Parameter calculation and verification of concrete plastic damage model of ABAQUS

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Abstract. The purpose of this paper is to study the method for determining the parameters of ABAQUS CDP model based on the concrete stress-strain curve provided by the code for concrete structure design. A finite element model was established to calibrate the value of the stress-strain curve cutoff and the damage factor of the concrete, and a calculation method of damage factor was recommended. The results show that the relative errors between first crack load, ultimate load and deflection at ultimate load with the experimental results were less than 5%. It is accordingly concluded that the finite element analysis results adequately reflected the experimental results.

1. Introduction

ABAQUS software shows good applicability in solving nonlinear analysis. The concrete damage plasticity model (CDP model) provided by ABAQUS was first proposed by Lubliner[1], and the concept of stiffness recovery introduced by Lee[2] improved its model. The CDP model realizes stiffness change through damage factor, and considers crack development, crack closure and partial stiffness recovery of concrete under cyclic loading[3-5]. The basic rules include: yield criterion, flow rule and hysteresis rule. The CDP model has been widely used in seismic analysis. It can be used to simulate the behavior of concrete structure and composite structure under cyclic loading, and can properly predict the punching shear response of the slab-column composite structures[6-8]. Rama et al.[9] used the concrete plastic damage model to evaluate the fracture energy and characteristic length for different grades of concrete using CDP model, and studied the effect on fracture properties of different input parameters like dilatation angle and eccentricity. Wosatko et al.[3] studied the development and closure of cantilever beam cracks in the concrete plastic damage model based on the plasticity theory. The study showed that the model could be applied to isotropic plastic materials, and the reduction and recovery of stiffness were considered in both the tensile stage and the compression stage, which could be used to analyze crack closure. Fang et al.[10] simulated the reinforced concrete under cyclic loading and compared the influence of concrete uniaxial stress-strain curve on the simulation results. It is recommended to use the formula provided in the Chinese code as the tensile curve and other parts of the concrete. Reasonable selection of CDP model parameters is the key to improve the accuracy of numerical simulation. In this paper, based on the constitutive relationship provided in the concrete structure design code[11] (GB 50010-2010), a test beam was selected to establish a finite element model, and to calibrate the CDP model parameters.
2. Concrete damage plasticity model

The concrete damage plasticity model (CDP model) assumes that the concrete material is continuous, isotropic and uniform, and the elastic modulus of concrete will be lost when the concrete shows inelastic strain. As the stiffness reduction under cyclic loading can be partially restored, the stiffness recovery coefficient \( w \) is defined to control this phenomenon. Under uniaxial cyclic loading, stiffness reduction and restoration of concrete under tensile and compressive loading are different. Therefore, the stiffness recovery factor needs to be defined separately in both directions. The damage factor \( d \) which is defined as the reduction of secant modulus relative to the initial elastic modulus at a certain point, as presented in the Equations (1) and (2).

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

Where the damage factor \( d \) is a function of stress state and uniaxial tensile and compressive damage variables \( d_t \) and \( d_c \). Under uniaxial cyclic loading, ABAQUS assumes:

\[
(1-d) = (1-s_d)(1-s_c)
\]

Where \( s_t \) and \( s_c \) are respectively functions of the stiffness recovery stress state related to stress inversion, and are determined as:

\[
\begin{align*}
\left\{ 
&s_t = 1 - w_t r^*(\overline{\sigma}_{11}) \quad 0 \leq w_t \leq 1 \\
&s_c = 1 - w_c \left[ 1 - r^*(\overline{\sigma}_{11}) \right] \quad 0 \leq w_c \leq 1
\end{align*}
\]

(3)

\[
r^* (\overline{\sigma}_{11}) = H (\overline{\sigma}_{11}) = \begin{cases} 
1 & (\overline{\sigma}_{11} > 0) \\
0 & (\overline{\sigma}_{11} < 0)
\end{cases}
\]

(4)

Where \( w_t \) and \( w_c \) are the tension and compression stiffness recovery coefficient. Under the uniaxial cyclic load (tension-compression-tension), the reduction and recovery of concrete stiffness are shown in Figure 1. When the concrete is in an axially stretched state, the tensile stress increases linearly. When the peak tensile stress of concrete (point A) is reached, the concrete cracks and then loads to point B. When the tensile stiffness of concrete decreases, the unloading will be carried out according to the effective stiffness \( (1-d_t)E_0 \), just as the path BC. When the axial pressure is applied to the concrete in the reverse direction, if \( w_c = 0 \) (the compression stiffness does not recover after the tensile damage occurs), it is loaded by the path CD, and if \( w_c = 1 \), it is loaded by the path CMF. When point F is reached, it is unloaded and then reverse loaded and stretched. If \( w_t = 1 \), it is loaded according to path GJ. If \( w_t = 0 \), it is loaded by path GH.
3. Model parameters determination method

3.1 Concrete model
The concrete constitutive relationship is not given in the CDP model, and the ABAQUS user needs to define the constitutive relationship. The most representative concrete constitutive relations are three kinds: the Chinese code [11] (GB50010-2010), the European code [12] (EN 1992-1-1: 2004) and the full stress-strain curve equation proposed by American scholar Kent-Park [13]. The European code does not give the tensile stress-strain curve of concrete. The stress-strain curve in the Chinese code introduces the damage evolution parameters, which has better convergence in calculation compared with the Kent-Park model. Therefore, the stress-strain curve provided by the Chinese code is used to determine the parameters in the CDP model. The uniaxial stress-strain curve in the code is calculated by the following Equation (5).

$$\sigma = (1-D)E_0 \varepsilon$$  \hspace{1cm} (5)

Where $D$ is the damage evolution parameter and $E_0$ is the initial elastic modulus. $f_{tg}$ and $f_{tr}$ use the standard values of axial tensile strength and axial compressive strength.

3.2 Damage factor
The CDP model directly uses the damage evolution parameters provided by the Chinese code, which leads to the difficulty of convergence of the calculation. According to the principle of energy equivalence, the calculation method of concrete damage factor proposed by Sidoroff [14] can be applied to the calculation of concrete damage factor under tension and compression. The results are practical and easy for iterative convergence. The damage factors were determined by referring to Equation (6).

$$d = 1 - \sqrt{\frac{\sigma}{E_0 \varepsilon}}$$  \hspace{1cm} (6)

Where $\sigma$ and $\varepsilon$ are determined by equation (5), $E_0$ is the initial modulus of elasticity of the concrete.

3.3 CDP model parameters
The CDP model considers the inelastic behaviour of concrete by defining damage factors in both compression and tension. It is assumed that the failure modes of concrete mainly include crack and crush. The evolution of yield surface is mainly controlled by tensile equivalent plastic strain $\varepsilon_{pl}^{t}$ and compressive equivalent plastic strain $\varepsilon_{pl}^{c}$. The strain input in the model is inelastic strain, and it is necessary to ensure that the corresponding equivalent plastic strain and $\varepsilon_{pl}^{c}$ are greater than 0 and increase with the increase of damage factor. Accordingly, the stress-strain curve section of concrete between 0.5 $\varepsilon_{tg}$ (0.5 times the peak compressive strain of concrete corresponding to uniaxial compressive strength) and 0.6 $\varepsilon_{tr}$ (0.6 times the peak tensile strain of concrete corresponding to uniaxial tensile strength) is selected as the elastic section.

Figure 2 shows the relationship between the compressive strains of the model. The compressive inelastic strain can be calculated by the following equations:

$$\varepsilon_{in}^{c} = \varepsilon_{c} - \varepsilon_{el}^{c}$$  \hspace{1cm} (7)

$$\varepsilon_{el}^{c} = \frac{\sigma_{c}}{E_0}$$  \hspace{1cm} (8)

$$\varepsilon_{pl}^{c} = \varepsilon_{in}^{c} - \frac{d_{e}}{1 - d_{e}} \frac{\sigma_{c}}{E_0}$$  \hspace{1cm} (9)
Where \( \varepsilon_{ci}^{\text{in}} \) is the compressive inelastic strain, and \( \varepsilon_{0i}^{\text{el}} \) is the elastic compressive strain corresponding to the initial elastic modulus, \( \varepsilon_{pi}^{\text{pl}} \) is compressive plastic strain, \( d_i \) is the compressive damage factor.

Figure 3 shows the relationship between the tensile strains of the model. The tensile cracking strain can be calculated by the following equations:

\[
\varepsilon_{ct}^{\text{ck}} = \varepsilon_t - \varepsilon_{0t}^{\text{el}}
\]

\[
\varepsilon_{0t}^{\text{el}} = \frac{\sigma_t}{E_0}
\]

\[
\varepsilon_{pi}^{\text{pl}} = \frac{d_i}{1-d_i} \left( 1 - \frac{\sigma_t}{E_0} \right)
\]

Where \( \varepsilon_{ct}^{\text{ck}} \) is the tensile cracking strain, and \( \varepsilon_{ct}^{\text{el}} \) is the elastic tensile strain corresponding to the initial elastic modulus, \( \varepsilon_{pi}^{\text{pl}} \) is tensile plastic strain, \( d_t \) is the tensile damage factor.

\[
\varepsilon_{ct}^{\text{ck}} = \varepsilon_t - \varepsilon_{0t}^{\text{el}}
\]

\[
\varepsilon_{0t}^{\text{el}} = \frac{\sigma_t}{E_0}
\]

\[
\varepsilon_{pi}^{\text{pl}} = \frac{d_t}{1-d_t} \left( 1 - \frac{\sigma_t}{E_0} \right)
\]

Where \( \varepsilon_{ct}^{\text{ck}} \) is the tensile cracking strain, and \( \varepsilon_{ct}^{\text{el}} \) is the elastic tensile strain corresponding to the initial elastic modulus, \( \varepsilon_{pi}^{\text{pl}} \) is tensile plastic strain, \( d_t \) is the tensile damage factor.

![Figure 2. Uniaxial compression stress-strain curve of CDP.](image)

![Figure 3. Uniaxial tensile stress-strain curve of CDP.](image)

### Table 1. Some parameters of CDP.

| \( \psi^{(c)} \) | \( \lambda \) | \( f_{so} / f_{co} \) | \( K \) | \( \mu \) |
|----|----|----|----|----|
| 30 | 0.1 | 1.16 | 0.6667 | 0.0005 |

Table 1 shows the recommended values for other parameters of the CDP model for ordinary concrete. The expansion angle \( \psi \) and eccentricity \( \lambda \) are parameters related to the yield surface flow rule. \( K \) is the parameter that controls the shape of the yield surface. \( f_{so} \) is the concrete biaxial compressive strength, \( f_{co} \) is the uniaxial compressive strength, and the ratio of the two is taken as the recommended value. \( \mu \) is the viscous parameter defined by the CDP model. The larger \( \mu \) is, the easier it is to converge. The smaller \( \mu \) is, the higher the accuracy is. When \( \mu \) is 0.0005, the accuracy and convergence can be satisfied.

### 4. Model parameters calibration

The CDP model does not specify the ultimate inelastic strain of concrete. Therefore, it is necessary to calibrate the truncation of tension and compression stress of concrete. Taking the test beam STEEL-40S in the literature [14] as an example, the finite element analysis was carried out in order to test the damage factors calculated by the formula recommended in this paper. At the same time, the cut-off of the stress-strain curve of the concrete was preliminarily calibrated.
4.1 Test beam and parameters

Figure 4 shows detailed views of the simply supported beam STEEL–40S. The beam was designed and fabricated with a length of 2400 mm (span 2200 mm), a cross sectional area of 150 × 250 mm, the depth of outer reinforcing bar of 215 mm and the depth of inner reinforcing bar of 165 mm. SD400 D10 reinforcement was used for compression reinforcement, tensile reinforcement and stirrup. Table 2 shows...
the material properties of SD400 D10. The specified design strength of concrete applied for forming the specimens was 40 MPa. The measurements of compressive strength were 40.91 MPa.

The standard value of the compressive strength after conversion is \( f_{ck} = 27.3 \text{MPa} \). The standard value of concrete compressive strength is used in the calculation of CDP model parameters. Table 3 lists the calculated damage factors and related parameters.

The model was established according to the geometry, loading mode and constraint position of the STEEL-40S test beam. The material properties of concrete adopt the parameters in Table 3. The constitutive model of reinforcement adopted bilinear model. In the model, the concrete elements were represented using C3D8R hexahedral elements, while the reinforcement is simulated using truss elements. The reinforcement was embedded in the concrete and the degrees of freedom are the same as the values of the concrete element’s degrees of freedom at the corresponding position. The element size for both concrete and steel was 50mm\(^3\). This model adopted the method of setting steel plate to avoid the phenomenon of stress concentration at the loading point and the supporting point and adopted the displacement method in the loading process.

\[
\text{Table 4} \quad \text{Analytical results and discussion}
\]

In Figure 5, the test results were compared with the results of the finite element analysis. In order to study the influence of the truncation of the stress-strain curve and the value of damage factor on the calculated results, different values were taken for \( A \) and \( B \) in the finite element analysis. When \( A \) and \( B \) were less than 3, the load-mid-span deflection curve of the finite element model was greatly different from the test value. Therefore, finite element models were established to take 3, 9, 15, and 20 for \( A \), and take 3, 6, 10 and 40 for \( B \). The cracking load of the test beam STEEL-40S is 13.28kN, the ultimate load is 56.91kN, and the deflection at the ultimate load is 40.51mm. Table 4 shows the first crack load and ultimate load in the finite element analysis. When \( A \), the theoretical value of the ultimate load was 60.69kN, and the deflection at the ultimate load was 14.20mm, which did not reflect the actual situation of the test. When \( B \), the theoretical value of the cracking load was 3.26kN from the true value, there was no falling section in the load-span deflection curve within deflection=100mm. When \( A \), the values of tensile damage factor and compression damage factor were both greater than 0.95, and the relative errors between first crack load, ultimate load and deflection at ultimate load with the experimental results were less than 5%. It is accordingly concluded that the finite element analysis results adequately reflected the experimental results.

\[
\text{Table 4} \quad \text{The first crack moment and the experimental and analysis values of the maximum moment.}
\]

| Specimen | \( x_{\text{cr max}} \) | \( x_{\text{u max}} \) | First crack load \( P_{\text{cr}} \) (kN) | Ultimate Failure load \( P_{\text{u}} \) (kN) |
|----------|----------------|----------------|-----------------|-----------------|
| C20T3    | 20             | 3              | 18.92           | 60.69           |
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5. Conclusion
This paper investigated the effects of the value of the stress-strain curve cutoff and the damage factor of the concrete on finite element analysis. Through the above discussions, the following conclusions can be drawn:

1) According to the damage factor calculation formula recommended in this paper, the concrete stress-strain curve provided by the code for concrete structure design was applied to the finite element model. The obtained model parameters have been verified, and the finite element model can be used for the crack resistance check and bearing capacity check.

2) When the values of tensile damage factor and compression damage factors were both greater than 0.95, the relative errors between first crack load, ultimate load and deflection at ultimate load with the experimental results were less than 5%. The deformation and damage of the finite element model were consistent with the experimental phenomena. Therefore, the recommended damage factor is greater than 0.95.

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| C20T6  | 20  | 6   | 17.96 | 58.74 |
|--------|-----|-----|-------|-------|
| C20T10 | 20  | 10  | 17.64 | 58.05 |
| C20T40 | 20  | 40  | 16.54 | 56.37 |
| C3T40  | 3   | 40  | 16.54 | -     |
| C6T40  | 6   | 40  | 16.54 | 57.41 |
| C9T40  | 9   | 40  | 16.54 | 55.74 |
| C15T40 | 15  | 40  | 16.54 | 55.99 |
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