**Influence of Interfilament Bond Characteristics on the Load Deflection Behaviour of 3D Printed Beam-A Numerical Study**

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**Abstract.** Additive manufacturing, commonly known as 3D printing, offers unique advantages in the fabrication of structural components due to its ability to create complex geometries and customize material properties. However, the limited understanding of how various printing-based parameters affect the load carrying capacity of 3D printed structural elements poses one of the technical obstacles to the widespread adoption of this technology. Consequently, this study investigates the load deflection behaviour of 3D printed beams under four-point loading condition employing a finite element framework. In this work, two types of additively manufactured beam specimens are numerically modelled in Abaqus®. In one type of specimen, the extruded layers are assumed to be made of uniform cross-section replicating the rectangular type of nozzle. Whereas, in the second case, an average interfilament pores at different layers across the thickness of the beam are taken into account. Constitutive behaviour of each extruded filament of concrete is represented through a damage and plasticity incorporated material model. Whereas, a cohesive zone based bond characteristics is employed to replicate the interaction of two successive extruded concrete layers. Along with different interfilament pore condition, influence of interfilament bond strength and loading direction on the mechanical behaviour of 3D printed concrete beam is also investigated. The simulated results highlight various crucial insights on the relative variation in the load capacity of 3D printed beam for different interfilament pore, bond strength and loading direction. Consequently, the present works highlights opportunities for optimizing designs for specific load-bearing applications.

**Keywords:** Numerical model; Tensile damage; Load deflection; Interfilament pore; Loading direction

# Introduction

Modern construction techniques, such as additive manufacturing, have given rise to new opportunities in the sector due to its significant advantages over conventional concrete procedures [1]. The primary advantages of additive manufacturing are its ability to execute complex architectural designs, cost saving, minimize the need for manual labour, and reproduce custom geometries without formwork issues that makes additive manufacturing more and more desirable in modern construction practices [2]. Additive manufacturing has the potential to completely transform the industry, but before it is widely used, it must overcome a number of difficulties and barriers. The absence of thorough research linking from printing properties to mechanical performance is a significant barrier impeding additive manufacturing's wider use in the construction industry [3–5].

In past few years, significant number of research articles have been published in the field of 3D concrete printing which mostly used experimental approaches to investigate the early-stage printing properties such as extrudability, buildability [6–8]. Along with printing characteristics, mechanical characteristics [9–11] like compressive and flexural strength as well as long time deformation like shrinkage [12] has also received a lot of attention. Understanding the physics behind the process or to evaluate how small-scale samples behave under mechanical loads require experimental research. However, in order to analyse the mechanical behaviour of a large-scale specimen or looking at the wider scale applicability of additive manufacturing in construction sector, it is imperative to develop a physics-based mathematical models through which the structural response of a 3D printed concrete samples can be predicted under mechanical loading. Making use of numerical models could greatly reduce the time and expense involved in conducting experiments. Nevertheless, to create a numerical model that faithfully captures reality, it's essential to represent the governing physics of the problem in a more realistic manner.

In an extrusion-based layering technique, each concrete layer is printed sequentially and the characteristics of each individual layer as well as the interaction between these layers affect the overall mechanical performance of the additively produced composite system. Weaker interface zones between successive printed layers are one of the primary characteristics that makes the difference between a 3D printed specimen and a traditional mold-cast concrete sample. Hence, investigating the characteristics of interfilament bond in the case of 3D printed concrete specimen has attracted the attention of most of the researchers. However, till date, there hasn't been much focus in the literature on identifying interfilament bond characteristics and studying the influence of the same on the mechanical performance of 3D printed concrete specimen.

With regards to studying the mechanical properties of additively constructed concrete samples, most researchers have concentrated on characterising the interlayer bond properties between two consecutive printed layers through various experiments [13,14]. This interlayer bond properties have a strong dependency on the interfilamnet printing time interval [15]. For instance, the experimental results of [16] reported that the interfilamnet bond strength decreases with increase in the interlayer time gap and for a time gap of higher than fifteen minutes, the interface region failed. Analogous outcomes from experimental works have also been reported in [17,18]. Further, based on the experimental research, researchers [19] [20] also reported that the moisture present in the interfilament region also plays a pivotal role in the bond characteristics.

Apart from the bond characteristics, various other mechanical properties of the 3D printed concrete samples, such as compressive [21], tensile [22], and flexural strength [23], have also been the major focus of research over the years. In this context, the existing work of Kruger and van Zijl [24] highlights that, depending on the interfacial characteristics, the compressive strength of additively constructed concrete sample can drop by as much as 45% when compared to traditional mold cast samples. Further, through experiments, researchers investigated the influence of various direction of loading on the mechanical properties of concrete i.e., the anisotropic characteristics of printed samples [21–23]. Zareiyan et al. [24] reported that when printed specimens are loaded perpendicular to the printing direction, their compressive strength is higher in comparison to the loading in other direction. Nonetheless, a contrasting nature in the published data on compressive strength of printed specimen has been found. One set of researchers [29, 30] asserted greater compressive strength in a certain printing direction, whilst the opposite pattern in the reported data has been found in [16] [19]. Similar opposite trends in the flexural strength of printed concrete samples have also been reported in [9,19,25]. These disparities in the outcomes could be caused by a number of coupled nonlinear characteristics, ranges from the strength properties of each layer of concrete to the bond properties of various interfaces, all of which would interact to affect the system's composite behaviour. Moreover, through experiments, researchers also studied the mechanical performance of additively manufactured concrete samples made of geopolymer or other waste-based binders [26,27].

Contrary to extensive experimental investigations, very few articles have been found that utilized a mathematical framework to investigate the mechanical behavior of 3D printed concrete specimens. Feng et al. [35] adopted a finite element (FE) based tool with an orthotropic assumption for the material to numerically explore how the printing and loading direction affects the load carrying capacity of 3D printed arch structures. The orthotropic assumption of the material implicitly incorporates the bond characteristics. Similarly, Shakor et al. [36] studied the mechanical behavior of printed concrete specimen numerically by integrating the experimentally obtained material properties of printed concrete samples that were tested by applying the loading from various direction of printing. However, the primary shortcomings of these models are their applicability in general due to non-considering explicitly the interfilamnet bond properties. Later, Bos et al. [37] investigated the flexural performance of fiber-reinforced 3D printed concrete sample using a concrete damage-plasticity (CDP)-based constitutive relation for the concrete. However, the study does not account for different bond properties in the numerical model. Following this, a discrete-element method (DEM) was utilized in [28] to study the behavior of printed concrete specimens subjected to different loading scenario. However, in DEM, the primary challenge lies in accurately defining the contact properties and it entails significant computational costs. Further, Heever et al. [29] applied classical laminate theory (CLT) to study the mechanical behaviour of printed concrete samples subjected to tensile loading condition. On the other hand, Xiao et al. [30] utilized the CDP model for the concrete layer and traction-separation type constitutive relation to define the interfilamnet bond to investigate the influence of interfacial bond on the variability of the mechanical properties of the concrete element in different printing directions. However, the numerical works [30] lacks with respect to considering a fix value of interfilament bond properties in the numerical model i.e., the influence of various bond parameters (presence in the constitutive relation of interfilamnet bond) on the mechanical behavior of the additively constructed concrete specimen have not been investigated. Further, the effect of interlayer pores/gaps (that could arise due to the use of circular nozzle or could be due to the variability in material type or printing process) on the behavior of the printed samples under mechanical load has not been studied.

Hence, a critical review of literature pertaining to 3D printed concrete highlights a dearth of mathematical model that consider the governing physical mechanism of extruded layer as well as the interfilamnet bond under mechanical loading and investigate the influence of various printing parameters, ranging from bond characteristics to interfilmanent pores, on the directional dependency of compressive strength of printed concrete samples. Consequently, there is a need to develop a continuum based mathematical modelling framework considering the variable compressive and tensile strength properties of concrete along with the tensile and shear bond characteristics to study the behaviour of printed concrete samples under 4-point load. Therefore, this article employs a finite-element (FE) framework to numerically capture the flexural behavior of 3D printed concrete sample. In the developed model, each of the extruded filament of concrete is represented through a constitutive relation that includes both damage and plasticity aspects of concrete. While the interfilamnet bond is represented through a cohesive zone-type constitutive relation that replicates the zero-thickness interactive zone between two consecutive filaments. The required input properties of concrete (e.g., tensile and compressive strength) are obtained through the specific tests [31]. Subsequently, comprehensive sensitivity analyses are performed for different printing related parameters. Within the various types of printing parameters, influence of bond strength, interfilment pores, and the loading direction on the flexural behavior of 3D printed concrete specimen are investigated. The simulated results under the wide variety of above-mentioned parameters are compared with that of the traditional mold cast samples. Such exhaustive parametric investigation can aid the researcher in calculating the flexural strength of 3D printed concrete for different printing conditions and loading directions which ultimately would help in the design of the 3D printed concrete based on load deflection characteristics.

# Methodology

## Constitutive behaviour of materials

Any object produced through the technology of 3D printing has highly anisotropic mechanical performance. The anisotropic nature of the 3D printed specimen is created from the interaction of the printed layers through the adhesive bond. With respect to the material behaviour of 3D printed concrete, till date, there is no well-established material model has been developed by the researchers [39], particularly examining the current viewpoint in which different agro-industrial waste generally replace Ordinary Portland Cement (OPC). The employed material in this work consists of OPC along with two waste materials, bagasse ash (BA) and fly ash (FA) in a mass proportion of 60:20:20. The chosen mix proportion of the three primary constituents are decided among the trial designs of various mixes that satisfy the printing performance and compressive strength. Since, the main goal of this work is to investigate how different aspects of concrete printing, such as bond strength, stiffness of the bond, post-peak or plastic bond displacement, interfilment pores, and the number of extruded layers affects the uniaxial compressive behavior of 3D printed concrete specimen, thus, a comprehensive list of trial mix design is not provided here.

In this work, the mechanical behaviour of the extruded concrete filament is represented through the plasticity and damage-based model present in Abaqus®, known as concrete damage plasticity (CDP) model [30,32]. In the CDP model, the failure of concrete is considered to be occured either through crushing due to compression or due to cracking in the case of tensile loading. Within each type of failure mode, initiation of damage or cracks and its propagation is described through separate criterion, which are described in detail later in this section. Numerous studies, e.g., [32], have confirmed the effectiveness of the CDP model among the variety of plasticity and damage-based models available in Abaqus® for capturing the softening behavior of concrete under diverse loading scenarios. By utilizing the stress–strain behaviour under uniaxial compressive and tensile loading, the model computes the needed inelastic or plastic deformation and cracking strains that are required for numerical analysis. As a result, the model automatically accounts for any rapid decrease in the stress values when peak stress is reached in a uniaxial stress-strain relationship, a characteristic frequently seen in brittle materials like concrete. Consequently, to describe the mechanical behavior of either plain concrete or concrete reinforced with steel, the Concrete Damage-Plasticity (CDP) model has been widely used in literature [33,34], along with the current work.   
In the CDP model, a scalar damage variable is used to represent the continuum-based damage in concrete, and a non-associated Drucker–Prager type yield function with predetermined cutoffs under the tensile loading characterizes concrete's plastic behavior. Additionally, the Mohr–Coulomb model formulation defines the flow behavior in the plasticity. On the other hand, the cohesive zone technique is employed to describe the adhesive contact between two subsequent extruded layers of concrete.

The behavior of a system subjected to quasi-static mechanical loading can be characterized by the balance of linear momentum, expressed as follows [35]

(1) (1)

Where, *is* the stress tensor**,**  represents the operator “divergence” that acts on ,  stands for density and represents the body force. Appropriate boundary conditions must be given in order to solve the governing equation mentioned above. A mechanical system's boundary conditions can be defined as follows: traction type boundary conditions represented as  on surface and displacement based conditions as  on surface . In the CDP model, the description of plasticity and damage through the constitutive relation is represented as

(2)

Here, and presents the Cauchy stress and effective stress tensors, is the scalar damage component which is isotropic and depends on the , i.e., , where represents the equivalent plastic strain tensor. In the CDP model, is decomposed into equivalent tensile and compressive plastic strain  that separately controls the tensile and compressive damages ) evolution. The failure surface in the CDP model is represented as [36,37]

(3)

Where, , .

Here, is the maximum principal stress. Whereas, , , are represented as:

; ; (4)

In Eq.(4), and represent the biaxial and uniaxial compressive yield stress, respectively, stands for the ratio of second stress invariant on the tensile meridian to that of the compressive meridian at initial yield point, and represent the effective compressive and tensile cohesion stress.

The coupled plasticity-damage based-model is based on the non-associated flow rule, which is described as:

(5)

Where  denotes the dilatation angle measured in the *p-q* plane, , is the eccentricity parameter used in flow potential. Compressive damage variable ) is related to plastic strain through the following relation

(6)

Here, represents the inelastic strain under compressive loading, is the compressive yield stress,  stands for the undamaged elastic modulus. On the other hand, to alleviate the mesh dependency, the tensile damage variable ) is evaluated as

(7)

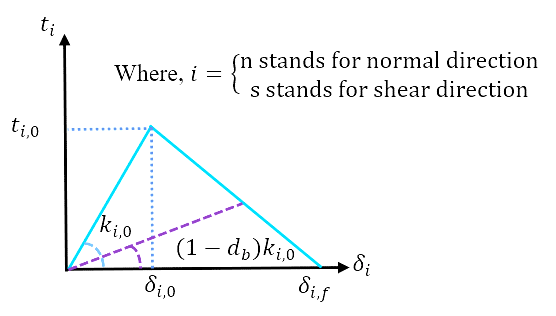
Here, denote the plastic and cracking displacement under tensile loading, represents the tensile stress. The input parameters of the CDP model [38], as used in the present study, is given in Table 1.

Table 1: Input parameters of the CDP model [38]

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Dilation angle | Eccentricity | fby / fcy | K | Viscosity parameter |
| 31 | 0.1 | 1.16 | 0.67 | 0.01 |

**2.2 Modelling of bond/interaction between successive layers**

A zero-thickness cohesive element whose constitutive behaviour in both normal and shear direction is governed through a traction-separation law with softening, as shown in Fig 1.



**Fig 1.** Constitutive relation (traction-separation) of cohesive elements in normal (tn-δn) and shear direction (ts -δs)

In the cohesive zone model, the damage (*db*) of the cohesive element is assumed to initiate when the following quadratic stress based criterion is satisfied

(8)

Where **< >** is the Macaulay bracket. Depending on the damage (*db*) in cohesive element, the slope of the traction-separation based constitutive relation in the unloading and reloading condition can be expressed as and [39]. The evolution of damage (*db*) in cohesive element is considered to be dependent on the effective relative displacement as follows

(9)

Where, , represents the maximum relative slip or displacement that is reached throughout the loading history, and are the relative values of effective displacement which correspond to and ; and and (see Fig.1).

**2.3 Modelling details in Abaqus**

***2.3.1 Loading and boundary conditions***

A schematic representation of the boundary conditions and loading used in the simulation is shown in Fig. 2. The loading conditions are four point with simply supported ends. At the left support, there are constraints on the x, y, and z axes of displacement. Conversely, the right support only keeps the y axis at zero displacement. The loading approach used in the simulation is gradual displacement-controlled, and the corresponding reactions are computed. The two load/displacement applied points in the beam are connected to a "reference point (RP)" in order to assess the reaction using the "Equation" interaction features in Abaqus. The reaction at the reference point is then computed and reported to determine the load for a given applied displacement.

A diagram of a rectangular object with a rectangular object in the middle

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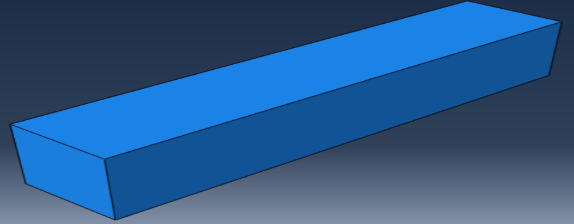
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(a) (b)

Fig 2. (a) Schematic representation of boundary and loading condition in case of 4-point loading as used in the simulation, (b) cross section of the beam

***2.3.2 Geometry built up and defining interactions between layers***

In this study, two categories of beam specimen are analysed: conventional (Fig.3a) or mold cast and printed specimen (Fig.3b-3c). Within the category of printed specimen, two cases are considered. The printed beam is made of straight extruded layers without any cross sectional curvatures (Fig. 3b) and with pore of radius 1 mm (Fig.3c). Further, the analysis has been made for different bond strength and interfilamnet pores condition and the resultant load-deformation responses are compared for the load applied in two different directions. Based on the geometric information of the layers, an 3D printed concrete specimens are constructed in Abaqus®. Here, the “solid extrusion" feature available in Abaqus is used to build the geometry. Along with that, the geometrical coordinates are utilised to represent the cross-sectional curvatures. Whereas, the interaction between two layers are described through a cohesive zone interaction feature available in Abaqus®. Four nodded tetrahedral elements are used to mesh the specimen.

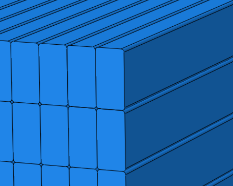
A blue rectangular object with black stripes

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(a)

(b)



(c)

**Fig. 3.** Three different types of simulated beam specimens: (a) mold cast, (b) printed with no pore, (c) printed with pore of radius 1 mm along with enlarged view

# Results and Discussions

## Simulation of mold cast specimen

Fig. 4 presents the load deflection behavior of mold cast specimen, from which the peak load capacity of the beam is found to be approximately 9273 N. Beyond the peak load value, the post peak behaviour of concrete typically belongs to material with brittle to quasi-brittle in nature.

**Fig. 4.** Load deflection behavior of mold cast beam

* 1. **Simulation of printed specimen**

Fig.5 presents the load deflection behavior of printed specimen loaded in y direction for two pores conditions: one with no pore (Fig.5a) and another with an average interfilamnet pore of radius 1 mm (Fig.5b). Similarly, Fig.6(a-b) shows the load deflection characteristics of the same specimen when loaded in X-direction. In the case of both of above condition, two extreme values of tensile bond strength are considered, 0.25 MPa and 1.78 MPa. Here, the highest value of bond strength is taken as the split tensile of monolithic concrete layer. Whereas, the lowest value is inspired by the possible reported value of bond strength by previous researchers such as in [31] that could occur if the printed time gap between layers is higher. It is observed that interlayer bond strength has a stronger effect on the resultant load capacity of the beam when the load is applied in Y direction than X direction. In the case of Y direction loading, without any inter filament pore, the possible load capacity can range between 7959 N to 5847 N for the two extreme values of tensile bond strength. However, with interfilamnet pore of 1 mm radius in the case of Y direction loading, the same load capacity ranges between 7359 N to 3806 N. This implies for the two pores conditions (no pore and 1 mm pore), the load value can drop upto 26.5% and 48% with the drop in tensile bond strength from 1.78 MPa to 0.25 MPa. Lowering the interlayer bond strength introduces additional weak regions in the printed beam that resulted in the drop in load capacity of the printed beam when bond strength decreases. Further, introduction of interfilamnet pore of 1 mm radius resulted in the drop in load capacity by 7.5% and 35% for the interfilament bond strength values of 1.78 MPa and 0.25 MPa. Similar to interlayer bond strength values, introduction of pores or gaps between extruded layers effectively weaken the structure which causes the peak load value to drop with the introduction of inter filament pores. Fig.7 shows the damage pattern of the printed specimen under four point loading, in which damage or crack occur at the centroid of the specimen.

(a)

(b)

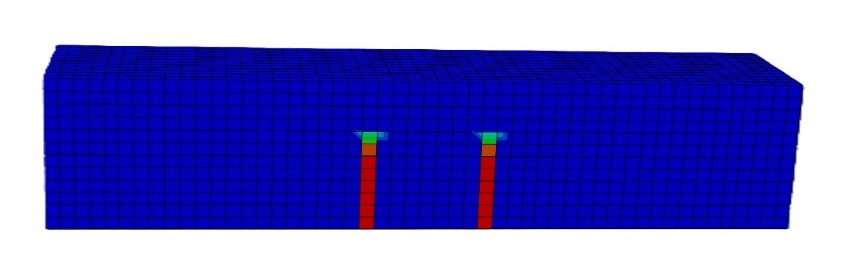
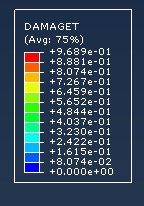
**Fig. 5.** Load-deflection behavior of printed sample with each extruded layer of size 20mm x 10mm for load applied in Y direction in the case of (a) without pore, (b) with average pore of 1 mm

On the other hand, in the case of X direction loading, the relative difference in peak load for the two bond strength values is insignificant in the case of no pore and 1 mm pore conditions. However, the introduction of pore has an effect on the resulted peak load value in the case of X-direction loading condition also. Although the same effect is minimal with approximately 4.5% reduction in the peak load value with the introduction of 1 mm pore in comparison to the load value in the case of no pore condition. Such variable effect of the different loading direction on the peak load value of 3D printed beam implies the resultant anisotropic characteristics that could arise due to the effect of printing and loading direction. Consequently, a designer can choose the optimum printing direction of the beam based on the required performance and other constraints. Further, the comparison of the peak load of the printed specimen (loaded in X and Y direction) with respect to the mold cast sample shows a relative drop in the load value upto 60%. Incorporation of different degree of weakness in the system either through lowering the bond strength or through pore results in such drop in the load capacity of the printed beam with respect to the mold cast sample.

(a)

(b)

**Fig.6.** Load-deflection behavior of printed sample with each extruded layer of size 20mm x 10mm for load applied in X direction in the case of (a) without pore, (b) with average pore of 1 mm



**Fig. 7.** Typical tensile damage pattern of printed beam under 4-point load along with the tensile damage value (dt)

# Conclusions

In this study, load deflection behaviour of 3D printed beams under four-point loading condition is simulated employing a finite element framework. In the model, two different types of interfilmant pore is considered, one with no pore and another with pore size of radius 1mm. Along with different interfilament pore condition, influence of interfilament bond strength and loading direction on the load deflection behaviour of 3D printed concrete beam is also investigated. Based on the simulated results, the following conclusions can be drawn:

* Direction of loading with respect to the printing direction has a strong effect on the load deflection behaviour of 3D printed beam under four-point loading.
* Interfilament pore of radius 1 mm could result in upto 35% reduction in load capacity of 3D printed beam considering different direction of loading.
* Interlayer bond strength has stronger effect on the load capacity when loaded perpendicular to thickness direction of extruded layer (Y-direction, see Fig.3b) than X-direction.

The present work can further be extended to study the influence of varying interfilmant pores across the beam thickness that occurs in a real printed specimen. In addition, the effect of other loading types, e.g., compressive load on the mechanical behaviour of printed specimen can be investigated.

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