Meso-concrete Uniaxial Compression Experiment Based on ABAQUS

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Abstract. Plain concrete is made of cement matrix and aggregates. The current numerical model researches mostly consider the cement matrix and ignore the existence of coarse aggregates, which is not consistent with the reality. In view of that, this article uses ABAQUS as the platform to establish a meso-concrete damage model based on the concrete coarse aggregates and CDP (Concrete Damaged Plasticity) model constructed in Python language. The results show that: (1) The main failure mode of concrete model is shear failure, and the crack is about 45° to the vertical plane. (2) Under the action of the load, multiple micro-cracks are formed at the end of the concrete, which are gradually extended to each other, and finally a macroscopic large crack is formed. (3) The damage model proposed in this article is in line with reality and provides guidance for concrete damage research.

Keywords: Concrete, Uniaxial compression, Python, CDP model.

1. Introduction

Concrete structure is one of the most widely used structures in engineering construction, of which concrete is the main material of concrete structure. In order to ensure the safety of the building, concrete needs to be tested. But the use of actual concrete materials is time-consuming and laborious. Concrete numerical simulation tests are more common by comparison. Therefore, it is of great significance to carry out the numerical simulation experiment of meso-concrete uniaxial compression.

Concrete numerical simulation experiments have been around for a long time, and scholars at home and abroad have made dazzling achievements. In the freeze-thaw environment, Bai et al. discussed that the mechanical properties of concrete structures and the evolution trend of meso-damage processes under different freeze-thaw cycles obey certain laws [1]. With the support of 3D printing technology, Zhang et al. reconstructed the concrete model to make the internal structure of concrete transparent, which provided a new idea for studying the mechanical properties of concrete materials [2]. Concrete is a material with initial damage. Shi et al. used DS2 series full information acoustic emission signal analyzer to complete the data acquisition and three-dimensional damage localization of the whole process of concrete compression, and obtained that the correlation coefficient of acoustic emissivity in different stress stages has been linearly fitted. The results show that the associated dimension of acoustic emissivity shows a gradual downward trend with the increase of different initial damage [3]. Song et al. created two-dimensional and three-dimensional geometric models of foam concrete. Then, they explored the whole process of foam concrete from initial micro-cracks to compression failure. Finally, they obtained stress-strain curves [4]. Dang et al. used the Monte Carlo method to establish a concrete model and conducted simulation experiments to reflect the mechanical properties of concrete under uniaxial compression [5]. Liu et al. used ABAQUS finite element software to establish a model to simulate the temperature field change of reinforced concrete beam section under fire. Then, they analyzed the distribution law of beam section temperature and studied the influence of fireproof coating type and coating thickness on beam section temperature field distribution. In the end, they concluded that fireproof coating can effectively improve the fire resistance of reinforced concrete beam [6]. Cha et al. used the SST model in Fluent software to numerically simulate the unsteady flow of stationary elliptical cylinders under different Reynolds coefficients. They explored the influence of elliptical cylinder shape on the drag coefficient and obtained the resistance coefficient value of different shapes of elliptical cylinders at the same speed

along the long axis. At last, they obtained the change law of drag coefficient [7]. Taking Poyue Reservoir as the research object, Zhang et al. used ABAQUS finite element software to simulate the value of the in-situ shear test. They analyzed the stress-strain relationship, stress distribution and failure mechanism of the cemented surface under different conditions and fully revealed the fracture damage evolution law at the interface of dam foundation. They provided a theoretical basis for dam construction and safety [8]. Qin carried out finite element simulation of the hydration temperature field. Then, they analyzed the temperature-actual history curve of the test and discussed the influence of thermal parameters on the thermal behavior. Finally, they proposed an effective solution——Duct cooling [9]. Fu et al. compared the load-deflection curve of precast concrete beams at the measurement point obtained by the actual experiment and numerical simulation with the help of finite element software. The results showed that the two had a good consistency. On the basis that the concrete beam meets the requirements of the specification, it provides theoretical and technical support for production and construction [10].

However, above numerical model studies only consider the cement matrix and ignore the presence of coarse aggregates. In view of that, this article combines the actual mechanical properties of concrete and uses Python language to component concrete coarse aggregate. At the same time, the CDP model is used to establish a concrete damage failure model. This numerical method has guiding significance for the study of concrete damage law.

2. Model Establishment

The modeling flow chart is shown in Figure 1.

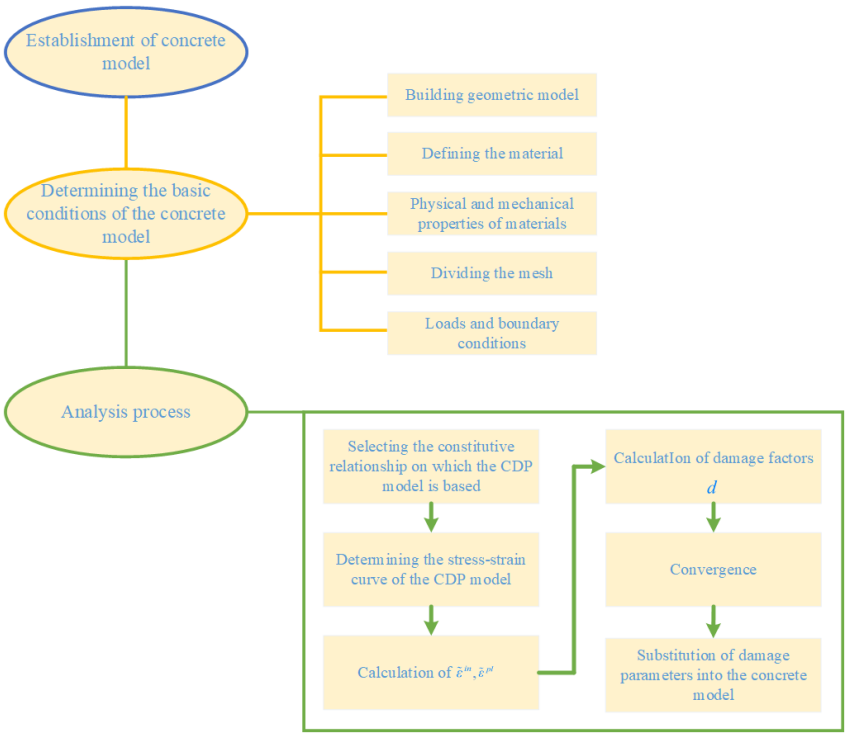


Figure 1. Modeling flow chart

2.1. Model Calculation

The size of the concrete model is 150mm×150mm×300mm. The aggregates are embedded in the concrete model, which contains about 40% of the volume of spherical coarse aggregates, and the diameter of the aggregates is 15-30 mm (Figure 2). The concrete model is divided into 72,963 mesh cells with the mesh type C3D8R. The aggregate model is divided into 21,102 mesh cells with the mesh type C3D10.

The model adopts the display dynamic analysis method. The bottom of the model is vertically constrained, and the upper surface is loaded by displacement. The maximum displacement is 30mm, and the loading rate is 0.005mm/step (Figure 3). In the model, the Z-axis direction is the vertical direction, and the X and Y axes are the horizontal direction. Within the calculation range, the model is isotropic.

According to Table 1, the concrete model has the bulk weight of 23.2 kN/m^3, the Elasticity modulus of 25.00 GPa, the Poisson's ratio of 0.2, the Viscosity parameters of 1×10^{-5}, the Eccentricity of 0.1, and the Expansion angle of 38°.

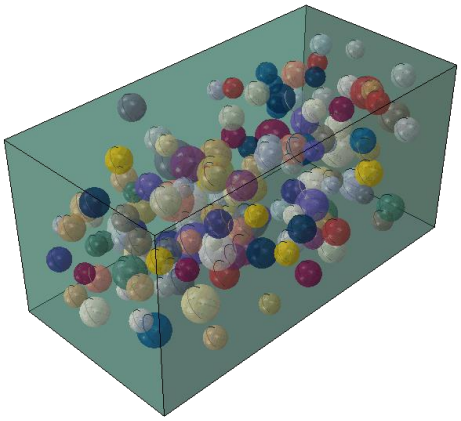


Figure 2. Concrete model

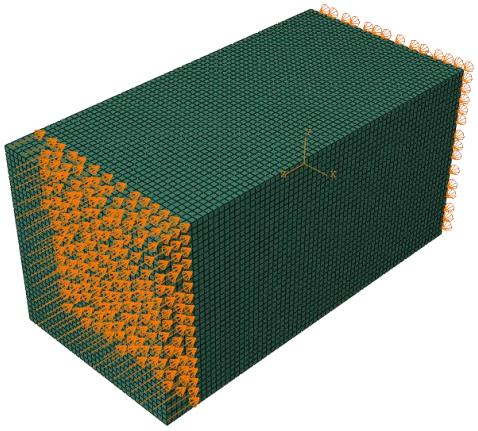


Figure 3. Mesh model

Table 1. Physical and mechanical parameters of the concrete model

Category	Bulk density γ /(kN/m^3)	Elasticity Modulus E/GPa	Poisson's Ratio μ	Expansion Angle ψ /(°)	Eccentricity	Viscosity parameters
Concrete	23.20	25.00	0.20	38	0.10	1×10^{-5}

2.2. CDP Model

The CDP model in ABAQUS uses the stress and inelastic strain of concrete in the uniaxial compressive stress state, where the inelastic strain are converted according to the uniaxial stress-strain relationship of concrete (Figure 4). The constituent relationship in *Code for the Design of Concrete Structures* [11] (GB50010-2010) is used in this article to determine the parameters in the CDP model. The assumptions of the model are as follows:

(1) The concrete material is continuous;

(2) The main failure mechanisms of concrete materials are tensile cracking and compression crushing;

(3) The uniaxial tensile and compressive response of concrete is characterized by damage plasticity.

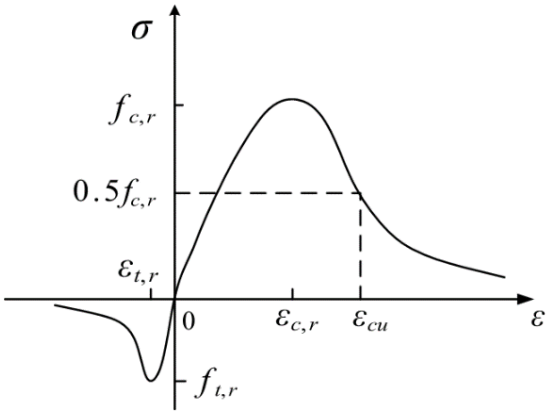


Figure 4. The stress-strain curve

$$\rho_c = \frac{f_{c,r}}{E_c \varepsilon_{c,r}} \tag{1}$$

$$n = \frac{E_c \varepsilon_{c,r}}{E_{c,r} - f_{c,r}} \tag{2}$$

$$d_c = \begin{cases} 1 - \dfrac{\rho_c n}{n - 1 + x^n} & x \leqslant 1 \\ 1 - \dfrac{\rho_c}{\alpha_c (x-1)^2 + x} & x > 1 \end{cases} \tag{3}$$

$$\varepsilon = x\varepsilon_{c,r} \tag{4}$$

$$\sigma = (1 - d_c) E_c \varepsilon \tag{5}$$

Where, $f_{c,r}$ is the representative value of uniaxial compressive strength of concrete material; $f_{t,r}$ is the representative value of uniaxial tensile strength of concrete material; $\varepsilon_{c,r}$ is the peak compressive strain corresponding to the representative value of uniaxial compressive strength $f_{c,r}$; ε_{cu} is the ultimate compressive strain of concrete; E_c is the modulus of elasticity of concrete material.

There are two main forms of concrete damage in the CDP model: softening after tensile yielding leading to cracking and softening after compressive yielding leading to crushing damage. The stress-strain relationships in the CDP model are shown in Figures 5 and 6.

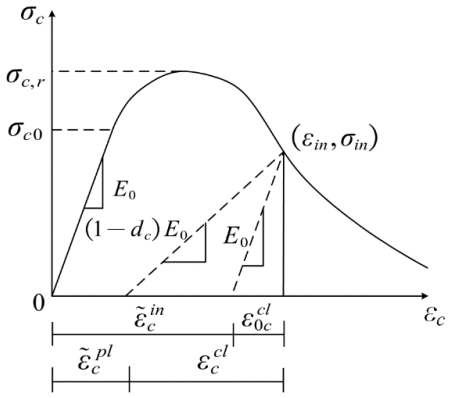


Figure 5. Compressive stress-strain curve in the CDP model

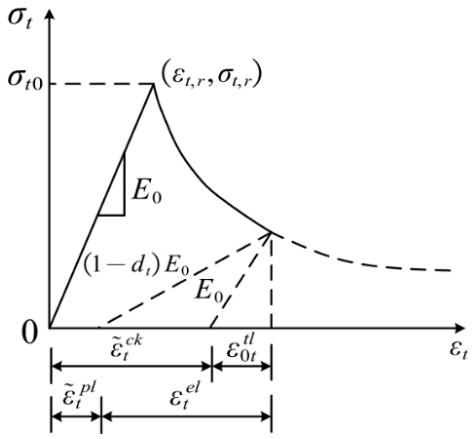


Figure 6. Tensile stress-strain curve in the CDP model

$$\tilde{\varepsilon}_c^{in} = \varepsilon_c - \varepsilon_{0c}^{el} \tag{6}$$

$$\varepsilon_{0c}^{el} = \frac{\sigma_c}{E_0} \tag{7}$$

$$\tilde{\varepsilon}_c^{pl} = \tilde{\varepsilon}_c^{in} - \frac{d_c}{(1-d_c)} \frac{\varepsilon_c}{E_0} \tag{8}$$

Where, $\tilde{\varepsilon}_c^{in}$ is the compressive inelastic strain; σ_c and ε_c is the compressive stress and compressive strain in *Code for the Design of Concrete Structures* (50010-2010); ε_{0c}^{el} is the elastic compressive strain corresponding to the initial modulus; $\tilde{\varepsilon}_c^{pl}$ is the plastic strain in the compressed condition.

$$\tilde{\varepsilon}_t^{ck} = \varepsilon_t - \varepsilon_{0t}^{el} \tag{9}$$

$$\varepsilon_{0t}^{el} = \frac{\sigma_t}{E_0} \tag{10}$$

$$\tilde{\varepsilon}_t^{pl} = \tilde{\varepsilon}_t^{in} - \frac{d_t}{(1-d_t)} \frac{\varepsilon_t}{E_0} \tag{11}$$

Where, $\tilde{\varepsilon}_t^{ck}$ is the tensile cracking strain; σ_t and ε_t is the tensile stress and tensile strain in *Code for the Design of Concrete Structures*; ε_{0t}^{el} is the elastic tensile strain corresponding to the initial modulus of elasticity; $\tilde{\varepsilon}_t^{pl}$ is the plastic strain in the tensile state.

Damage factor calculating:

$$d_c = 1 - \sqrt{\frac{\sigma_c}{E_0 \varepsilon_c}} \tag{12}$$

$$d_t = 1 - \sqrt{\frac{\sigma_t}{E_0 \varepsilon_t}} \tag{13}$$

Where, E_0 is the initial modulus of elasticity of concrete.

The parameters obtained from the calculations are shown in Tables 2 and 3.

3. Results Analysis

Under vertical loading, the parameters in Tables 2 and 3 are substituted into the CDP model in ABAQUS in this section. It is set that the concrete units will crumble away when the damage level reaches 95%.

Table 2. Concrete compression damage parameters

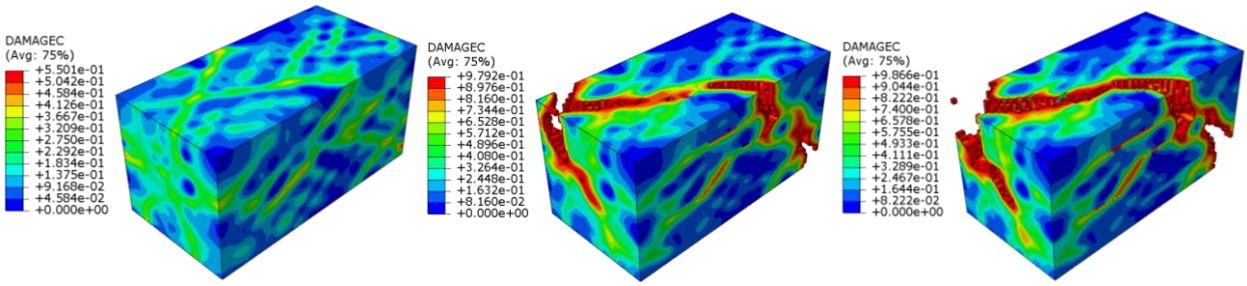
Category	Yield stress	Damage Parameter	Inelastic Strain
1	20.6615	0	0
2	21.5423	0.068725547	0.000211969
3	22.1483	0.0821809	0.000264419
4	22.6399	0.096238117	0.000321445
5	23.019	0.110936185	0.000382971
6	23.2875	0.126317473	0.000448922
7	23.5	0.159318364	0.000593801
8	22.7665	0.234501012	0.000929899
9	21.1625	0.315543224	0.001300822
10	19.3025	0.395235601	0.001681983
11	17.4898	0.469188797	0.00206125
12	15.8436	0.535344091	0.002433857
13	14.3941	0.593198277	0.002798598
14	13.1336	0.643127157	0.003155778
15	12.0413	0.685918371	0.003506232
16	11.0934	0.722492138	0.003850905
17	10.268	0.753753171	0.004190681
18	9.54579	0.780522667	0.004526331
19	8.91046	0.803514766	0.004858505

Table 3. Concrete tensile damage parameters

Category	Yield stress	Damage Parameter	Inelastic Strain
1	1.91276	0	0
2	2.39	0.06038246	1.87E-05
3	2.26961	0.15767766	4.742E-05
4	2.14977	0.21349816	6.417E-05
5	2.02995	0.26367236	7.969E-05
6	1.91007	0.3114282	9.507E-05
7	1.79021	0.35797649	0.0001108
8	1.66926	0.40438629	0.00012745
9	1.5484	0.45059722	0.00014521
10	1.42836	0.4965826	0.0001644
11	1.30823	0.54285313	0.00018566
12	1.1875	0.58970782	0.00020982
13	1.06749	0.63666945	0.00023759
14	0.94751	0.6839796	0.00027056
15	0.82801	0.73134699	0.00031084
16	0.70803	0.77892229	0.00036256
17	0.5884	0.82597281	0.0004322
18	0.46866	0.87198906	0.0005338
19	0.34878	0.91579002	0.00070024

At the early stage of loading (Figure 7(a)), under the uniaxial compression, the stresses at both ends of the concrete model kept increasing. Some regions showed the concentration of tensile and shear stresses, but the regions that reached the damage conditions had not yet appeared. In the middle

state of loading (Figure 7(b)), the concrete unit body at the end of the model was the first to reach the damage condition removal, Next, a large number of tiny cracks were generated on the surface of the concrete model. At the late stage of loading (Figure 7(c)), with the continuous concentration of stress, the damage area expanded and the width of cracks gradually expanded. Finally macroscopic cracks were formed, which are roughly at 45° to the vertical surface.



(a) Early stage of loading (b) Middle state of loading (c) Late state of loading

Figure 7. Concrete model destruction diagram

The stress-strain curve of concrete was extracted from the model (Figure 8). The peak compressive strength of concrete was 20.1 MPa, and the peak strain at this time was 0.0012. During the early compression of concrete (OA section), the concrete microcracks didn't develop significantly and elastic deformation occurred. The relationship between stress and strain was approximately straight line, and the volume change of concrete was small. With the continuous action of the load (AB section), due to the stress concentration at the microcracks, the cracks began to extend and concrete produced partial plastic deformation. The strain growth was accelerated, and the stress-strain curve gradually deviated from a straight line. Under this stage, some internal micro-cracks were interconnected and the crack development had become unstable. When the concrete reached the peak compressive strength, i.e. the yield point of concrete (point C), the internal micro-cracks were connected to each other and a damage surface was formed, after which the strain growth rate was significantly accelerated. When the point D is reached, the concrete formed a visible crack with an angle of 45° to the vertical plane. With the growth of strain, multiple discontinuous longitudinal cracks appeared on the concrete specimen. The transverse deformation developed sharply, and the bearing capacity decreased significantly. Under the long-term effect of this stress, the cracks would continue to develop eventually leading to damage.

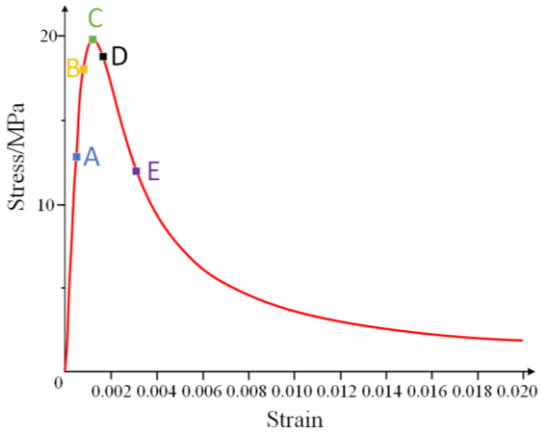


Figure 8. Concrete uniaxial compressive stress-strain diagram

4. Conclusion

(1) The main failure mode of concrete model is shear failure, and the crack is about 45° to the vertical plane.

(2) Under the action of the load, multiple micro-cracks are formed at the end of the concrete, which are gradually extended to each other, and finally a macroscopic large crack is formed.

(3) The damage model proposed in this article is in line with reality and provides guidance for concrete damage research.

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