Modeling and analysis of 3D-printed reinforced and prestressed concrete beams

by Jimmy Chandra

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Modeling and analysis of 3D-printed reinforced and prestressed concrete beams

J Chandra[1*], H Wibowo[2], D Wijaya[1], F O Purnomo[1], P Pudjisuryadi[1] and A Antoni[1]

[1] Civil Engineering Department, Petra Christian University, Siwalankerto 121-131, Surabaya, Indonesia
[2] Department of Civil, Construction, and Environmental Engineering, Iowa State University, 813 Bissell Road, Ames, Iowa, United States of America

*Corresponding author's e-mail: chandra.jimmy@petra.ac.id

Abstract. Three-dimensional (3D)-printed concrete is believed to have a significant impact in the construction industry in the future. Some research has been conducted experimentally and analytically to investigate the structural behavior of 3D-printed concrete elements, such as beams. Previous study by the authors attempted to analytically model 3D-printed reinforced concrete (RC) beams failing in flexure that were tested by other researchers. The study was done with the aid of a finite element software. However, there are some limitations of the analytical model to simulate the failure mode of the specimens. In this study, an improvement of the analytical model is proposed in order to simulate the behavior of the 3D-printed RC beams more accurately. Furthermore, the analysis was also expanded for 3D-printed prestressed concrete (PC) beam. From the analysis results, it can be concluded that the improved analytical model is able to predict more accurately the failure mode as well as the hysteretic behavior of the 3D-printed RC beams. Nevertheless, a more sophisticated analytical model is needed to improve the accuracy of the prediction for the 3D-printed PC beam.
Keywords: analytical model, 3D-printed RC beam, 3D-printed PC beam, hysteretic behavior.

1. Introduction

Recently, three-dimensional (3D) printing method in the form of additive manufacturing has been applied in various fields. In the industrial sector, for example, 3D printing technology supports the industry 4.0 concept and it has increased the productivity of the sector due to the possibility to create better products. Moreover, it is more practical and does not rely on manual methods which are known to be slower [1].

Concrete is one of the most popular materials in the construction industry. Beside conventional concrete, 3D printing technology has also been applied in concrete manufacturing [2]. It is believed that in the future, 3D-printed concrete will have a significant impact in the construction industry. This is because the technology allows the creation of various complex geometrical shapes without the use of formworks [3].

Modeling and analysis of 3D-printed concrete members have not been fully explored. So far, there were several studies conducted regarding modeling and analysis of 3D-printed concrete structures [4-6]. In these studies, there were some limitations in modeling the constitutive laws of 3D-printed concrete and the type of elements used to simulate its modes of failure. Hence, some of the analyses did not represent well the real behavior of 3D-printed concrete structures.

This study focuses on improving the analytical model used by the authors in the previous study [6]. In this study, OpenSees computer software [7] developed by the Pacific Earthquake Engineering Research Center (PEER) was used to model some 3D-printed reinforced concrete (RC) and prestressed concrete (PC) beams. The analysis results were then compared with the experimental results in order to verify the accuracy of the model in simulating the behavior of 3D-printed concrete members. The analysis results are presented in terms of force-displacement relationships of the specimens as well as their maximum strengths.

2. Past experimental research on the behavior of 3D-printed RC and PC beams

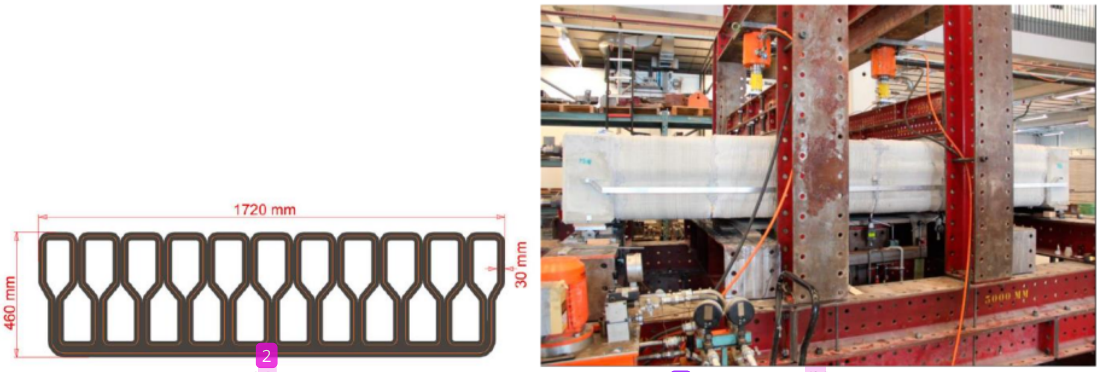
Al-Chaar et al. [8] performed bending tests on nine 3D-printed RC beams to investigate the flexural behavior of these beams since it might differ from the conventional RC beams. The flexural capacity of 3D-printed RC beams might be affected by the interfacial bonding between concrete mortar layers which is limited in 3D-printed concrete. The beams were truss beams with a total length of 4.88 m, 203 mm depth, and 140 mm width. The shear span ratio of the beams was 6.0 or greater. Concrete compressive strength used was 15 MPa and steel rebar yield strength used was 240 MPa. The cross section of the truss beams as well as typical test setup are shown in Figure 1.

(a) (b)

Figure 1. (a) Cross section of typical truss beams and (b) Aerial view of 3D-printed RC beams tested by Al-Chaar et al. [8].

In this paper, three specimens tested by Al-Chaar et al. [8] were selected to be modeled and analyzed. These specimens are 3DR-S-6B, 4DR-S-0, and 5DR-B-0. Specimen 3DR-S-6B was a doubly-reinforced beam with three 10-mm diameter steel bars each in the tension and compression sides, along with 6 mm basalt mesh. Specimen 4DR-S-0 was similar to specimen 3DR-S-6B, except for the basalt mesh. Specimen 5DR-B-0 was similar to specimen 4DR-S-0, but it used basalt bars instead of steel bars for the tension and compression reinforcement. These specimens were subjected to cyclic loading for both positive and negative directions with an increment of 38 mm in each loading cycle.

Another specimen studied in this paper was a 3D-printed PC beam tested by Salet et al. [9]. They used a half-scale 3D-printed model in order to investigate the structural performance. The specimen cross-section dimensions were 1,720 mm in width and 460 mm in height with concrete compressive strength of 21.5 MPa. The specimen had six segments with a length of 500 mm per segment which were combined together using prestressing tendons with diameter of 15.7 mm and tensile strength of 1860 MPa. There was a total of nine tendons that were stressed with an initial load of 120 kN. The specimen was tested using four-point bending test scheme as shown in Figure 2. The testing protocol was a loading-unloading sequence with an initial load of 120 kN and increment of 30 kN in each cycle.



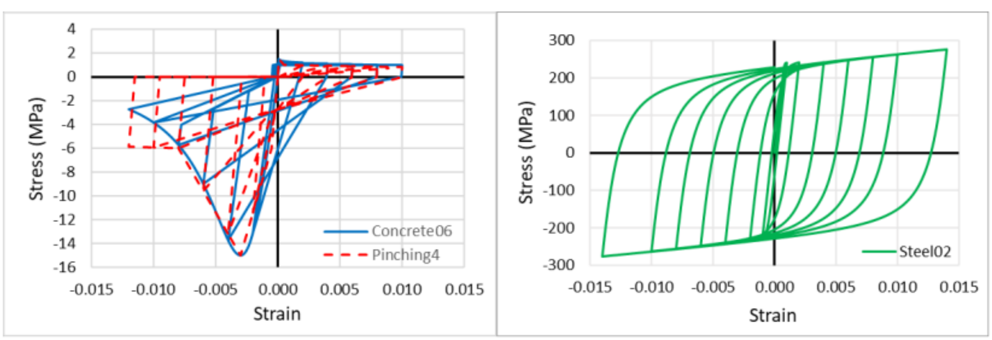
(a) (b)

Figure 2. (a) Cross section of the 3D-printed PC beam and (b) Four-point bending test setup of the specimen tested by Salet et al. [9].

3. Modeling of the 3D-printed RC and PC beams using OpenSees

The type of element chosen to model the 3D-printed RC and PC beams is the Displacement-Based Beam-Column element available in OpenSees [7]. The element was chosen since it could consider the spread of nonlinearity along the element. Furthermore, Truss element was also used in modeling basalt mesh of specimen 3DR-S-6B tested by Al-Chaar et al. [8]. For the element cross-section, Fiber section available in OpenSees [7] was used to model the section of the 3D-printed RC and PC beams.

The basic material used for 3D-printed concrete was Concrete06 that is available in OpenSees [7]. Concrete06 material is originally developed using compressive stress-strain curve proposed by Popovics [10] and tension stress-strain curve developed by Belarbi and Hsu [11]. Later on, after preliminary analysis, the authors decided to slightly modify the unloading-reloading paths of the 3D-printed concrete material using Pinching4 material for the specimens tested by Al-Chaar et al. [8]. This was done to improve the accuracy of the model in predicting the hysteretic behavior of 3D-printed RC beams. A sample of the stress-strain curve of concrete used in this paper is displayed in Figure 3a. To model the rebar, Steel02 material that is available in OpenSees [7] was used. It is based on formulation by Menegotto and Pinto [12] that is generally used to model the constitutive law of steel under cyclic loading. A typical of the stress-strain curve of Steel02 material is displayed in Figure 3b.



(a) (b)

Figure 3. Typical stress-strain curve of materials used in the analysis: (a) concrete and (b) rebar.

The analyses were carried out using nonlinear static analysis with several load cases to simulate the loading conditions as defined in the experiment by Al-Chaar et al. [8] and Salet et al. [9]. For the PC beam tested by Salet et al. [9], horizontal forces and end moments were preloaded to the beam, in order to take into account the prestressing effect from the tendons. During the analysis, the total applied force and the displacement of the beams were recorded in order to plot the force-displacement curves of the specimens. Subsequently, the curves were compared with those obtained from the experiment by Al-Chaar et al. [8] and Salet et al. [9], in order to evaluate the accuracy of the analytical model in simulating the behavior of 3D-printed RC and PC beams.

4. Analysis results

The analysis results were compared to the experimental results from Al-Chaar et al. [8] and Salet et al. [9] in terms of the force-displacement curves and the maximum strengths of the specimens. The comparison of maximum strengths between experimental and analytical results are presented in Table 1 for all specimens. Furthermore, the comparison of force-displacement curves between experimental and analytical results are presented in Figures 4-7.

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

Specimen ID	Maximum Experimental Strength (kN)	Maximum Analytical Strength (kN)
	Al-Chaar et al. [8]	
3DR-S-6B	18.207	15.039
4DR-S-0	14.154	13.388
5DR-B-0	7.958	8.159
	Salet et al. [9]	
Prototype	350	308

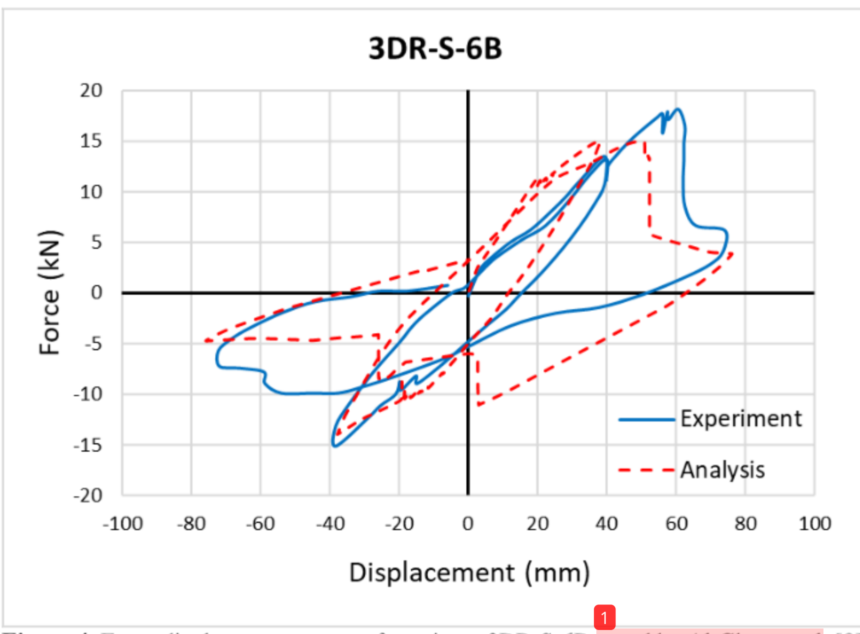


Figure 4. Force-displacement curves of specimen 3DR-S-6B tested by Al-Chaar et al. [8].

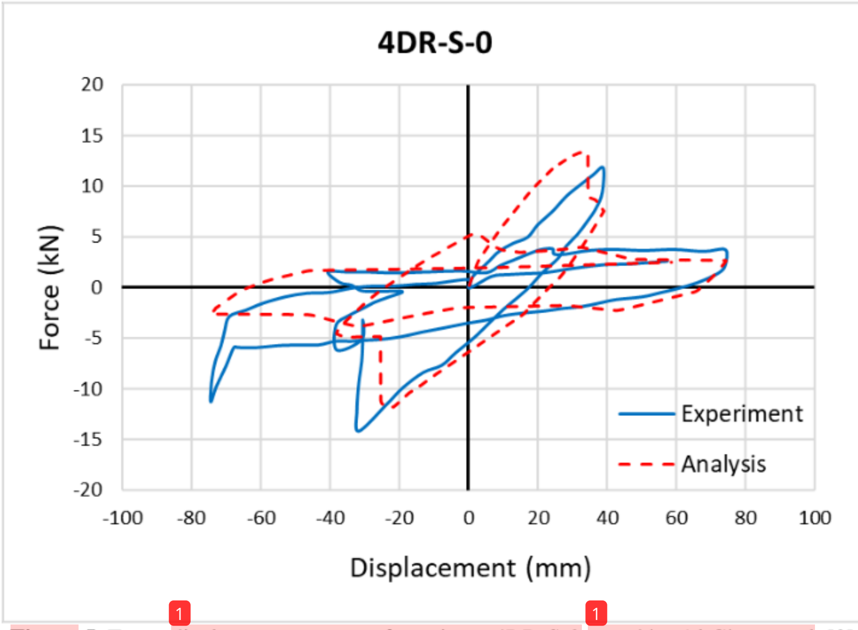


Figure 5. Force-displacement curves of specimen 4DR-S-0 tested by Al-Chaar et al. [8].

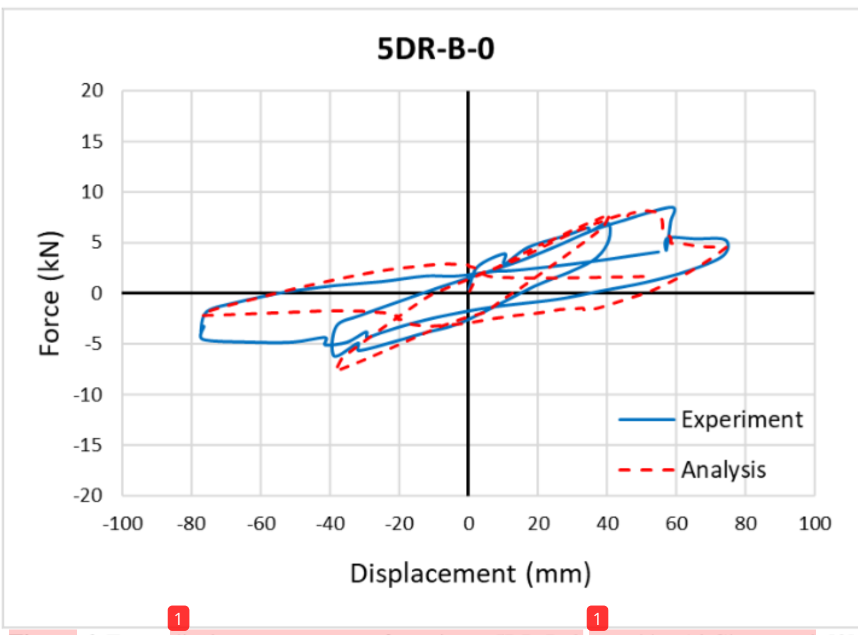


Figure 6. Force-displacement curves of specimen 5DR-B-0 tested by Al-Chaar et al. [8].

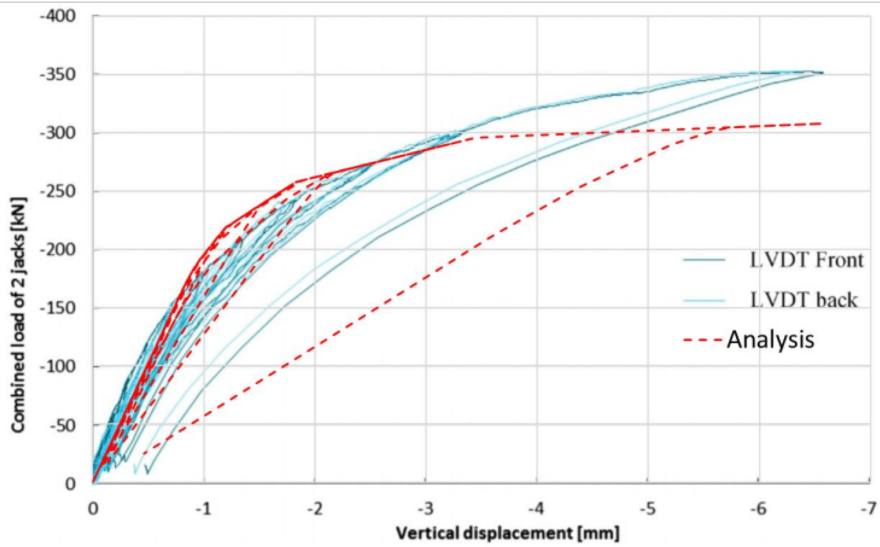


Figure 7. Force-displacement curves of PC beam specimen tested by Salet et al. [9].

The discussions for each specimen are presented herein:

1. Specimen 3DR-S-6B: It can be seen in Figure 4 that the analytical model predicts a higher initial stiffness compared with the experimental result. Furthermore, the analytical model gives almost the same maximum strengths in positive and negative directions whereas the experimental result shows higher maximum strength in positive direction. Thus, the analytical model underestimates the maximum strength of the specimen for about 17.4%. Moreover, it can be seen in Figure 4 that the analytical model can predict the hysteretic behavior of the specimen as well as the mode of failure reasonably well. The failure observed in the experiment was nodal failure which caused the load carrying capacity to drop significantly.
2. Specimen 4DR-S-0: For the force-displacement curve, similar to specimen 3DR-S-6B, it can be seen in Figure 5 that the analytical model predicts a higher initial stiffness compared to the experimental data. The maximum strengths in both directions are similar for the analytical model whereas the experimental result shows higher maximum strength in the negative direction. From Figure 5, it can be seen that the analytical model can predict well the hysteretic behavior of the specimen as well as the failure mode, i.e. nodal failure, including the significant degradation in strength and stiffness. From Table 1, it can be seen that the maximum strength predicted by the analytical model is very close to the experimental strength. It only differs by 5.4%.
3. Specimen 5DR-B-0: It can be seen in Figure 6 that the analytical model can predict the initial stiffness, the hysteretic behavior, and the failure mode of the specimen quite accurately. From Table 1, unlike the two previous specimens, the analytical model slightly overestimates the maximum strength, with a difference of about 2.5%.
4. PC beam specimen: It can be seen in Figure 7 that the analytical model can predict the early-stage behavior of the PC beam specimen quite well. However, starting from the load of 150 kN onwards, the prediction begins to deviate from the experimental result. Ultimately, the analytical model underestimates the peak strength of the specimen by about 12.0%. The difference in the peak strength possibly came from the contribution of prestressing tendons to bending capacity of the 3D-printed PC beam. In the analytical model, the prestressing tendons were not modeled explicitly. Instead, the prestressing forces were applied as horizontal forces and end moments

to the beam. Hence, the bending capacity of the analytical model depends only on the prestressing forces as well as the tensile strength of concrete. This is not the case for the actual specimen that had prestressing tendons in the bottom side of the beam that might contribute to its bending capacity. As mentioned by Salet et al. [9], visually noticeable flexural crack was observed at the load of 300 kN. This means from this point forward, the tensile stresses were carried mostly by the prestressing tendons. Therefore, in the testing done by Salet et al. [9], the PC beam specimen could resist a higher load up to 350 kN before the testing was stopped.

5. Conclusions

From the results of this study, some conclusions can be drawn:

- The constitutive law for conventional concrete can adequately be used to model 3D-printed RC and PC beams failing in flexure. In this study, Concrete06 material that was developed based on compressive stress-strain curve proposed by Popovics [10] and tension stress-strain curve developed by Belarbi and Hsu [11] were used to model the 3D-printed concrete. However, some modifications on the unloading-reloading paths were introduced to the material model using Pinching4 material in order to improve the accuracy of the analytical model in predicting the hysteretic behavior of the specimens tested by Al-Chaar et al. [8]. For specimen tested by Salet et al. [9], the original Concrete06 material that is available in OpenSees [7] library was used since the loading of the specimen was done only in one direction.
- Based on the analysis results, the mode of failure of the specimens can be predicted quite accurately by the analytical model. This shows an improvement from the previous study by the authors [6]. In the previous study, the analytical model did not correctly predict the mode of failure. Nevertheless, in the current analytical model, the maximum strengths predicted were not close enough to the experimental strengths for some specimens.
- The analytical model predicts a higher initial stiffness for some specimens tested by Al-Chaar et al. [8]. This might be due to the initial defects of the specimens as described by Al-Chaar et al. [8] while the analytical model assumes perfect geometry of the specimens and no initial damage.
- For the specimen tested by Salet et al. [9], the prediction of the analytical model can be improved if the prestressing tendons are modeled explicitly. However, since the cross-section of the beam is quite unique, a more sophisticated analytical model is needed to model the beam with prestressing tendons. In this case, future research is needed to properly model the 3D-printed PC beam in order to predict the response more accurately.

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