Numerical simulation of high-strength concrete under uniaxial/triaxial compression based on meso-scale model

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Abstract: According to the meso-scale characteristics and structural composition of concrete, a three-dimensional finite element mesoscopic model is established based on the random aggregate generation method and the background grid projection method. Based on the improved Ottosen yield conditions, the stress-strain curves and damage parameter data of concrete are calculated, and the CDP model is applied to carry out numerical simulation under static uniaxial and triaxial compression conditions. The results show that the stress-strain curve obtained from the numerical simulation is basically consistent with the experiment, and the crack development along the ITZ can be observed in the meso-scale model, which is consistent with the experimental details. It is proved that the modeling method and parameter calculation method in this paper is accuracy and have good applicability.

1. Introduction

On the meso-scale level, concrete can be regarded as a three-phase composite material composed of aggregate, cement mortar, and the interface transition zone (ITZ). The elastic modulus and strength of the ITZ are lower than that of cement mortar, so in terms of mechanical properties the ITZ will be significantly different from aggregate and cement mortar. Relevant experiments and studies have shown that the performance of concrete is largely related to the geometric and physical characteristics of the ITZ. The ITZ is considered to be the weakest part of concrete, and cracks in normal concrete usually appear first at the ITZ at the edge of the aggregate. For high-strength concrete, the increase in the strength of the cement mortar makes the difference between the strength of the cement and the aggregate smaller, the strength of the ITZ is also improved, and the mechanical properties are different from normal concrete. Cracks in high-strength concrete can pass through the aggregate and the damage surface is smoother [1]. It can be seen that the macro mechanical properties and meso damage of high-strength concrete are very different from normal concrete, and traditional homogeneous modeling methods cannot reflect the characteristics of details. Therefore, it is necessary to carry out high-strength concrete meso-scale numerical simulation, establish a concrete meso-scale model, and combine the characteristics of the high-strength concrete material constitutive model to study the differences of damage modes between different strength concrete.

Wittmann et al. [2] proposed the concept of "numerical concrete", and many scholars began to
study the structural characteristics and numerical simulation of concrete based on the meso-level of materials. Bentur et al. [3] pointed out that the thickness of the ITZ was only 0.01-0.1 mm. Schlangen et al. [4] and Liu et al. [5] increased the thickness of the ITZ to adapt to the meshing. Ren et al. [6], Liu et al. [7], and Ma [8, 9] et al. used the Walraven formula [10], randomly generated and placed concrete aggregates using the Monte Carlo method, and projected them into the background grid to complete the establishment of the meso-scale two-dimensional finite element model. Dang et al. [11, 12] measured the material parameters of aggregate, cement mortar, and ITZ, obtained a three-dimensional meso-scale model, and carried out numerical simulation of uniaxial compression experiments. Chen et al. [13] and Wang et al. [14] used the Voronoi block to represent the microparticle model of minerals, and considered the elastic-plastic contact deformation of particles. Fang et al. [15-20] developed a polyhedron spatial random convex growth algorithm based on octahedral random aggregate, and proposed an efficient comprehensive delivery algorithm to improve the modeling efficiency. Deng et al. [21-24] carried out experiments to analyze the bonding strength of ITZ, used random convex polyhedrons to simulate the three-dimensional geometry of aggregates, and used background meshing to project the meshing of the concrete media in each phase, and carried out a series of simulations.

At present, there is a lack of corresponding numerical simulation and comparative research on high-strength concrete in existing work. As the strength of the cement mortar of the high-strength concrete increases, the properties of the ITZ, which has a major effect on the damage to the concrete, will also change, which will also affect the damage to the concrete. Therefore, it is necessary to carry out three-dimensional meso-scale numerical simulation of high-strength concrete. Investigate the damager details of high-strength concrete finite element model in mechanical performance simulation. Pay attention to the influence of three-phase strength change of concrete on the overall mechanical properties, and provide data support and detailed analysis methods for numerical calculation and related experiments. In this paper, a three-dimensional meso-scale finite element model is constructed, and uniaxial, biaxial compression simulations of high strength concrete specimens are carried out based on ABAQUS. The results of the constitutive model based on Ottosen yield conditions were applied to the concrete plastic damage (CDP) model to reflect the mechanical properties and meso-scale damage characteristics of concrete, and compared with experimental and numerical results.

2. Three-dimensional meso-scale finite element model of concrete
Concrete aggregate can be divided into coarse aggregate and fine aggregate according to the particle size. The distribution law can be calculated by the formula proposed by American scholar Fuller W B. This formula indicates the proportion of aggregates with a particle size not larger than a certain value, as shown in table 1. Based on the formulations of C80 high-strength concrete in the existing work, as shown in table 2, combined with the particle size distribution, the number of aggregates at various levels of the concrete specimen can be calculated.
Table 1. Particle size distribution of concrete aggregate.

| Aggregate type | Aggregate grading | Ratio   |
|----------------|-------------------|---------|
| Aggregate size | Primary grading   | 5:0:0:0 |
|                | Secondary grading | 5.5:4:5:0:0 |
|                | Three grading     | 3:3:4:0 |
|                | Four grading      | 2:2:3:3 |

Table 2. Formulations of C80 high-strength concrete.

| Cement | Mineral powder | Silica fume | Sand | Stone | Admixture |
|--------|----------------|-------------|------|-------|-----------|
| C80    | 310            | 60          | 40   | 720   | 1260      | 15        |

The concrete specimen is a 150mm cube. Within the specimen boundary, based on the random number generation method and the number of aggregates, considering that the aggregates do not overlap each other, aggregates with random locations and radius are generated. Subsequently, a finite element model of the piece is established, and the model is meshed. The finite element model is projected to the random aggregate model, and the mesh material properties are determined according to the relative position relationship between the mesh and the aggregate. When all 8 node coordinates of a finite element are located inside the aggregate, this element is an aggregate element, when it is all outside the aggregate, it is a mortar element, and the rest are ITZ elements. This determines the material properties of the elements in the test piece. The test piece model is generated in ANSYS, and the random aggregate generation program and element material attribute determination program were compiled in APDL language. The finite element model of the concrete test piece is shown in figure 1, figure 2, and figure 3.

Figure 1. Aggregate finite element model.
Figure 2. ITZ finite element model.

Figure 3. Cement finite element model.
3. Material property

The concrete plastic damage model provided by ABAQUS is determined based on the models proposed by Lubliner et al.[25], Lee et al.[26]. It can analyze the mechanical response of concrete structures under cyclic loading and dynamic loading. The difference in tensile and compression properties of the material is considered, and it is used to simulate the material degradation behavior caused by damage under low hydrostatic pressure. In the elastic stage, the model is described by a linear elastic model. After the material enters the plastic stage, the material evolution is controlled by tensile and compression equivalent plastic strains, and damage factors are introduced to characterize the material damage. The uniaxial tensile and compressive stress-strain curves of the material are shown in figure 4.

\[ \frac{e^{\text{in}}}{e^{\text{ck}}} = \frac{E}{\alpha} - \frac{\sigma}{E_0} \]  \hspace{1cm} (1)

\[ y = \frac{x}{\alpha (x-1)^{1.7} + x} \hspace{1cm} x > 1 \]  \hspace{1cm} (2)

Figure 4. Uniaxial tension and compression stress-strain curve of CDP model.
\[
    y = \alpha_a x + (3 - 2\alpha_a) x^2 + (\alpha_a - 2) x^3 \quad x \leq 1
\]
\[
    y = \frac{x}{\alpha_d (x - 1)^3 + x} \quad x > 1
\]  

(3)

**Figure 5.** Compression stress-strain curves of concrete with different strengths.

Based on the Ottosen yield conditions, the hardening and softening parameters were established with the plastic volume strain as an internal variable, and a cap model was introduced to reflect the yield behavior under high hydrostatic pressure. Based on this, a plastic potential function is established and a constitutive model suitable for high-strength concrete is established. The yield function and plastic potential function are shown in Eq. (4) and (5). The calculation results of the stress-strain curve of normal concrete and high-strength concrete under uniaxial compression are shown in figure 5. It can be seen that the calculation results are in good agreement with the experimental values, and are better than those based on the empirical formula. The stress-strain data is applied to the CDP model.

\[
    \frac{a}{k^2} \frac{J_2}{f_c^2} + \left(1 - \frac{q}{k^2}\right) \lambda \sqrt{\frac{J_2}{f_c}} + \left(1 - \frac{q}{k^2}\right) F b \frac{I_1}{f_c} - c = 0
\]

(4)

\[
    \frac{a}{k^2} \frac{J_2}{q f_c^2} + \left(1 - \frac{q}{k^2}\right) \left(\lambda \sqrt{\frac{J_2}{f_c}} + F b \frac{I_1}{f_c}\right) - a = 0
\]

(5)

In the CDP model, the elastic modulus \( E \) of the concrete after it starts to damage can be expressed as the relationship between the damage factor \( d \) and the initial lossless elastic modulus \( E_0 \), as shown in Eq. (6). The calculation equation of the damage factor provided in the ABAQUS manual is shown in equation (7), where \( \beta \) is the ratio of plastic strain to inelastic strain. According
to empirical results, \( d \) is 0.35-0.7 when under compression and 0.5-0.95 when under tension. It can be seen that the value of the damage factor depends on empirical parameters, and the difference between different strength concrete cannot be determined.

\[
E = (1 - d) E_0
\]  
(6)

\[
d_k = \frac{(1 - \beta) e^{m} E_0}{\alpha_k + (1 - \beta) e^{m} E_0} \quad k = t, c
\]  
(7)

According to the Sidoroff energy equivalence principle, the elastic residual energy produced by stress on a damaged material is the same as the elastic residual energy produced by a non-destructive material. Therefore, the ratio of the strain residual energy to the total strain energy can be used to represent the damage parameters of the material, as shown in figure 6, and the expression is shown in Eq (8). Based on the calculated stress-strain curve data of the high-strength concrete, the residual energy of the strain can be calculated, and then the damage parameters can be obtained.

\[
d = \frac{\sum \sigma \varepsilon - \sum \sigma f(\varepsilon)}{\sum \sigma \varepsilon}
\]  
(8)

According to the Ref. [21-24], the strength of ITZ is obtained by multiplying the strength of the matrix by a reduction factor. For C80 high-strength concrete, the strength of the matrix is 80MPa, the strength of the ITZ is 60MPa, and the strength of the aggregate is 160MPa. The material parameters of the three materials are shown in the table 3.
Table 3. Material property.

| Material type | Density/kg/m³ | Elastic Modulus/GPa | Fc/MPa | Ft/MPa | fb/fc |
|---------------|---------------|---------------------|--------|--------|-------|
| Aggregate     | 2400          | 33.9                | 60     | 6.3    | 1.1   |
| ITZ           | 2500          | 36.9                | 80     | 7.4    | 1.08  |
| Cement        | 2660          | 45.5                | 160    | 13.3   | 1.03  |

4. Simulation results and discussion

Figure 7 is uniaxial loading of the model, the loading is quasi-static, the upper and lower platens are rigid, the lower platen is fixedly supported, and the upper platen is loaded by displacement. For quasi-static problems, the implicit algorithm is not affected by inertia and loading kinetic energy, and can more accurately reflect the force state of the test piece. Therefore, the Standard implicit calculation module is used for simulation. The comparison of uniaxial compressive stress-strain curves with experimental results is shown in figure 8. It can be seen that the simulation results, and experimental results agree well on the peak stress, the overall trend is the same, and the simulation results can accurately reflect the experimental situation. Figure 9 (a) and (b) show the surface and internal damage of the test piece. It can be seen that the outer surface of the test piece shows x-shaped cracks, which is consistent with the experimental results. For the meso-modeling test specimens, it can be seen that ITZ has larger damage, the matrix has less damage, the aggregate has almost no damage, and the cracks develop along the ITZ, similar to the experimental results. It is proved that the meso-model modeling and improved CDP parameters can reproduce the experimental data, reflect the macro and meso damage of the experiment, and have higher accuracy and credibility.

![Figure 7. Uniaxial compression loading of the test specimen.](image)
Figure 8. Stress-strain curves of simulation and experiment.

Figure 9. (a) Surface damage and (b) internal damage of test specimen.

Figure 10 is triaxial compression loading. The test specimen is loaded with a confining pressure of 2 MPa, the lower platen is fixedly supported, and the upper platen is loaded by displacement. The obtained stress-strain curve is shown in figure 11. It can be seen that compared with the uniaxial pressure, the peak intensity of the triaxial pressure is improved. And due to the lateral constraint, the descending section of the stress-strain curve is slower, which is in line with the trend of experimental results.
5. Results

Based on the random number generation method and the background grid projection method, a three-dimensional meso-scale finite element model of concrete is established. Based on the improved Ottosen yield conditions, the stress-strain curves and damage parameters of mortar, ITZ, and aggregate are calculated and applied to the CDP model. Numerical simulation results of uniaxial and biaxial pressures under quasi-static conditions are obtained, and the following conclusions are obtained.

1. The established three-dimensional meso-scale finite element model and the calculated CDP model parameters can well reproduce the experimental stress-strain curve data with good accuracy. The peak stress of the biaxial compression is improved compared to the uniaxial compression, and the
stress-strain curve decreased more slowly, which is consistent with the experiment.

2. During the loading, the ITZ suffered large damage, and the cracks developed along the ITZ. The crack development is consistent with the experimental phenomena, which proved that the meso-scale element model can reflect the experimental details well.

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