Mechanical Properties and Failure Pattern of 3D Printed Hollow Cylinders and Wall Segments Under Uniaxial Loading

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Abstract. Extrusion-based 3D printed structures are heterogeneous with a combination of solid layers and weak bonds. The weak bonds can be considered to be an amalgamation of hydrated products and air voids. The hardened state properties of 3D printed structures depend on several factors such as layer strength, bond strength, geometrical imperfection, anisotropy, and printing parameters. The geometrical imperfections may be due to compression of individual layers or localized buckling during printing. This research aims to study the mechanical properties of 3D printed hollow cylinders and wall segments. The hollow cylinders correspond to hollow printed columns, whereas wall segments are cut from printed walls. The wall segment used in this study had a fixed design. The study is divided into three phases: hollow cylinders were printed with different aspect ratios (L/D), and compressive strength was measured at different ages in the first phase. The second phase included displacement control tests on 150 mm diameter and 300 mm height hollow printed cylinders. The post-peak behaviour was evaluated. The cylinder fails much later than the initiation of the first crack, but the crack propagates diagonally through the bonds and layers at ultimate failure. The effect of curing (water and air curing) on the compressive strength of hollow cylinders was further evaluated. In the last phase, 1 m by 1 m walls were printed, and segments were cut. The compressive strength was evaluated on the cut segments. This study shows that the initiation of crack is majorly influenced by geometrical irregularity and bond strength between the layers for the hollow cylinders. Whereas, for the wall segment, cracks initiated and propagated through the wall leaves and ribs connection.

Keywords: Hardened properties · Hollow cylinder · Aspect ratio · Uniaxial elastic modulus · Wall segment

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1 Introduction

The mechanical testing of 3D printed structures is a critical challenge for researchers considering the heterogeneity and complexity of the elements. A few researchers determined the mechanical behaviour of the printed structure by extracting prisms and performing flexural and compressive strength tests. Nerella et al. [1] extracted prisms of 120 mm × 25 mm × 25 mm from a printed wall, whereas Paul et al. [2] extracted 50 mm cubes and 140 mm × 40 mm × 40 mm prisms from a larger printed structure. Alchar and Al-Tamimi [3] printed 50 mm cubes with 20 mm layer thickness. Most of these printed elements were 2 to 4 layers thick and the study was primarily concerned about the difference in behaviour between cast and printed specimens. The anisotropy in mechanical properties is noted by a number of authors and the defects between layers are reported to be a critical parameter for strength determination. Le et al. [4] concluded that the presence of faults between two printed layers leads to stress concentration, significantly influencing the behaviour. Ding et al. [5] reported the cracks to propagate diagonally or along the layer interfaces for compressive load with different loading directions. All the studies were performed on cut specimens.

The objective of this study is to understand the behaviour of printed hollow cylinders under compressive load, to observe the crack propagation, and to determine the post-peak behaviour of the printed cylinders. The effect of size and curing condition is a primary concern in the paper. Further, the criticality of the joint between ribs and wall for a large-scale wall element with ribs as infill is studied.

2 Experimental Methodology

2.1 Materials and Mix Design

The printable mix studied consists of 53 grade ordinary Portland cement (OPC) (confirming to IS12269-1987), processed class F fly ash (conforming to ASTM C618), quartz sand with maximum aggregate size of 2 mm, polypropylene fibers (12 mm in length and 40 microns in thickness), PCE based superplasticizers (SP), cellulose-based viscosity modifying agent (VMA), and aluminium sulphate based accelerating admixture (Acc.). The mix proportion is shown in Table 1. A pan-type mixer was used to mix the ingredients at 30 rpm. The mix with SP and VMA was pumped using a screw-based pump to the nozzle head where the accelerator was mixed before extrusion.

Table 1. Mix proportion

Material	OPC	Quartz sand	Fly-ash	Water	SP	VMA	Fibers	Acc.
Proportion (to binder content)	0.8	1.5	0.2	0.32	.05% (solid content)	0.22%	0.2%	1.5–2%

[a]Note: SP, VMA, Fibers and Acc. are presented in terms of % of cementitious material

2.2 Test Procedures for Mechanical Properties of Printable Mix

The mechanical properties of the printable mix with and without accelerator were evaluated in terms of cylinder compressive strength and uniaxial elastic modulus. The cylinders of 100 mm diameter and 200 mm height were cast using the extruded mix from the printer. The test was performed using a closed loop servo-hydraulic testing machine with a capacity of 1000 kN load. The movement of the actuator in the machine was captured using an inbuilt LVDT and the piston deformation was also measured. The stiffness of the configuration used was 740 kN/mm and required correction was performed to determine the exact compression of the specimen. Another strain gauge was connected at the center of cylinder (longitudinal side) with gauge length of 100 mm to determine the elastic modulus of the material following the procedure in [6].

2.3 Test Procedures for Mechanical Properties of Printed Structures

The mechanical properties of two types of printed structures were evaluated (Fig. 1) – a. hollow cylinder and b. wall segment. The cylinders were capped with mortar (cement to sand ratio of 1:4) and moist cured for 24 h before testing. The wall element was capped with plaster of paris and air cured for 24 h before testing. The capping was done to make the top and bottom surface parallel.

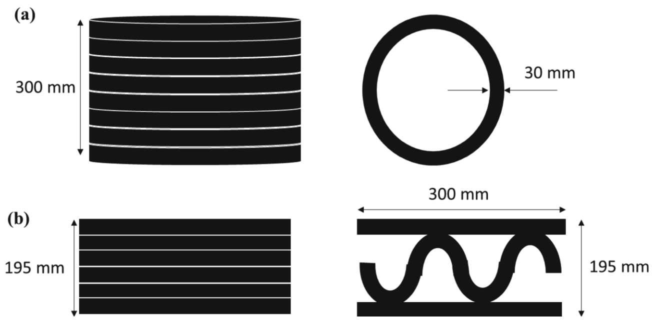

Fig. 1. Experimental setup: a) hollow cylinder and b) wall segment

Effect of Height to Diameter Ratio and Curing on Printed Cylinder

The compressive strength test was performed on the printed cylinders of two different diameters - 150 mm and 200 mm - with a height of 300 mm, as per IS 516-1959 (loading rate at 140 kg/cm^2/min). Further, the post peak behaviour was determined using the same closed loop servo-hydraulic testing machine mentioned in previous section, with a loading rate of 0.005 mm/s.

Failure Analysis of Printed Wall Segments

Two wall segments were obtained from a 1 m by 1 m printed wall. The compressive strength test was performed, on specimens with a length of 300 mm, height of 195 mm, and width of 195 mm. The crack pattern and maximum load are reported.

3 Results and Discussions

Mechanical Properties of Printable Mix

The mechanical properties for the mixes with and without accelerator are highlighted in Table 2. The 28 days compressive strength and uniaxial elastic modulus is determined to be increased with the addition of accelerator. Further, the accelerated mix was used for studies with the printed samples. Hence, the mix used for printing is having a maximum compressive strength of 44.4 MPa and uniaxial elastic modulus of 27.6 MPa.

Table 2. Mechanical properties of the mixes at 28 days

Sample	Accelerator	Curing days	Cylinder compressive strength (MPa)	Elastic modulus (GPa)
Printable mix	✗	28	36.3 ± 0.2	24.9 ± 1.3
	✓	28	44.4 ± 0.5	27.6 ± 1.3

Mechanical Properties of Printed Hollow Cylinders

Cylinders with diameters of 150 mm and 200 mm were printed (height of 300 mm) using the accelerated mix. The stress for the printed cylinder is based on the area of loading surface, i.e., the compressive stress is the ratio of compressive load to initial loading surface contact area. The cylinders are grouped into three sets based on the extent of curing and age of testing. In set 1, the cylinders were moist cured for 7 days and tested at 7^{th} day from printing. It is found from the results in Table 3 that the hollow cylinder with higher diameter has lower strength. Higher deviations could be seen in the compressive strength values. In set 2, the cylinders are moist cured for 7 days and tested at 28^{th} day from printing. A marginal increase of about 20% and 30% is observed for cylinders of 150 mm and 200 mm diameter, respectively, as compared to the 7-day values. In set 3, the cylinders were moist cured for 28 days and tested at 28^{th} day. The compressive strength increased significantly by 45% and 80% against the 7^{th} day strength of Set 1 cylinders. The curing period is therefore a very significant factor for the strength evolution in 3D printed concrete structures. Additionally, the effect of height to diameter is significant as the compressive strength reduced from 23.5 MPa to 19.4 MPa on increase of L/D for the hollow printed cylinders.

To further understand the failure of printed cylinders, a post peak analysis is performed as shown in Fig. 2. It is observed that even after the initiation of cracks, a few layers of the structure resisted a certain amount of load. This implies that a sudden failure may not be observed for a printed column, and a few uncracked layers can provide resistance against the load. Further studies are required to understand the post-peak behaviour of the printed compressive elements.

Table 3. Compressive strength of printed hollow cylinders with different curing ages

Sample	Height to diameter	Diameter (mm)	Curing days	Compressive strength (MPa)	
				7 days	28 days
Printed cylinder with layer width of 30 mm and thickness of 15 mm	2	150	7	16.1 ± 3.4	19.3 ± 0.8
			28	–	23.5 ± 3.3
	1.5	200	7	10.3 ± 4.4	13 ± 4.3
			28	–	19.4 ± 1.6

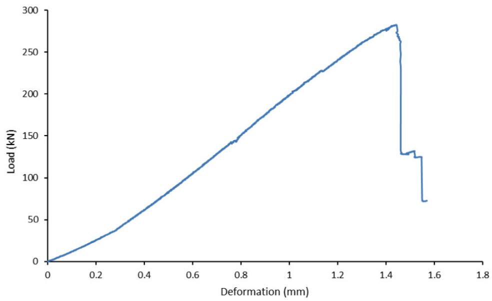

Fig. 2. Post-peak behaviour of the printed compressive elements

The crack propagation in the cylinders is further evaluated by visual method. It is seen that a diagonal crack is propagated as shown in Fig. 3. Also, for a few cylinders multiple staggered cracks are observed to form near the loading end. Localised failure of individual layers and crack initiation due to layer joints may govern the failure.

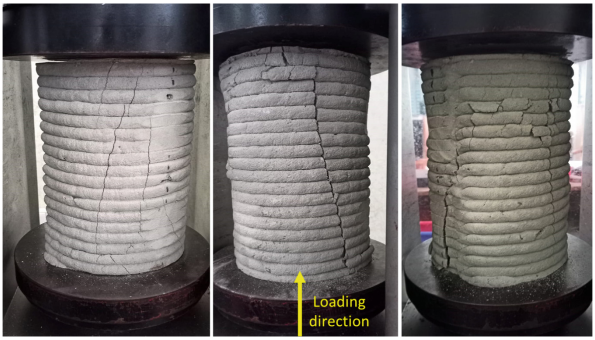

Fig. 3. Crack propagation in printed hollow cylinders

Failure of Printed Wall Elements

Wall segments were cut out from a printed wall as shown in Fig. 4. The failure load is found to be 863 kN (works out to approximately 15 MPa considering the loading area). The crack is observed to propagate through the joint between the wall leaves and the infill ribs. The failure is governed by the geometry of the structure, with joints playing a major role in the overall structural integrity. The role of the joints in governing the strength may be more critical than the strength of the mix. A more thorough study is required to understand the effect of geometry on the overall strength of the printed structures.

Fig. 4. Crack propagation in printed wall element

4 Conclusions

An increase in diameter for a fixed height (reducing height to diameter ratio) leads to a reduction in overall compressive strength of a hollow printed cylinder. Both size and shape govern the strength of the printed elements. The failures at joints and localized layer failure also affect the overall strength. Curing increases the strength significantly and a prolonged curing may be prescribed for 3D printed elements with OPC and VMA. Further, a few uncracked layers in the elements resist the loads even when a part of the structure is cracked. It can be concluded from the studies that creation of a representative volumetric element is critical for understanding the printed element behaviour. The strength of the mix or cubes with two or three layers might not represent the behaviour of the whole printed structure.

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