzle, mounted on either a gantry or a robotic arm, to form the structure. For the construction of large-scale buildings, which is the central topic of this discussion, the most widely adopted process is an automated technique called Contour Crafting (CC), which was developed by Khoshnevis [1]. The use of 3D printed concrete (3DPC) in construction offers several notable benefits. Despite some ongoing debate, it is widely believed that the cost of producing structural elements through 3D printing is lower compared to conventional construction methods, and the total time required to complete a building project can be greatly reduced mainly by eliminating the need for formwork. Additionally, the approach is seen as more environmentally friendly because 3D printing produces significantly less material waste and dust than traditional building practices [2]. The composition of 3DPC mixtures is based on wet-mixed mortars initially developed for spray applications. The mortar used generally contains a high concentration of cement and fine aggregates, because the use of coarse aggregates could cause nozzle blockage. Coarse aggregates play a key role in minimizing shrinkage, therefore, in combination with the low water-to-cement ratios, printable concrete mixes are highly prone to cracking. To address this issue, the inclusion of additives such as superplasticizers and retarders, viscosity-modifying agents and accelerators is necessary. The rheological characteristics of low-flowable mixtures continually evolve due to the ongoing hydration reactions defining a limited time window within which the 3DPC maintains acceptable performance in a fresh-state. If long interruptions occur during the printing process, extended pauses between layers may result in cold joints, where weak interlayer bonding compromises structural integrity.

The fundamental difference, compared to the conventional concrete, is the anisotropy of 3DPC, mainly due to the layered structure created during the printing process. While cast concrete cubes fail in a typical cone-shaped manner, cracks in the printed samples develop parallel to the direction of compression [3]. This crack pattern results from the alignment of deposited filaments parallel to the load direction, with the interfaces between these filaments being inherently weak and more susceptible to separation or cracking under stress [3]. Conse-

quently, 3DPC exhibits greater strength in the vertical (layer-stacking) direction than in the horizontal one. In study by Pham et al. [4] the printed sample tested in direction perpendicular to the layer orientation showed greater flexural strength than the cast samples.

2 Reinforcement strategies

For 3DCP to be viable in real-world structural applications, components must withstand significant tensile forces. Mortar alone is insufficient, so steel or other reinforcement is needed. These must allow for ductile structural performance, be cost-effective, maintain geometric flexibility, and align with automated production methods.

2.1 Conventional reinforcement

The first and most straightforward method for integrating reinforcement involves using traditional steel reinforcement within the printed structure according to current engineering standards. Reinforcing bars are placed manually into the printed concrete and then covered with a following layer of concrete. In addition to steel bars, steel wire mesh could be placed manually onto the freshly printed concrete [3] (Figure 1a). An additional method is to vertically install steel mesh in place first and then apply concrete layer by layer, effectively enclosing the mesh reinforcement from both sides [5] using a modified forked nozzle (Figure 1b). This technique has been commercially employed by the Chinese company HuaShang Tengda [6]. While promising, this approach faces several constraints - the mesh height is limited by the nozzle size, reinforcement is restricted to layers close to the wall's centerline and only vertical walls (without slope) can be produced [7]. Generally, the major issue is the lack of continuous vertical reinforcement and bonding between reinforced bars and 3D printed specimens, considering that reinforcement is placed on top of every layer manually. In [8] authors noted that the bond strength of reinforcement bars and 3DPC was lower than in mold-cast samples, due to inter-layer defects introduced during the extrusion-based printing process. A contributing factor is the low fluidity of the freshly printed mortar, which limits its ability to properly fill reinforcement grooves. Furthermore, the printing direction also influenced bond performance, in particular, parallel-printed specimens demonstrated slightly higher bond strength between reinforcing bars and concrete compared to inclined ones, while vertically printed specimens had the weakest bonding performance. Most common method to include steel reinforcement in 3DPC is to create a permanent integrated formwork and place both vertical and horizontal reinforcements inside before pouring in the concrete

(Fig 1c) [9]. This technique maintains the mold-free benefit of 3DPC while aligning with conventional reinforcement practices, thereby enabling the continued use of existing structural design standards.

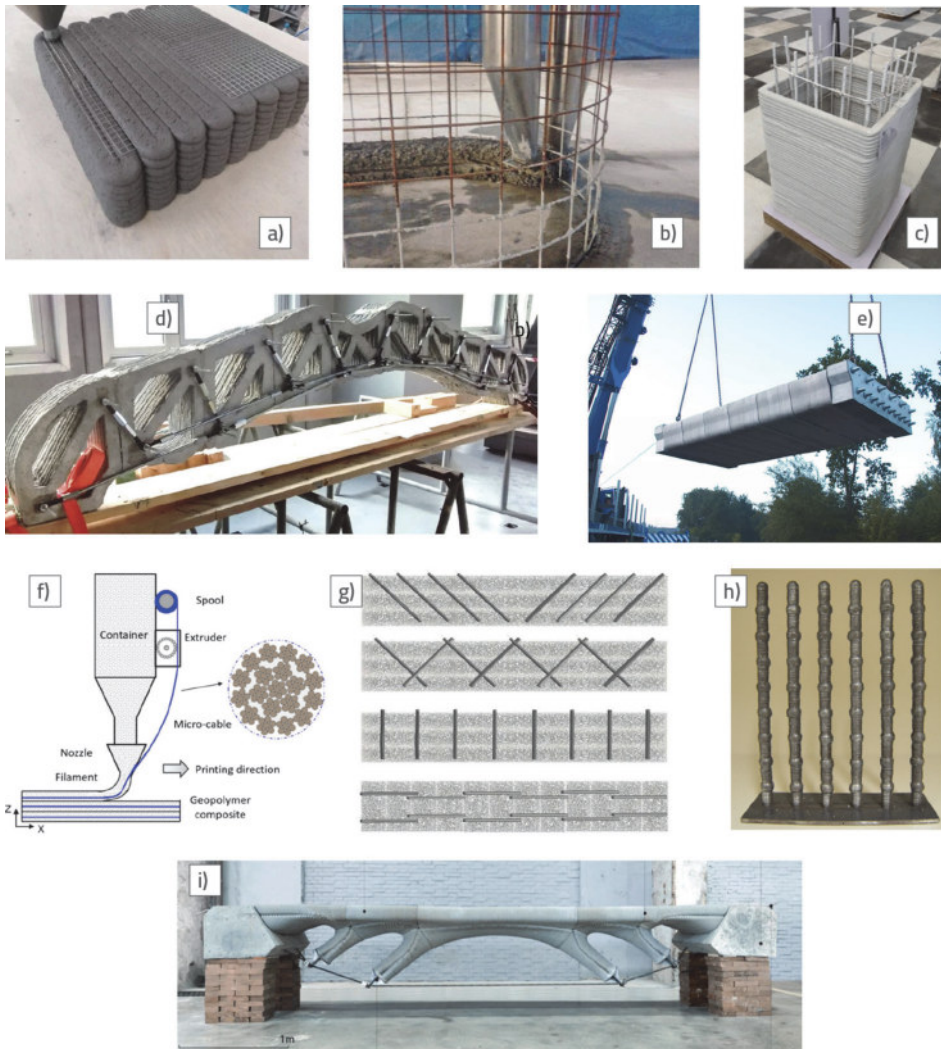


Figure 1. Different reinforcement strategies: a) manual placement of wire mesh [3], b) modified forked nozzle [7], c) permanent formwork produced by CC [2], d) externally prestressed girder [10], e) on site assembly of bicycle bridge [11], f) schematic illustration of printer with embedded micro-cable [12], g) scheme of nail placement across the layers [13], h) profiled 3D printed reinforcement bars [14] i) steel cable supported bridge [15]

Reinforcement elements can be inserted across the interfaces between layers to improve bonding between layers and mechanical performance (Fig 1g). The addition of nails to the layered structure of the printed cement [13] enhanced bending strength by up to 50%, depending on whether the nails were smooth or rusty and the angle at which they were inserted. U-shaped nails [16] have been shown to act as dowels when placed across interfaces, leading to improvements in tensile bonding strength up to 62% and shear bonding strength by as much as 120%.

2.2 Automated reinforcement

Mechtcherine et al. [14] proposed a novel approach to overcome challenges like pre-bending bars, automated placement and bonding between reinforcement and concrete by printing both the reinforcement and the concrete as simultaneously as possible. In WAAM (Wire Arc Additive Manufacturing) method, the reinforcement is constructed drop by drop, allowing for high geometric flexibility i.e. locally increasing thickness of the printed bars to enhance the bond between concrete and the reinforcement (Figure 1h). However, this approach is challenged by high localized temperatures in reinforcement zones, which could possibly damage the concrete, and shorter printing time of steel reinforcement than concrete which could form cold joints in concrete. In addition to short fibers, long reinforcements—like wires, chains, and cables—can also be embedded within the extruded material during the printing process (Figure 1f). Including embedded flexible wire reinforcement directly into the extruded filament through devices attached to the nozzle [12], eliminates the need for additional placement automation. In such cases, the reinforcement material needs to be flexible enough to change direction easily with the printer head, but not too soft to avoid tangling. Furthermore, the reinforcement feeding must be synchronized with nozzle movement to prevent misalignment. Both swinging (in a case of excessively stiff reinforcement) and poor synchronization can displace the reinforcement relative to the cement matrix, leading to voids. These voids and air gaps pose a serious risk to 3D printed structures by allowing harmful substances to penetrate, ultimately reducing long-term durability. Another limitation is that this method only provides interlayer reinforcement and does not bridge layers. Because of that, it is often used with other reinforcement strategies.

2.3 Prestressed reinforcement

External prestressed reinforcement is a commonly used approach in the assembly of prefabricated components for large-span structures, such as bridges. This method was explored in the assembly of structurally optimized post-tensioned

3D printed girder with a span of 3 m [10]. In this case, steel bars were placed externally, anchored into holes at the corners of the printed components, which were later filled with high-strength cement-based mortar (Figure 1d). The researchers showed that the initial flexural stiffness of the externally reinforced beam structure was comparable to that of an equivalent solid beam. However, cracks formed at the anchor points during tensile testing, compromising the structure's overall nonlinear flexural performance. This strategy must also address the issue of corrosion of exposed steel reinforcements.

Another approach involves designing internal voids into the print, forming conduits which allow placement and anchoring of steel reinforcement or cables, which are eventually prestressed and grouted. A practical implementation of post-tensioning strands is the world's first 3D-printed bicycle bridge, developed by TU Eindhoven and BAM [11]. Its segments were fabricated off-site and then assembled using prestressed steel strands anchored in cast concrete end blocks, passing through internal integrated channels of printed parts (Figure 1e). Li et al. [15] utilized composite structural system where pre-tensioned steel cables supported the 3DPC components, allowing them to perform at high levels without additional reinforcement, particularly suitable for structural applications like bridges and roofs.

2.4 Fibers

Although fiber-reinforced concrete (FRC) has been researched for years, its practical use remains limited to elements where compressive forces are dominating, mostly because conventional FRC often exhibits strain-softening behavior, which leads to localized failure and lacks the ductility needed for reliable structural design.

In 3DPC, fibers are typically added after the initial wet mixing phase to ensure uniform dispersion while maintaining the mix's rheological properties essential for smooth extrusion. When the brittle cement-based matrix experiences cracking under tensile stress, the randomly distributed fibers within the composite are capable of bridging across the crack. These fibers limit the crack's width, while simultaneously bearing the tensile load. Because of this mechanism, it is energetically more demanding to further widen the existing microcrack than to initiate a new microcrack in a different area of the matrix [17]. This way, composite material evenly distributes the deformation and effectively prevents catastrophic brittle failure. Based on [18] increasing the fiber ratio, the crack spacing and number of cracks increased, regardless of fiber length. In the Figure 2, flexural stress – strain curves for brittle and ductile failure of fiber reinforced 3D printed concrete (FR3DPC) are shown. Curve representing ductile failure has three significant stages. The first stage ends when the initial cracking occurs, it demonstrates a

linear-elastic behavior in flexural response and is based on tensile resistance of cement-based matrix. After the initial drop in stress, FR3DPC shows a renewed increase in stress, indicating strain-hardening behavior and beginning of the next stage. Stress transfer between fibers and matrix occurs, known as fiber bridge mechanism. Bending stress increases non-linearly up to ultimate value. In the final stage, flexural stress decreases with displacement. Although the material still exhibits a strain-softening response after peak load, the increase in both flexural strength and fracture energy proves beneficial.

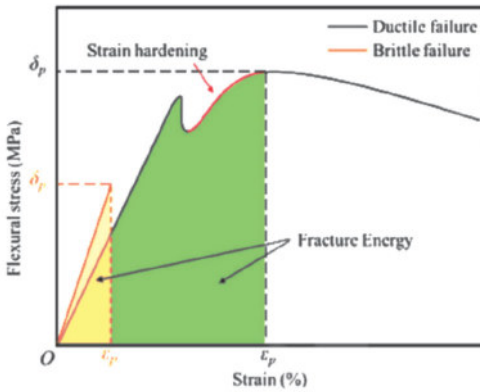


Figure 2. Stress strain curve of FR3DPC [19]

[18] showed that specimen's failure with fiber reinforcement, compared to one without reinforcement, was no longer primarily due to the weak interface created by 3D printing. Pham et al. [4] highlighted that fiber orientation, critical length and volume fraction are key factors in enhancing flexural performance via fiber bridging. Volume fraction refers to the amount of fibers added to a concrete mix, expressed as a percentage of the total volume of the composite. In case of FR3D-PC, it usually ranges from 0,1% to 3% [20]. During the extrusion process, fibers tend to align with the path of the filament because of the constrained size and flow direction of the filament. This preferential alignment in printed materials leads to pronounced anisotropic mechanical behavior. Regarding the fiber orientation, maximum performance is reached with fibers oriented perpendicular to the compressive load direction [21] because fiber resistance is based on pull-out behavior rather than yielding, as is the case with traditional rebars. In [18] authors demonstrated that post-peak performance was directly related to fiber length. In contrast, shorter fibers are less effective due to limited bonding and a lower probability of intersecting cracks. It is important to note that although longer fibers improve post-peak behavior, they also impose higher requirements on the printer's mixing process and the design of the print head.

Fibers can be generally categorized as rigid or flexible depending on their elastic modulus and aspect ratio where flexible fibers have a higher aspect ratio compared to rigid ones [22]. Flexible fibers, such as polypropylene (PP) have a lower modulus than the cement-based matrix and they tend to break under stress transfer. Polyethylene (PE) fibers have superior tensile strength and are hydrophobic, compared to the commonly used polyvinyl alcohol (PVA) fibers. The hydrophobic nature of PE fibers reduces fiber-matrix chemical bonding, significantly increasing the complementary energy during fiber bridging [23]. Rigid fibers, like steel fibers, have higher modulus than cement matrix and are successful in shifting stress from the matrix to the fiber which enhances compressive strength by means of fiber pull-out [19]. In the following table, a review of investigative studies on the effect of different types of fibers on mechanical properties is given. All values are representative for testing load direction perpendicular to the printing path, hence fiber orientation (Z direction). Increase (+) or decrease (-) of flexural and compressive strength in comparison to non-reinforced specimen is presented if data was available.

Table 1. Effect on mechanical properties of various fiber types

Reference	Fibers	Volume fraction (%)	Flexural strength (MPa)	Compressive strength (MPa)
[23]	*PE	1	15.6	39.8
		1.5	19.4	44.6
		2	14.5	47.3
[24]	flax	1	9 (+30%)	48 (+6%)
	carbon	1	8.1 (+17%)	39 (-14%)
[18]	PE	0.25	5.97 (+87%)	
		0.5	4.94 (+54%)	
		1	9.53 (+200%)	
		1.4	10.29 (+220%)	
[25]	glass	0.25	4.05	24
		0.5	4.6	22
		0.75	5	23
		1	5.82	22.74
[26]	basalt	1	13.8 (+30%)	33.7 (+13%)
	carbon	1	29.1 (+175%)	27.4 (-8%)
	glass	1	12.4 (+17%)	20.6 (-30%)
[27]	PP	0.25	7.8 (+2.6%)	35.8 (+60%)
		0.5	7.1 (-7%)	34.3 (+53%)
		0.75	6.1 (-20%)	25.9 (+13%)
		1	7.5 (-1.3%)	18.2 (-18%)
[28]	steel	2.1	5.96 (+422%)	
[29]	PVA	1	5.17 (-5%)	37.66 (-2.5%)
		1.5	4.91 (-8%)	29.95 (-22%)
*UHDC - ultra high ductility concrete				

3 Conclusion

The ability of 3D printing to create low cost and architecturally complex housing could greatly accelerate the widespread use of 3D printing in commercial construction. It is expected that the mechanical properties of printed components are at least comparable to those of parts produced by conventional techniques. Anisotropic behavior, introduced by extrusion-based technique of 3DPC, as well as application of standardized, continuous, two-directional reinforcement presents a major challenge in achieving load-bearing behavior of conventional reinforced concrete. This paper examines the strengths and weaknesses of different reinforcement techniques. Current reinforcing strategies are limited to low-rise buildings and low design forces, because they either don't meet design regulations, are too expensive or limit the full benefits of 3D printing technology, like speed and automatization. Strategy with most potential, in authors' opinion, is prestressed reinforcement and fiber reinforcement. Further research should focus on improving these strategies, possibly with "smart" reinforcement materials to back-up smart technology of 3D printing. One proposal is shape memory alloy, material developed just recently, having unique properties, such as super-elasticity and shape memory effect. Such a materials could enhance durability of concrete structures due to their ability of crack recovery, self-centering and strength enhancement.

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