A finite element analysis on compressive properties of ECC with PVA fibers

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Abstract. In order to analyze the compressive performance of ECC with PVA by finite element method, in this paper the three-dimensional distribution model of PVA fiber was established by compiling the random sequence program of Matlab considering the random distribution of PVA in matrix ECC. On this basis, the finite element model of ECC was established by ABAQUS software to study the stress and deformation properties of ECC with different PVA fiber content under axial compression.

1. Introduction
Engineered Cementitious Composites (ECC) with strain hardening characteristics were developed by using cement-based cementitious materials, fine sand and PVA fibers[1, 2]. Under tensile and bending loads, multi-cracks was appeared and the maximum crack width could be controlled within 0.1 mm, which could effectively improve the structural resistance, ductility, toughness and energy absorption capacity[3, 4]. In recent years, the researches of ECC materials were mainly focused on macroscopic tensile properties[5-7]. The research of mesoscopic numerical simulation was relatively few. In this paper, ECC was simplified as cement mortar matrix and fiber two-phase composite material, and the mesoscopic numerical model was established based on Matlab software. Then the finite element model was established by ABAQUS, and the stress and deformation performance of ECC with different PVA fiber content under axial compression was studied.

2. Establishment of randomly distributed PVA fiber model
Based on the required dosage, the randomly distributed of PVA fibers in the ECC matrix can be realized by compiling the Matlab random sequence program. The length and diameter of the PVA fiber

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were 12mm and 4μm, respectively. The ECC specimen was adopted cube with 13mm in side length. The fiber numbers can be calculated by Equation 1. The results were shown in table 1.

\[
N = \frac{4 \times V \times V_f}{100 \times \pi \times d^2 \times L} \tag{1}
\]

Where \( V \) was the volume of specimen (mm\(^3\)), \( V_f \) was the volume fraction of PVA fiber (%), \( L \) was the length of the fiber (mm), \( D \) was the diameter of the fiber (mm).

| \( V_f \) ( % ) | 0.5  | 1.0  | 1.5  | 2    |
|-----------------|------|------|------|------|
| Number          | 766  | 1533 | 2299 | 3066 |

Table 1. The number of fiber in different volume content

The coordinates of fibers produced in Matlab were imported into Autocad. In addition, the model was stored in the IGES format which can be recognized by Abaqus. Finally, the IGS file was imported into Abaqus to generate the finite element model. The ECC finite element model with 1.5% fiber content was shown in figure1.

**Figure 1.** ECC finite element model with 1.5% fiber content

3. **Constitutive model of concrete and PVA fiber**

The plastic damage model of concrete can well describe the damage change law of cement-based materials. Therefore, the elastic-plastic damage model was adopted in the constitutive model of mortar in this paper. The standard of GB50010-2010 provided a classical plastic damage constitutive relation for concrete, which was widely used in cement-based materials. The stress-strain curves of cement mortar under uniaxial compression can be determined according to equation 2.

\[
\sigma = (1 - d_c)E_c \varepsilon \tag{2}
\]

\[
d_c = \begin{cases} 
1 - \frac{\rho_c n}{\rho_c + x / n} & x \leq 1 \\
1 - \frac{\rho_c}{\rho_c (x - 1)^2 + x} & x > 1 
\end{cases} \tag{3}
\]

\[
\rho_c = \frac{f_{cr}}{E_c \varepsilon_{cr}} \tag{4}
\]
\[ n = \frac{E_c \varepsilon_{cr}}{E_c \varepsilon_{cr} - f_{cr}} \]  
(5)

\[ \alpha_c = 0.157 f_{cr}^{0.785} - 0.905 \]  
(6)

\[ x = \frac{\varepsilon}{\varepsilon_{cr}} \]  
(7)

Compared to concrete, mortar has better ductility[9]. The peak strain can be calculated by equation 8.

\[ \varepsilon_{cr} = 4.75 \times (700 + 172 \sqrt{f_{cr}}) \times 10^{-6} \]  
(8)

Where, \( d_c \) was the damage evolution parameter under uniaxial compression; \( \alpha_c \) was the descending section parameter of stress-strain curve; \( f_{cr} \) was the uniaxial compressive strength value; \( \varepsilon_{cr} \) was the strain corresponding to peak compressive stress.

The stress-strain curves of cement mortar under uniaxial tension can be determined according to equation 9.

\[ \sigma = (1 - d_t) E_c \varepsilon \]  
(9)

\[ d_t = \begin{cases} 
1 - \rho_t (1.2 - 0.2x^5) & x \leq 1 \\
1 - \frac{\rho_t}{\alpha_t (x-1)^{1.7} + x} & x > 1 
\end{cases} \]  
(10)

\[ \rho_t = \frac{f_{tr}}{E_c \varepsilon_{tr}} \]  
(11)

\[ \alpha_t = 0.312 f_{tr}^2 \]  
(12)

\[ x = \frac{\varepsilon}{\varepsilon_{tr}} \]  
(13)

The peak strain can be determined by equation 14.

\[ \varepsilon_{tr} = f_{tr}^{0.54} \times 65 \times 10^{-6} \]  
(14)

Where, \( d_t \) was the damage evolution parameter under uniaxial tension; \( \alpha_t \) was the descending section parameter of stress-strain curve; \( f_{tr} \) was the uniaxial tension strength value; \( \varepsilon_{tr} \) was the strain corresponding to peak tension stress.

The mechanical parameters of mortar matrix were shown in table 2.

| Table 2. Mechanical parameters of mortar |
|-----------------------------------------|
| Mechanical parameters | Elastic modulus/GPa | Compressive strength/Mpa | Tensile strength/Mpa |
|-----------------------|---------------------|--------------------------|---------------------|
| Mortar                | 16.2                | 41.2                     | 2.4                 |

Elastic-plastic model was used for the constitutive relation of PVA fiber. In this study, the elastic modulus of the PVA fiber was 42.8 GPa, and the yield strength was 1600 Mpa.

4. Finite element analysis result

Damage nephograms of mortar with 1.5% fiber content under different steps were shown in figure 2.
From figure 2, it can be seen that with the increase of steps, the damage of mortar increased gradually. The stress-strain curve was shown in figure 3.

**Figure 2.** Damage nephograms of mortar under different steps

From figure 2, it can be seen that with the increase of steps, the damage of mortar increased gradually. The stress-strain curve was shown in figure 3.

**Figure 3.** Stress-strain curve

From figure 3, it can be seen that with the increase of fiber content, the peak load of samples decreased gradually. With the increase of fiber content, the strain corresponding to the peak stress of the samples increased gradually, which indicated that PVA fiber improved the deformability of mortar.
5. Conclusions

(1) By compiling the random sequence program of MATLAB, the mesoscopic models of ECC material with different PVA fiber contents were established according to the content of PVA fibers. Using ABAQUS finite element software, the compression performance of ECC can be simulated using ABAQUS finite element software.

(2) According to stress-strain curve, with the increase of fiber content, the peak load of samples decreased gradually. With the increase of fiber content, the strain corresponding to the peak stress of the samples increased gradually, which indicated that PVA fiber improved the deformability of mortar matrix.

Acknowledgment

The authors would like to acknowledge the financial support provided by National Key R&D Program of China-Key materials and preparation technology of high crack resistant ready-mixed concrete(2017YFB0310100), National Natural Science Foundation of China (51678011); Beijing Natural Science Foundation (8162005).

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