Calculation Method for Normal Section Bearing Capacity and Crack width of Unreinforced SFRC Segment

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Abstract. In order to facilitate engineering applications, a reliable calculation method for the normal section bearing capacity and crack width of unreinforced SFRC segment is needed. Based on the results of the three-point bending test, a material constitutive model formula is established through elastic residual flexural tensile strength, and then the steel fiber stress increment after cracking of unreinforced SFRC is obtained. By steel fiber stress increment, an equilibrium equation is established to obtain the normal section bearing capacity of the segment. Assuming that the stress increment propagates along the length direction of the steel fiber and is linearly distributed in the conduction direction, the strain increment and conduction length of the steel fiber at the cracked section can be calculated, and the width of the crack can be ultimately calculated.

Keywords: unreinforced SFRC segment; normal section bearing capacity; elastic residual flexural tensile strength, steel fiber stress increment.

1 Introduction

With the increasingly mature application technology of prefabricated segments, the requirements for the comprehensive quality of the segments are also increasing. Ordinary reinforced concrete segments are gradually exposing a series of problems, including high steel consumption, low production efficiency, and local damage. The unreinforced SFRC segments have the advantages of low steel consumption, simple production process, sufficient bearing capacity, and good crack resistance[1-4]. Given the importance of calculating bearing capacity and crack width in segment design, a reliable method for calculating the normal section bearing capacity and crack width of unreinforced SFRC segments is needed.

The current specifications "Technical Specification for Fiber Reinforced Concrete Structures" (CECS 38:2004) and "Design Standard for Steel Fiber Reinforced Concrete Structures" (JGJT465-2019) both use the influence coefficient method for the design of steel fiber reinforced concrete structures. This method treats steel fiber reinforced concrete as concrete modified with steel fibers, seeks the influence coefficient of steel fibers on the mechanical properties of concrete, and uses this influence coefficient to modify the calculation formula of concrete. However, there are many micro factors that

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affect the performance of steel fiber reinforced concrete, including the types, tensile strength, length to diameter ratio, end hook form, maximum elongation, anchoring capacity, dosage, dispersibility, and so on of steel fibers. Given the multitude of influencing factors, if various variables need to be fully considered, there are tens of thousands of samples to be studied and tested. Therefore, achieving sufficient sample data and scientific decision-making is extremely difficult[5-7].

Using the mechanical index method instead of the influence coefficient method, based on the macroscopic mechanical performance tests of materials, the study focuses on the influence of damage on the macroscopic mechanical properties of materials. The obtained material mechanical performance indicators and constitutive models are used for the design and analysis of unreinforced and less reinforced steel fiber reinforced concrete pipe segments. This technical route is more conducive to the analysis of practical engineering.

2 Calculation of the Normal Section Bearing Capacity of Unreinforced SFRC Segment

The premise for calculating the normal section bearing capacity and crack width of unreinforced SFRC segments based on the mechanical index method is the quantitative measurement of the material properties of steel fiber reinforced concrete. That is, it is necessary to first study the mechanical properties of unreinforced SFRC materials with different dosages through three-point bending tests[8-9].

The three-point bending test of steel fiber reinforced concrete involves pouring SFRC with different dosages into 150mm×150mm×550m mspecimens. The steel fiber content in specimens is 25kg/m^3, 30kg/m^3, 35kg/m^3, 40kg/m^3, 45kg/m^3, and 50kg/m^3 for each cubic meter of SFRC. Cut the joint on the side of the specimen, with a depth of 25mm±1mm, a length of 150mm, and a width of 20-30mm. Stick a fixed steel plate at the cutting position and connect it to an extensometer. Place the test piece on a support with a span of 500mm±2mm, and continuously and uniformly apply external loads to the test piece. The test device is shown in Figure 1.

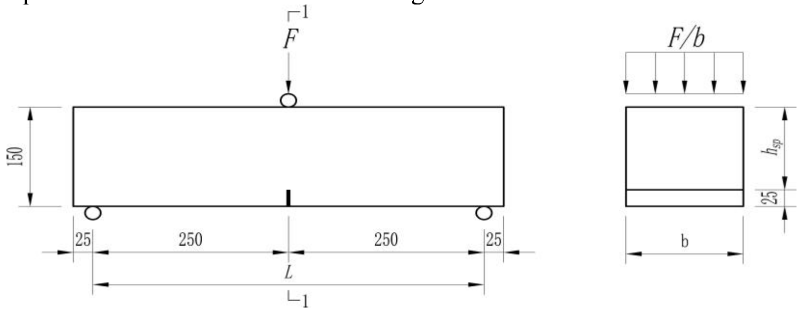
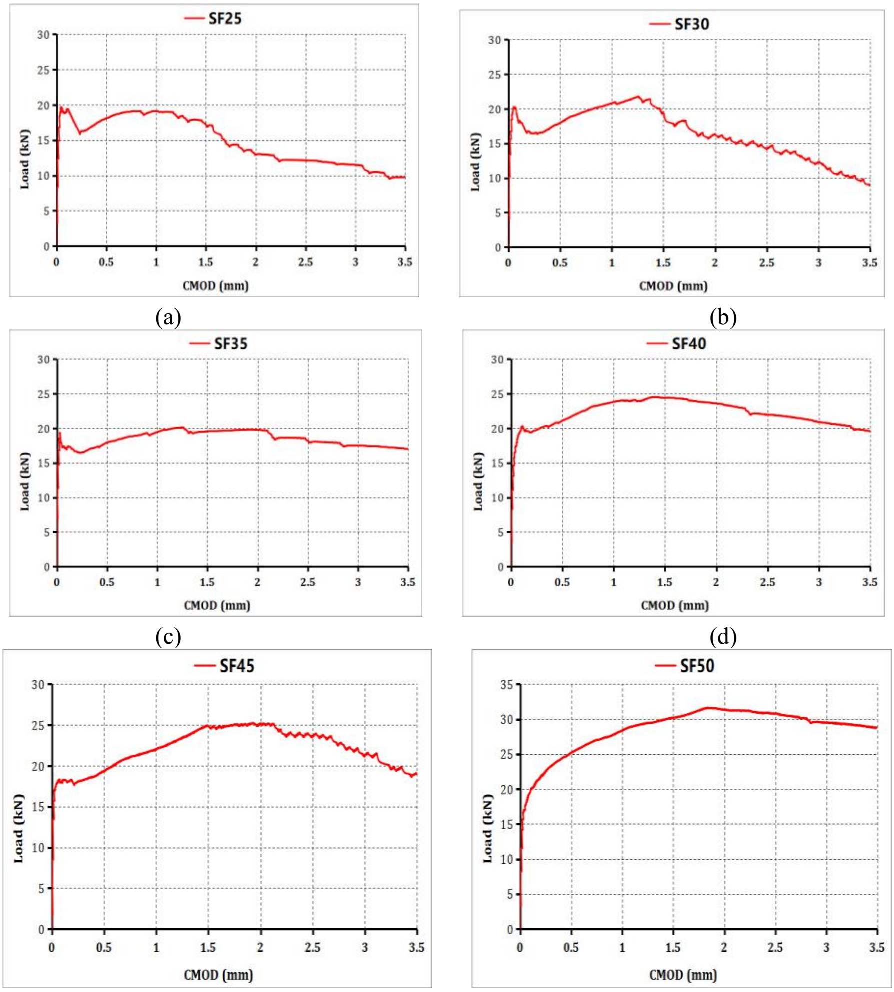


Fig. 1. 3-model of point bending test

The Load-CMOD curve of unreinforced SFRC with different dosages was obtained through experiments, as shown in Figure 2.



(a) (b)

(c) (d)

(e) (f)

Fig. 2. Load-CMOD Curve of C50 SFRC obtained by 3-model of point bending test

The steel fiber content of fig.a to fig.f test piece is 25kg/m^3 to 50kg/m^3

Based on the test curve, obtain the elastic residual flexural tensile strength fR under different CMOD.

$$f_R = \frac{3FL}{2bh_{sp}^2} \tag{1}$$

In the formula: F is the load loaded during the test; L is the spacing between test supports, which is 500mm; b is the width of the specimen, which is 150mm; h_{sp} is the height from the top of the cutting seam to the top surface of the specimen, which is 125mm.

Establish the relationship between the elastic residual flexural tensile strength ratio and the steel content, as shown in formula 2.

$$f_{R3}/f_{R1}=0.2798x^{0.3521} \tag{2}$$

In the formula: f_{R1} is the elastic residual flexural tensile strength when COMD is 0.5mm; f_{R3} is the elastic residual flexural tensile strength when COMD is 2.5mm; x is the amount of steel fiber added.

Using the elastic residual flexural tensile strength ratio as a criterion for determining the performance category of SFRC materials. When $0.9\leq f_{R3}/f_{R1}\leq 1.1$, SFRC is a rigid-plastic material, when $f_{R3}/f_{R1}<0.9$, it is a post crack softening material, and when $f_{R3}/f_{R1}>1.1$, it is a post crack harding material. The constitutive model formulas for these three materials are:

Constitutive formula of rigid-plastic material:

$$f_{Ftuk}=\frac{f_{R3}}{3} \tag{3}$$

Constitutive formula of post crack softening or harding material:

$$\begin{aligned} f_{Ftuk}&=f_{Fts}-\frac{w_u}{CMOD}(f_{Fts}-0.5f_{R3}+0.2f_{R1}) \\ f_{Fts}&=0.45f_{R1} \end{aligned} \tag{4}$$

In the formula: w_u is the ultimate crack width, $w_u=\varepsilon_{Fu}l_{cs}$; $\varepsilon_{\mathrm{Fu}}$ is the ultimate tensile strain of unreinforced steel fiber reinforced concrete. $\varepsilon_{\mathrm{Fu}}$ is taken as 1% in the rigid-plastic constitutive model, 2% in the post crack softening/hardening constitutive model, and the average crack spacing is taken as lcs.

Divide the standard value f_{Ftuk} of elastic residual flexural tensile strength under different categories by the material strength partial coefficient 1.4 to obtain the design value f_{Ftu} of elastic residual flexural tensile strength. Then, according to formula (5), the steel fiber stress increment after cracking of unreinforced SFRC can be obtained.

$$\Delta f_{\mathrm{f}}=f_{Ftu}\frac{\rho_m}{\rho_{\mathrm{f}}} \tag{5}$$

In the formula, ρ_{m} and ρ_{f} are the volume ratios of cementitious materials and steel fibers, respectively.

According to the increment of steel fiber stress determined by formula (5), the ultimate bearing capacity of the normal section is obtained through the static equilibrium equation of the section. The specific formula is as follows:

$$N_u=Bf_{cu}x_c/2-(\Delta f_{\mathrm{f}}\rho_{\mathrm{f}})B(H-x_c) \tag{6}$$

$$M_u = f_{cu} B x_c^{\,2} + (\Delta f_{\mathrm{f}} \rho_{\mathrm{f}}) B (H - x_c)^2 / 2 \quad (7)$$

$$x_c = \left(\sqrt{\left(V_{\mathrm{f}} \frac{E_{\mathrm{f}}}{E_{\mathrm{m}}} \right)^2 + 2 V_{\mathrm{f}} \frac{E_{\mathrm{f}}}{E_{\mathrm{m}}}} - V_{\mathrm{f}} \frac{E_{\mathrm{f}}}{E_{\mathrm{m}}} \right) H \tag{8}$$

In the formula: x_c is the height of the compression zone; f_{cu} and f_{tu} are the design values for compressive and tensile strength of concrete, respectively; B is the width of the pipe segment; H is the thickness of the pipe segment; V_f represents the unit volume content of steel fibers, and E_f and E_m represent the elastic modulus of steel fibers and concrete, respectively.

3 Calculation of crack width of unreinforced SFRC segment

According to formula (5), the steel fiber stress increment after cracking of unreinforced SFRC is obtained. Assuming that the stress increment of steel fibers propagates along the length direction of the steel fibers and is linearly distributed in the conduction direction, the conduction length can be obtained according to formula (9):

$$l = \frac{\Delta f_{\mathrm{f}} S_{\mathrm{f}}}{C_{\mathrm{f}} \tau} \tag{9}$$

In the formula, C_f is the circumference of the contact surface between steel fibers and concrete; S_f is the contact area; τ Is the interfacial bonding strength.

Similarly, according to the elastic formula, the average increment of steel fiber strain is obtained as:

$$\Delta \varepsilon = \frac{\Delta f_{\mathrm{f}}}{2 E_{\mathrm{f}}} = \frac{f_{Ftu} \rho_m}{2 E_{\mathrm{f}} \rho_{\mathrm{f}}} \tag{10}$$

Furthermore, the calculation formula for the crack width of SFRC is:

$$w_{\mathrm{f}} = 2l \left(\varepsilon_{tu} + \Delta \varepsilon \right) \tag{11}$$

In the formula: ε_{tu} is the allowable tensile strain of concrete.

4 Conclusion

Based on the three-point bending test of unreinforced SFRC, the elastic residual flexural tensile strength of unreinforced SFRC with different dosages are obtained, and the relationship between the ratio of elastic residual flexural tensile strength and the steel dosages is established. By studying the material constitutive relationship of SFRC with different dosages, a static equilibrium equation for the section was established, and the ultimate bearing capacity of the normal section was calculated. Similarly, the strain increment and conduction length of the steel fiber in the cracked section were determined based on the stress increment of the steel fiber after cracking, and the calculation formula for crack width was finally obtained.

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