INFLUENCE OF PRINT PARAMETERS ON FRACTURE RESPONSE OF PLAIN AND FIBER-REINFORCED 3D-PRINTED BEAMS

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Abstract

While much attention has been given to developing concrete mixtures for digital manufacturing (3D printing) and their associated rheological and mechanical properties, selecting appropriate printing parameters is also crucial for extrusion-based layered manufacturing. This paper explores the impact of layer height, a key parameter affecting rheology requirements, print quality, overall printing time, and interlayer bonding, on the flexural strength and fracture properties of 3D printed beams. This study investigates three-layer heights (LH) (5, 10, and 15 mm) corresponding to 25, 50, and 75% of the nozzle diameter (ND) (20 mm). The results show that smaller layer heights are more beneficial for both unreinforced and fiber-reinforced 3D printed mortars, despite the longer printing times and increased number of interfaces. Furthermore, adding a small amount of steel fiber reinforcement mitigates the adverse effects of weak interfaces on bulk properties. On average, flexural strengths are 30-40% higher, and fracture toughness and crack tip opening displacement are almost 30% higher than plain mixtures. The study employs strain energy release rates, digital image correlation, and optical images/micrographs to explain crack propagation in layered 3D printed mortars under unnotched four-point and notched three-point bending.

1. Introduction

Digital manufacturing, particularly 3D printing, is emerging as an effective technology for creating multifunctional concrete elements for various applications, including habitation facilities, complex architectural needs, and structural members for infrastructural applications. Although other approaches such as powder-bed fusion, injection 3D printing, and slip forming are also being evaluated, the layer-by-layer extrusion of cementitious matrices is the most common mode of digital manufacturing of concrete elements and structures. This article focuses on the influence of layer height (LH) on the flexural and fracture response of plain and fiber-reinforced 3D printed beams produced through the layer-by-layer extrusion process while keeping other process parameters like printing speed, nozzle shape, and nozzle diameter (ND) constant. The results are expected to provide a better understanding of the influence of layer dimensions on flexural, fracture, and crack propagation response, to facilitate the design of 3D-printed concrete elements for various applications. The article also discusses the effects of layer height on load-induced cracking, crack propagation, and failure of 3D-printed concrete beams.

2. Results

Optical microscopy revealed that selecting a larger layer height increased void content for both the unreinforced and fiber-reinforced print. The fiber-reinforced mixture used a higher amount of superplasticizer, resulting in a reduction in the void content compared to the respective unreinforced counterpart. However, for the smallest layer height, the void content for fiber-reinforced print was higher than that of the unreinforced counterpart, which can be attributed to the fiber length being significantly larger than the layer height, resulting in scratching of the surface.

As expected, the flexural strength of 3D-printed mixtures was lower than that of similar mold-cast mortars. Smaller layer heights led to higher flexural strength for unreinforced mortars. However, higher layer heights for fiber-reinforced mortars resulted in a slight increase in flexural strength, despite increased porosity. It was observed that for proper alignment of fibers, layer height in the range of fiber length is beneficial. The strain fields in unreinforced and fiber-reinforced specimens under four-point bending were evaluated from displacement fields using Digital Image Correlation (DIC). Strain localization was more prominent at higher layer heights, and enhanced energy dissipation led to lower strains. The crack starts to initiate at peak load in fiber-reinforced specimens, with strains at the crack tip around 6 times higher than in unreinforced samples. In the post-peak response, localized strains near the crack tip are about 4 times the value at the peak. The propagation and directionality of the main crack near the interfacial region were observed, and the crack direction seems to deviate at the interface.

The notched specimen's three-point cyclic bending test was performed to evaluate the fracture parameters. The unloading compliance showed that the increase in layer height made the unreinforced beams more compliant in the post-peak region. The fiber-reinforced specimen showed strain hardening behavior when the crack initiates, while only about 20% capacity decreased till the chosen crack-mouth-opening-displacement (CMOD) range. The strain energy release rate for the unreinforced beam was lower than that for the fiber-reinforced beam. The fracture parameters studied, fracture toughness (K_{IC}), critical crack tip opening displacement ($CTOD_c$), and strain energy release rate plateau ($G_{R\text{-}max}$), were higher for the fiber-reinforced specimen. Figure 1 shows the studied parameters normalized using the corresponding parameter for a mold-cast unreinforced mixture. It illustrates the positive effect of the addition of fiber to the mixture, as well as of selecting the proper layer height.

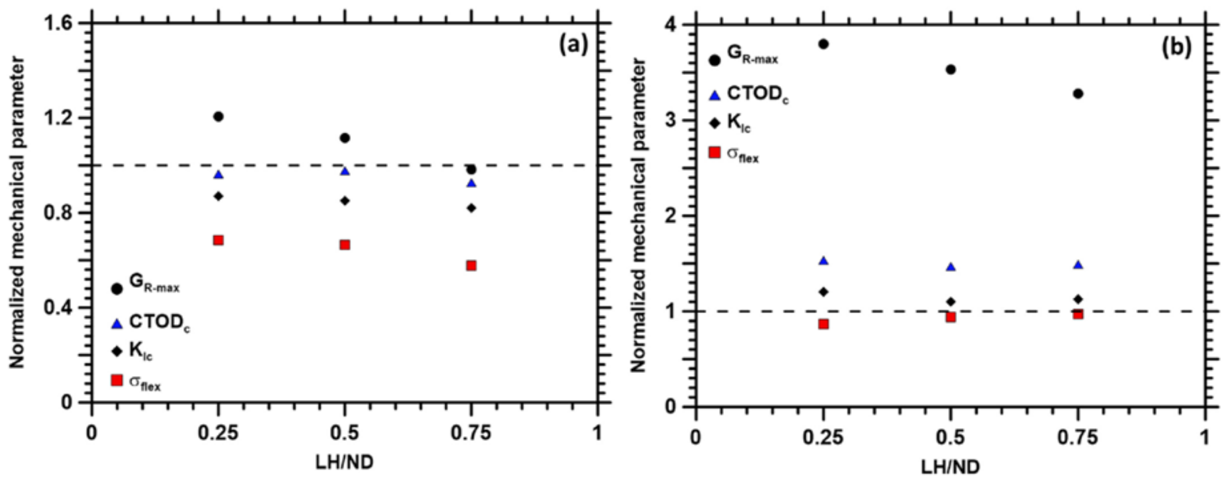

Figure 1: Normalized flexure and fracture properties as a function of layer height: (a) unreinforced, and (b) fiber-reinforced mortars. The normalization is carried out with respect to the properties of the unreinforced mold-cast mortar for both cases.

3. Conclusions

The results presented in this study indicate that using a lower layer height could benefit flexural and fracture properties. Still, managing fresh-state buildability, nozzle pressure, and printing time is essential. Larger layer heights create significant voids, even with overlapping adjacent layers in the printing path, which cannot be sealed during continuing hydration and could cause durability problems. However, adding a small amount of fiber reinforcement can offset the adverse effects of larger layer heights on mechanical properties. For plain mixtures, the minimum layer height can be established based on the particle sizes present in the mix and the desired vertical printing speed. When employing stiff fibers such as steel fibers, it is suggested to use a minimum layer height equal to the fiber length to avoid fiber misalignment in the layers, fiber protrusions from the layers, or layer surface defects caused by fiber drag with the nozzle.

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