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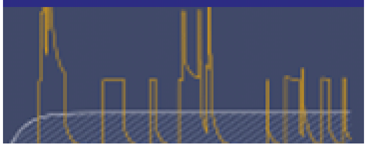

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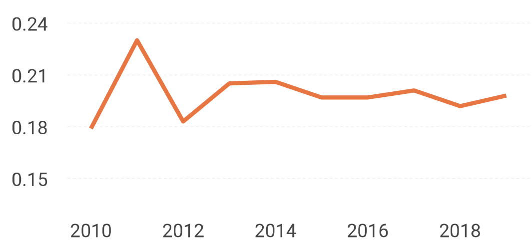

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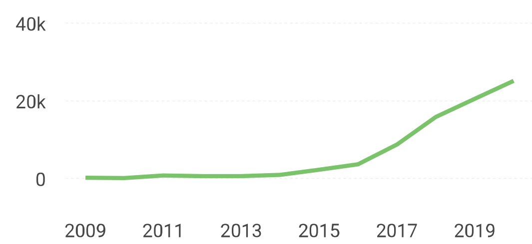

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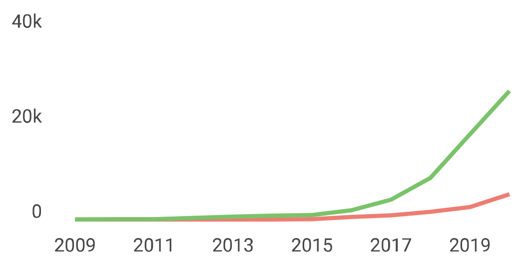

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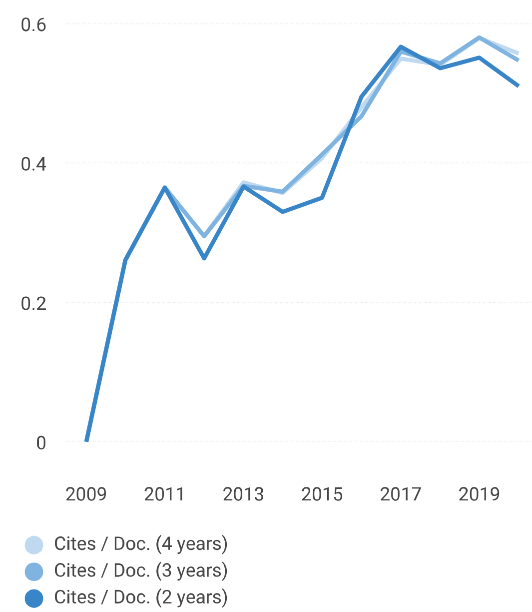

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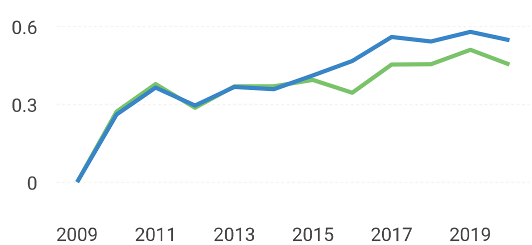

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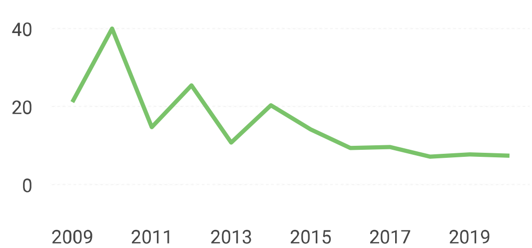

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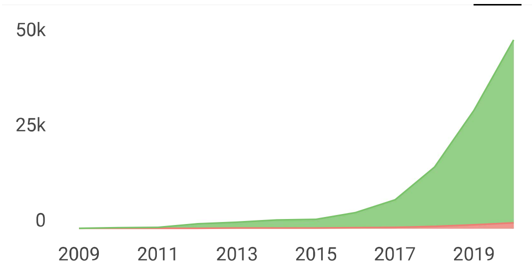

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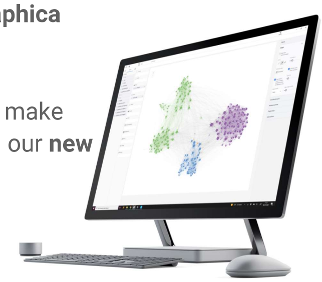

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Analytical modeling of 3D-printed reinforced concrete beams

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Abstract. Three-dimensional (3D) printing for cementitious materials such as concrete has become increasingly popular. Numerous research efforts have been undertaken to fabricate structural elements, such as beams, using 3D-printed concrete. Because the behavior of 3D-printed reinforced concrete (RC) beams is not well understood, research in this area is still ongoing to investigate the behavior and compare it with conventional RC beams. In this paper, the results of an analytical study using finite element software on 3D-printed RC beams are presented. The main challenge was to determine a constitutive material model of the 3D-printed concrete for nonlinear analysis that was quite different from normal concrete. The developed model was validated using the results from several past experimental tests on 3D-printed RC beams. The results showed that the analytical model can accurately predict the maximum flexural strengths of the 3D-printed RC beams. However, the analytical model overestimated the initial stiffness of the beams. Furthermore, several local failures, such as shear failure of nodal points and bond failure between rebars and concrete, could not be well simulated by the analytical model. Thus, future research is needed to correctly define the constitutive material model for 3D-printed RC beams.

1. Introduction

In recent years, new technology to produce concrete has been developed using three-dimensional concrete printing (3DCP) [1]. 3DCP is done by extruding mortar mixture gradually to form layers of concrete mortar and finally producing the expected shape according to the design. Therefore, in 3DCP, there is no need to build formwork as in conventional concrete construction. 3DCP uses an automatically controlled machine to produce any shape or geometric model of structural elements as desired [2].

3DCP for buildings is an environmentally friendly construction method that provides limitless possibilities for the realization of buildings with complex geometry [3]. With 3DCP, the paradigm of building designers is expanded as each building component can be unique without the need to spend extra cost on complex formwork as well as casting process. Other advantages of 3DCP are automation and timing optimization, lower construction cost, and reliability of the results [4, 5].

However, until now, the manufacturing process of 3DCP still encounters many obstacles, e.g., the concrete mixture condition is still inconsistent and requires a special base material [6, 7]. Moreover, there is limited research on the behavior of structural elements made using 3DCP in which the material

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properties are quite different than that of conventional concrete [8-10]. Thus, research in this area is still needed.

This paper focuses on studying the behavior of 3D-printed reinforced concrete (RC) beams. The study was done analytically using a finite element computer software [11] by comparing the available experimental results [12] with the numerical results of simulating said experiments in the software. Of particular interest is the load-deflection relationship of the specimens as well as their maximum strengths.

2. Past research on the structural behavior of 3D-printed RC beams

Al-Chaar et al. [12] have studied the flexural behavior of 3D-printed RC beams by performing bending tests on nine specimens with various combinations and types of meshes and bars. The objective of their study was to obtain flexural capacity of these beams whereby the behavior was different from that of conventional RC beams because the interfacial bonding between concrete mortar layers is limited. The beams were 4.88-m long, with a clear span of 4.57 m and shear span ratio of 6 or greater. The beams were truss beams with total depth of 203 mm and width of 140 mm. The longitudinal view of a typical beam is shown in figure 1.

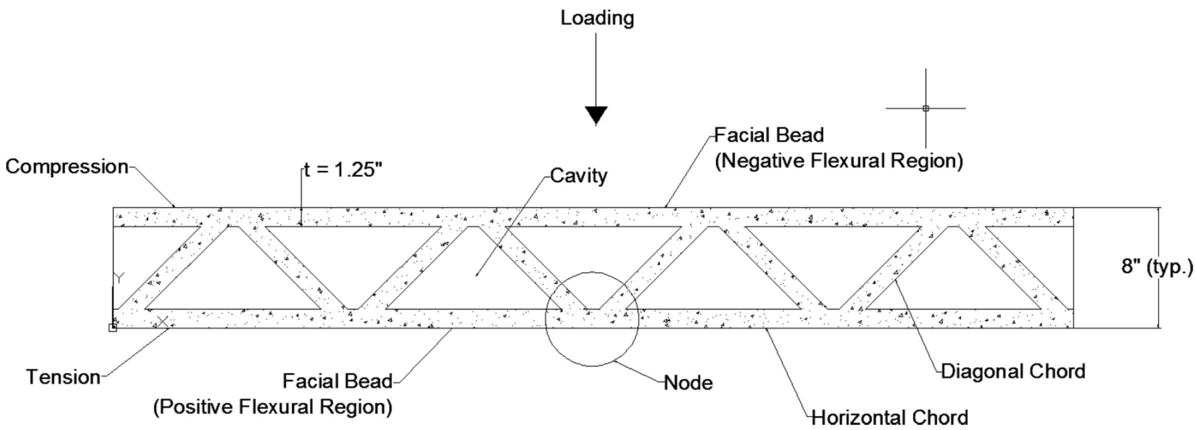

Figure 1. Longitudinal view of 3DCP RC beams tested by Al-Chaar et al. [12].

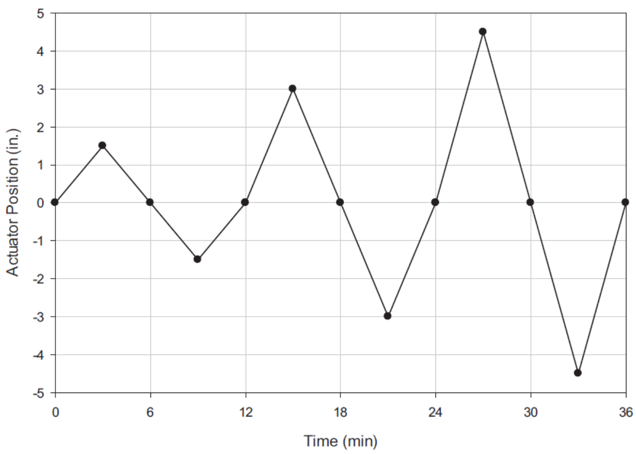

Figure 2. Loading protocol used by Al-Chaar et al. [12] (1 inch = 25.4 mm).

In this paper, only three out of nine specimens tested by Al-Chaar et al. [12] were investigated due to the limitation of the analytical model to simulate the basalt mesh used between the concrete mortar layers. These specimens are 1SR-S-0, 4DR-S-0, and 5DR-B-0. Specimen 1SR-S-0 was a singly-

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reinforced beam with three 10-mm diameter steel bars in the tension side while specimen 4DR-S-0 was a doubly-reinforced beam with three 10-mm diameter steel bars each in the tension and compression sides. Specimen 5DR-B-0 was a doubly-reinforced beam with three 10-mm diameter basalt bars in the tension and compression sides. Because specimen 1SR-S-0 was a singly-reinforced beam, it was cyclically loaded in one direction only, whereas specimens 4DR-S-0 and 5DR-B-0 were subjected to cyclic loading in both positive and negative directions. The loading protocol for the specimens is displayed in figure 2.

3. Analytical modeling of the 3D-printed RC beams

In this paper, the analytical modeling of the 3D-printed RC beams as tested by Al-Chaar et al. [12] was done using SAP2000 computer software [11]. The truss beams were modeled using frame elements for its tension, compression, and diagonal chords. Furthermore, fiber P-M-M hinge that is available in SAP2000 [11] was used to account for the material nonlinearity. The elevation view of the analytical model of the 3D-printed RC beams can be seen in figure 3.

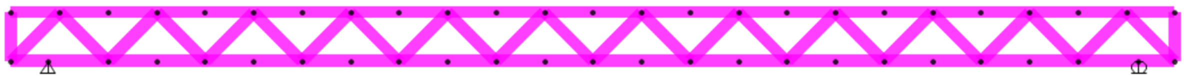
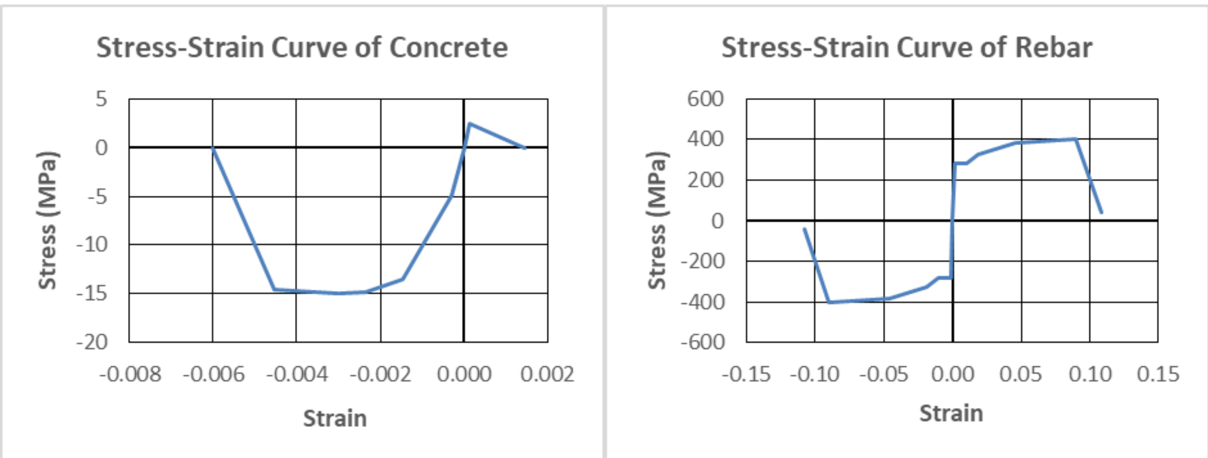


Figure 3. Elevation view of the 3D-printed RC beams as modelled in SAP2000 [11].

The most important parameter to be defined in this analysis is the constitutive material model for the 3D-printed concrete. According to a study by Le et al. [13], the hardened properties of 3D-printed concrete is different than that of conventional concrete due to anisotropy in the layered concrete mortar. The compressive strength of 3DCP was reduced by 5 to 15 percent, depending on the loading direction, for a straight-line printing structure and the reduction can go up to 30 percent for a curvy-shaped printing structure as compared with conventional concrete. In addition, because of the gap between its layers due to the printing process, the tensile bond strength between the layers of 3D-printed concrete is weaker. However, because the truss beams were modeled using frame elements, the reduction of tensile bond strength was not able to be taken into account in the analytical model.

In this analysis, the Mander's model for unconfined concrete [14] that is available in SAP2000 [11] was used as the constitutive material model for concrete as displayed in figure 4a. For rebars, Park's model for reinforcing bar [15] was used as displayed in figure 4b.



(a) (b)

Figure 4. Stress-strain curve of materials used in the analytical model: (a) concrete and (b) rebar.

The analyses were carried out using nonlinear static analysis with several load cases to simulate cyclic loading conditions as defined in the experiment by Al-Chaar et al. [12]. Displacement control was used to monitor the nodal displacement in order to simulate the loading protocol used in the experiment. From the analysis results, reactions in the supports were combined to obtain the total force applied to the 3D-printed RC beams. Subsequently, force-displacement curves of the beams obtained from the analyses were compared with those obtained from the experiment by Al-Chaar et al. [12] in order to see whether the analytical model could well simulate the behavior of 3D-printed RC beams.

4. Analysis results

The analysis results were compared with experimental results from a study by Al-Chaar et al. [12] in terms of the load-displacement curves of the specimens and their maximum strengths. The comparison of maximum strengths between experimental and analytical results can be seen in table 1 while the comparison of load-displacement curves between experimental and analytical results are displayed on Figures 5, 6, and 7 for specimens 1SR-S-0, 4DR-S-0, and 5DR-B-0, respectively.

Table 1. Comparison of maximum strengths between experimental and analytical results.

Specimen ID	Maximum Experimental Strength (kN)	Maximum Analytical Strength (kN)
1SR-S-0	12.881	11.898
4DR-S-0	14.154	12.924
5DR-B-0	7.958	8.416

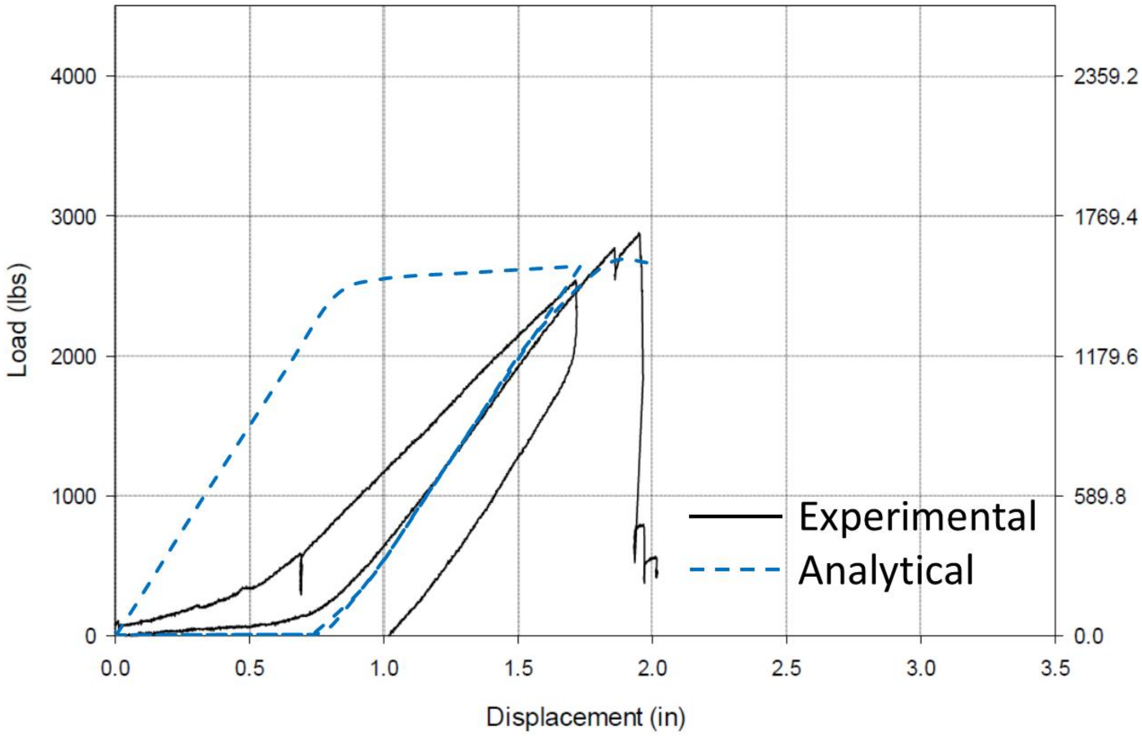


Figure 5. Load-displacement curves of specimen 1SR-S-0.

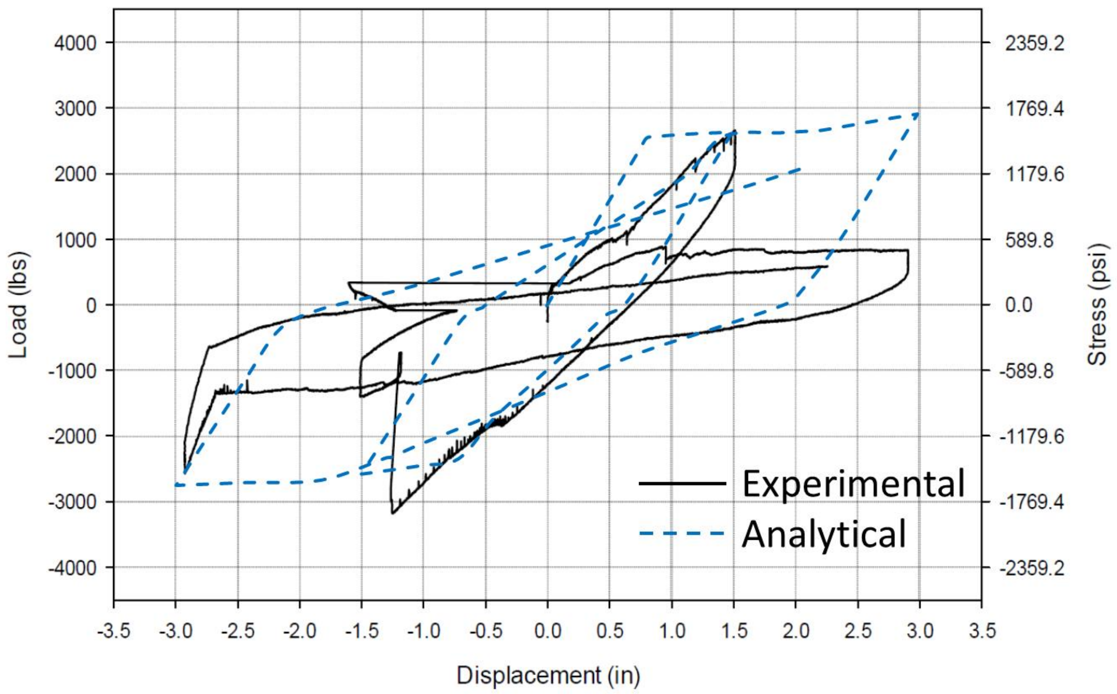


Figure 6. Load-displacement curves of specimen 4DR-S-0.

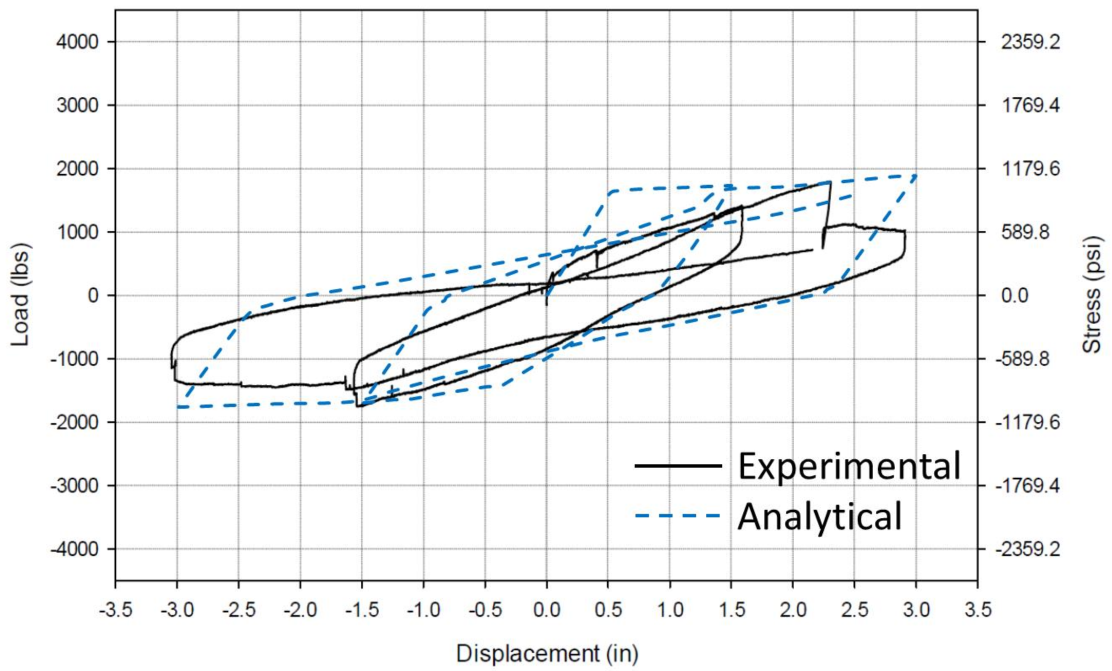


Figure 7. Load-displacement curves of specimen 5DR-B-0.

The observations and comparison for each specimen modeled analytically are presented as follows:

1. Specimen 1SR-S-0: For the load-displacement curve, it can be seen in figure 5 that the analytical model predicts higher initial stiffness compared with the experimental result. The experimental results, however, did not follow common behavior as there was a significant increase in the beam stiffness starting from displacement of 0.7 inches onwards. Usually, for RC beams, the

stiffness will decrease as the displacement increases because of crack propagation. For the second cycle, it can be seen in figure 5 that the analytical model can predict the reloading curve quite accurately, including the maximum strength. Nevertheless, for the degrading branch, the analysis could not proceed further due to convergence problems after the beam strength started to decrease. From table 1, it can be seen that the maximum experimental and analytical strengths for specimen 1SR-S-0 do not differ much, only by 7.63%.

2. Specimen 4DR-S-0: For the load-displacement curve, it can be seen in Figure 6 that the analytical model predicts a higher initial stiffness compared with the experimental result. Moreover, from the hysteretic behavior, it can be seen that the analytical model shows a ductile flexural response, whereas for the experimental result there was a significant reduction in strength and stiffness after the beam reached its maximum strength in negative direction. This was due to shear failure of the nodal points near the supports (complete detachment of the nodes from the horizontal chords). Nevertheless, this failure mode could not be simulated well by the analytical model that uses frame elements. From table 1, it can be seen that the maximum experimental and analytical strengths for specimen 4DR-S-0 only have 8.69% difference.
3. Specimen 5DR-B-0: For the load-displacement curve, similar to the other cases, it can be seen in figure 7 that the analytical model predicts a higher initial stiffness compared with the experimental result. Furthermore, the analytical model shows a ductile flexural response, whereas for the experimental result there was a reduction in strength after the beam reached its maximum strength in positive direction. This was due to bond failure between basalt rebars and concrete. However, this behavior could not be simulated well by the analytical model that assumed a perfect bond between the rebars and concrete. From table 1, unlike other cases that underestimate the experimental strengths, for this specimen, the analytical model predicts slightly higher strength with a difference of 5.76%.

5. Concluding remarks

From this initial study, the following remarks can be made:

- The analytical model consistently predicts a higher initial stiffness compared with the experimental result. This can be due to the stiffness of the 3D-printed RC beams being less than that of the conventional RC beams. The constitutive material model used for concrete in the analysis is the Mander's model for unconfined concrete [14], which is actually for conventional concrete and, thus, it results in higher initial stiffness of the beams. Furthermore, another possibility is that the analytical model assumed perfect geometry and no damage in the specimen before loading, whereas in the experiment there might be some imperfections in geometry as well as slight damage in the specimen before testing, as seen in specimen 1SR-S-0 that did not follow common material behavior (increase in beam stiffness as the displacement increasing).
- The analytical model can accurately predict the maximum flexural strengths of 3D-printed RC beams. The comparisons show that the difference between maximum experimental and analytical strengths are below 10% for all specimens.
- From the hysteretic behavior, it can be concluded that the analytical model that used frame elements with fiber P-M-M hinges could not predict some modes of failure of the 3D-printed RC beams, i.e., shear failure of the nodal points and bond failure between rebars and concrete. It is highly recommended to use a more advanced analytical model (i.e., solid element) in order to simulate the cyclic behavior of 3D-printed RC beams correctly.
- Future research is needed to define correctly the constitutive material model for the 3D-printed concrete which is different than that for conventional concrete, especially in terms of the stress-strain curve and its hysteretic behavior, the interfacial bonding between concrete mortar layers, and the bonding between rebars and concrete.

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