Finite Element Analysis of 3D Printed Steel-fiber RC Beam for Mechanical Performance

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Abstract. In this study, by referring to the existing test data and numerical simulation parameters of Bos, using the compression constitutive relationship of concrete proposed by Thorenfeldt and the tensile constitutive model proposed by Petersson, the numerical simulation of the flexural toughness of steel fiber notched beam by pouring and 3D printing is carried out by using the finite element software ABAQUS, and the load deflection curve is obtained, which is compared with the test curve of BOS to verify The rationality of the research model. Based on the verified model parameters, ABAQUS is used to simulate the four point bending test of steel fiber reinforced 3D printing concrete and plain concrete, focusing on the influence of steel fiber content and notch depth on the load deflection curve.

1. Introduction
3D printing technology is based on electronic data, through the continuous superposition of extruded materials, the 3D printing model is transformed into a real one [1]. 3D printing is one of the core technologies in the development of advanced manufacturing industry, which has broad prospects in various fields. At present, many research institutions are trying to apply 3D printing technology to the construction industry, in order to promote the modernization of the construction industry and accelerate the transformation and upgrading of the construction industry. Among them, the application of 3D printing concrete technology in the construction field is mainly limited to the production of reinforced structure, because based on the current printing technology, it is not possible to print the reinforced structure and concrete materials at the same time [2], but with the traditional cement-based materials, its strength, rheology and setting time are difficult to meet the requirements of 3D printing buildings.

With the continuous exploration of researchers, it is found that adding a certain amount of steel fiber material into cement-based materials can restrain the deformation of concrete components, effectively reduce the brittleness when under compression, improve the tensile strength and elastic modulus of printed concrete, improve the failure mode of materials under compression, and greatly improve the seismic and safety performance of buildings [3-4]. At the same time, adding steel fiber into concrete can ensure that the reinforced structure and concrete materials are printed at the same time [5]. Therefore, in the field of 3D printing concrete in the future, the research of steel fiber reinforced cement-based materials has broad development prospects.

In this study, adding short straight steel fiber to cement-based materials can significantly improve the mechanical properties of concrete beams by ensuring the printing of reinforced structure and concrete at the same time. At the same time, by using the finite element analysis software to simulate the three-point bending test of f.p.bos [6], on the basis of demonstrating the rationality of the model, the four point bending test is simulated, and the mechanical properties of steel fiber reinforced 3D printing concrete beam are explored.
2. Literature Review

3D printing technology, which adopts the concept of additive manufacturing, has been widely promoted with low processing cost, high production efficiency and high precision processing technology. In the field of construction, 3D printing can achieve Moldless, rapid and fine molding, so it has been playing a key role in the construction field. From the beginning, it was used to design and make the concept model of architecture, and now it can realize the integrated construction of building structure. The rapid development of its technology level also promotes the progress of the whole construction industry. Many scholars have done a lot of research on the selection of 3D printing concrete materials, the working performance and mechanical properties of printing components.

2.1. Development of 3D printing technology

The idea of 3D printing first appeared at the end of the 19th century. In 1981, householder, R. F. [7] and others first proposed the concept of selective laser sintering, that is, the method of layered manufacturing and layer by layer accumulation was used to make solid. In 1980, Hideo Kodama [8] proposed a design scheme of rapid prototyping system, which is similar to the later three-dimensional lithography 3D printing technology. In 1986, Charles hull [9] first proposed the 3D printing process of stereolithography and invented the first 3D printing machine in the world Printer, using 3D modeling software and solid scanning methods to create 3D digital model, and then through special software to cut the 3D model layer by layer, into slice file, guided by the data file to print layer by layer, establish the solid structure, realize the transformation from two-dimensional to three-dimensional. In the same year, Carl Deckard [10] invented the laser selective sintering technology, and invented a 3D printer using the laser selective sintering technology to print in 1987, and put forward the practical patent for the first time in 1989 [11].

In 1989, S. Scott Crump and Lisa Crump invented the melt deposition model, that is to use thermoplastic plastics to deposit materials on the construction platform in the 3D printing process. This technology is also the main method of 3D printing [12].

In 1997, Joseph Pegna [13], an American scholar, proposed a construction method for free-form components with layer by layer accumulation and selective solidification of cement materials, and applied 3D printing technology to the construction field for the first time. At present, the additive construction technology applied in the construction field mainly includes: contour technology proposed by Behrokh Khoshnevis [14], type D process invented by Enrico Dini, Monolite company, UK, concrete printing proposed by Richard Buswell of Loughborough University, and digital construction technology proposed by Professor Gershenfeld of Massachusetts Institute of technology.

2.2. Development of steel fiber reinforced concrete technology

Steel fiber reinforced concrete (SFRC) is a kind of concrete with cement as binder, which is reinforced by a certain amount of randomly distributed steel fibers. The random distribution of short steel fibers has significant anti cracking, strengthening and toughening effects on concrete. In 1910, H. F. Porter put forward the concept of "steel fiber reinforced concrete", and carried out the research on uniformly mixing steel fiber into concrete as reinforcement material. The results show that the strength and stability of concrete can be improved by adding steel fiber into ordinary reinforced concrete. In 1963, J. P. Romualdi and G. B. Batson published a series of research reports on the strengthening mechanism of steel fiber reinforced concrete. After the theory of average spacing of steel fibers was put forward, the development, test and application of steel fiber reinforced concrete developed rapidly. Ni Kun et al. studied the flexural behavior of concrete beams from three aspects: the amount of steel fiber, the ratio of length to diameter and the ratio of water to binder. Zhang Jingcai proposed the double-K criterion for steel fiber reinforced concrete.

2.3. Development of fiber reinforced 3D printing concrete test

Since the 1980s, a large number of researches have been carried out on the theory and engineering application of fiber reinforced concrete. The application of fiber reinforced concrete materials in engineering is expanding, and the types of fiber added are increasingly rich, such as steel fiber,
polypropylene fiber, glass fiber, basalt fiber, carbon fiber, polyvinyl alcohol fiber, etc. In 2006, Markovic verified that the short straight fiber of 6 mm can pass through the nozzle smoothly during the printing process, which will not cause blockage and will not significantly affect the workability of concrete. In 2015, Ma Yihe added chopped glass fiber and hydroxypropyl methylcellulose into concrete to increase the bonding capacity between concrete, making it suitable for rapid prototyping 3D printing buildings. In 2017, Hambach and Volkmers researched 3D printing composite materials of Portland cement paste and reinforced fiber (3-6mm basalt, glass and carbon fiber) for the first time, and invented composite materials with high bending strength and compressive strength. In the same year, Biranchi Panda et al. Explored the influence of glass fiber with different content and length on the tensile properties and fiber orientation of 3D printing concrete. In 2018, F. P. Bos et al. Carried out three-point bending test and numerical simulation of steel fiber reinforced 3D printing concrete beam, compared the mechanical properties between plain concrete and fiber reinforced concrete, and verified the accuracy of numerical simulation.

Although 3D printing has developed rapidly in the field of construction in recent years, the research on 3D printing concrete mainly focuses on the mix proportion of cement-based materials and the basic mechanical properties and working performance of concrete. There are few researches on Printing reinforced structures and concrete materials at the same time, and there are few numerical simulation and experimental studies on fiber reinforced 3D printing concrete, and steel fiber. The application in 3D printing process lacks sufficient data support.

3. Three point bending model validation

3.1. establishment of finite element model

In this paper, the concrete damage plasticity (CDP) model proposed by Lubliner [15] et al. Is used to describe the concrete with fiber and without fiber, and it is assumed that the fiber is uniformly distributed when the fiber exists. Therefore, in this simulation, the steel fiber is dispersed into the concrete and becomes a whole with the concrete. The steel fiber concrete is considered as a kind of continuous homogenization, and the steel fiber concrete is reflected in the material constitutive relationship to realize the establishment of the model.

3.2. constitutive relation of materials

The constitutive relationship of steel fiber reinforced concrete can be divided into compression constitutive relation and tensile constitutive relation. However, a large number of studies show that the reinforcement effect of steel fiber on the compressive performance of concrete is not obvious, and the finite element model is controlled by tensile failure, so the influence of steel fiber is not considered in the compression constitutive relationship.

3.2.1. Compression constitutive relation

In this paper, the constitutive relation of concrete under compression proposed by Thorenfeldt et al:

\[
\sigma_c(\varepsilon_c) = f_{cm} \frac{\varepsilon_c}{\varepsilon_{c1}} \left( \frac{n}{n-(1-\frac{\varepsilon_c}{\varepsilon_{c1}})k} \right)
\]  

(1)

Where \( n = 0.80 + \frac{f_{ck}}{17} \), \( k = \begin{cases} 
1, & 0 < \varepsilon_c < \varepsilon_{c1} \\
0.67 + \frac{f_{ck}}{62}, & \varepsilon_c \geq \varepsilon_{c1} \end{cases} \), \( f_{cm} \) is the peak stress, \( \varepsilon_{c1} \) is the strain corresponding to the corresponding peak stress, and \( f_{ck} \) is the standard value of axial compressive strength.

The constitutive relation proposed by Thorenfeldt et al. Consists of two stages: before and after concrete cracking. However, the CDP model in ABAQUS has a linear elastic stage before concrete cracking, which is not consistent with Thorenfeldt model. Therefore, the compressive constitutive relationship of concrete in this project can be divided into three stages, as shown in Figure 1: (I) linear
elastic stage; (II) hardening stage before peak stress (corresponding to Thorenfeldt model before cracking); (III) softening stage after reaching peak stress (corresponding to Thorenfeldt model cracking).

Fig. 1 Comparison between thorenfeldt model and CDP model for concrete under compression[3]

3.2.2. Tensile constitutive relation
For the behavior of concrete under tension, many researchers have proposed different constitutive relations, but these constitutive relations basically need two parameters, namely fracture energy GF and strain softening curve. The fracture energy is defined as

$$G_F = \int \sigma dw$$  \hspace{1cm} (2)

Where $\sigma$ is the normal tensile stress and $w$ is the normal crack width. In order to avoid the discretization of the results, Rots et al. pointed out that the fracture energy must be released within a certain crack width, that is, GF is constant and independent of the mesh size. Therefore, in the CDP model established in this project, the crack development width is set as a fixed value,

$$w = w_c \epsilon_f$$  \hspace{1cm} (3)

where $w_c$ is the corresponding crack opening displacement when the stress is completely released, and $\epsilon_f$ is the corresponding strain when the stress is completely released.

For the strain softening curve, the constitutive relation of plain concrete adopts the uniaxial tensile stress-strain curve proposed by hordijk, D.A., as shown in Fig. 2.

Fig. 2 stress strain curve of hordijk concrete under uniaxial tension
However, the fracture energy of SFRC is much larger than that of plain concrete, and there is no generally accepted formula for SFRC after cracking. Therefore, the behavior of SFRC after cracking is expressed by interpolating stress-strain values in CDP model. \( w_c \) is equal to the grid size and \( l_c \) is the average cell area.

The residual stress \( f_{R,j} \) is determined by the formula (4) (5),

\[
\begin{align*}
 f_{e,L}^{f} &= \frac{3F_{L}L}{2bh_{p}^{2}} \\
 f_{R,j} &= \frac{3F_{j}l}{2bh_{p}^{2}}
\end{align*}
\]  

(4)  
(5)

Among them, \( F_L \) is the tensile force corresponding to the proportional limit, \( j = 1,2,3,4 \) corresponding to the crack opening width of 0.5,1.5,2.5 and 3.5mm respectively, \( F_{jw} \) is the tensile force on the corresponding crack opening width, and the values of \( h_{sp} \) and \( l \) are shown in Table 2.

![Test model](image)

**Fig. 3 Test model**

| Table 1 model size parameters |
|--------------------------------|
| model | \( b=h \) (mm) | \( h_{sp} \) (mm) | \( l_{sp} \) (mm) |
|-------|----------------|----------------|---------------|
| 1     | 40             | 33             | 130           |
| 2     | 40             | 33             | 130           |

3.3. mesh generation and boundary conditions

Giaccio et al. Proposed that the thickness of the specimen has no significant effect on the bending performance, so ABAQUS is used to establish a two-dimensional model to simulate. In this simulation analysis, the concrete beam is meshed by bilinear plane stress element \( (CPS4R) \), and the smallest mesh unit is 10 mm. The model is divided into 521 elements.
The left end of the concrete beam is restrained vertically and horizontally, and the right end is restrained vertically. The load is applied above the crack opening.

4. **Four point bending test simulation**

According to the comparison between the simulation results of ABAQUS and the test results of f.p.bos [6], it can be seen that the three-point bending numerical simulation results of different gap opening width have the same change trend with the load displacement curve measured by the test. The numerical simulation results of the damage initiation point and damage evolution point are in good agreement with the experimental data, which verifies the feasibility of the numerical modeling process and the reliability of the simulation results. Therefore, the modeling method is used in the following numerical simulation.

5. **Conclusion**

The mechanical properties of 3D printed steel fiber reinforced concrete beam and plain concrete beam model were analyzed by finite element simulation

- For 3D printed steel fiber reinforced concrete beam model, fiber incorporation can significantly improve the flexural strength. Although the fiber orientation is very strong in the longitudinal direction, it has no significant effect on the performance of the test direction;

- Based on thorenfeldt's constitutive model compression law and customized constitutive law, the stress and strain values determined by CMOD test and grid geometry are reasonably fitted to the experimental results. However, for large separations, an accurate model needs to be tested based on uniaxial tensile constitutive relationship because the stress values cannot be determined clearly from CMOD tests.

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