Study on concrete damaged plasticity model for simulating the hysteretic behavior of RC shear wall

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Abstract. Abaqus is often used to analyze the dynamic elasto-plastic response of tall buildings under strong earthquake. However, the analysis results of the hysteretic behavior of RC shear wall are not very satisfactory. In this paper, the residual strain is proposed to determine the damage parameters in the concrete damaged plasticity model in Abaqus, which include the damage factor and compression stiffness recovery factor. The method can greatly reduce the lagging or exceeding of strain in the compression reloading path. The confinement effect of distributed bars on concrete of RC shear walls is also considered. In addition, a secondary-developed uniaxial constitutive model of steel is adopted to present the Baushinger effect under the reciprocating loading. Simulation results are in good agreement with the test results. It shows that the methods proposed in this paper can effectively realize the simulation of the hysteretic behavior of RC shear wall under the low cyclic reciprocating loading.

1. Introduction

RC shear wall member is the main lateral resistance member in the high-rise buildings because of its characteristics of high stiffness and high bearing capacity. In order to accurately analyze the non-linear response of high-rise buildings under strong earthquake, it is necessary to establish a reasonable mechanical model for RC shear wall member, which means high calculation accuracy and efficiency. In recent years, the layered shell element model of FEM, especially Abaqus, has gradually been regarded as an ideal model for RC shear wall [1].

Although the layered shell element model with the concrete damage plastic model of Abaqus has been used to analyze the nonlinear behavior of RC shear wall members and structures [2, 3], most researchers only study the skeleton curve under reciprocating loading [4].

The existing simulation results of hysteretic behavior of shear wall members are obviously fuller than the test results, which overestimates the energy dissipation capacity of members [5] and will greatly affect the accuracy of dynamic elastic-plastic analysis of the whole structure.

In order to accurately simulate the hysteretic behavior of RC shear wall members based on the layered shell element, the concrete damage plastic model of Abaqus as well as the steel constitutive model is studied in this paper.
2. Determination on parameters of concrete damage plastic model

2.1. Brief introduction of CDP model

In Abaqus, there are three concrete constitutive models, including the smeared cracking model, damage plasticity model (CDP model) and brittle cracking model. Among those models, the CDP model is recognized as the most effective model to simulate the inelastic behavior of concrete under reciprocating loading.

In the CDP model, a complete constitutive model of concrete material is formed by defining the material parameters of elastic stage, tension and compression plastic damage stage [6]. In the elastic stage, material parameters include elasticity modulus and Poisson's ratio, and the unloading-reloading modulus under reciprocating loading is kept as the initial elasticity modulus. In the plastic damage stage, the CDP model needs to define the stress-strain skeleton curve, plastic damage factor and stiffness recovery factor under compression and tension.

Plastic damage factor and stiffness recovery factor are used to describe the damage behavior of concrete under reciprocating loading, such as crushing, tensile cracking, crack closure and stiffness recovery. The relationship between unloading-reloading modulus and damage factor under reciprocating loading is shown in equation (1).

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

where, \( d \) is the damage factor in tension or compression, which ranges from 0 to 1. With the increase of the nonlinear behavior of concrete, the damage factor increases, so the unloading-reloading modulus decreases.

Equation (1) shows that the plastic damage factor \( d \) is essentially used to characterize the attenuation of the unloading-reloading modulus under reciprocating loading. The rationality of \( d \) determines whether the CDP model can accurately simulate the hysteretic behavior of concrete members. According to different damage theories, the relationship between the plastic damage factors and concrete strain varies greatly, which makes the unloading-reloading modulus determined by equation (1) is hard to correctly describe the loading-unloading law of actual concrete materials, and then causes the unreasonable results of hysteretic simulation of RC members. The Sidoroff energy method is usually used to determine the plastic damage factor [7], but its simulation results of hysteretic performance are usually poor.

At present, the Concrete02 model in OpenSees software can simply and reasonably describe the hysteretic behavior of concrete, and good results have been obtained in simulating the hysteretic behavior of shear walls [8, 9].

Therefore, in this paper, the Concrete02 model in OpenSees is referred to determine the material parameters of CDP model in Abaqus.

2.2. Determination of compression skeleton curve

In the Concrete02 model, the constitutive model proposed by Kent and Park [10] and then modified by Scott [11] are adopted, as shown in figure 1.

The Concrete02 model is mainly applied for the beam-column member, and its compression skeleton curve is divided into ascending stage, descending stage and platform stage. The skeleton curve equation is as follows:

\[ \varepsilon \leq \varepsilon_{cc}, f = f_{cc}[2(\varepsilon / \varepsilon_{cc}) - (\varepsilon / \varepsilon_{cc})^2] \]  

\[ \varepsilon_{cc} < \varepsilon \leq \varepsilon_{eq}, f = f_{cc}[1 - Z(\varepsilon - \varepsilon_{eq})] \]  

\[ \varepsilon > \varepsilon_{eq}, f = 0.2f_{cc} \]
where, \( \varepsilon_{cc} = 0.002K \), \( f_{cc} = Kf_{co} \), \( K = 1 + \rho_V \frac{f_{sh}}{f_{co}} \), \( Z = \frac{0.5}{145f_{co} - 1000} + 0.75\rho_V \left( \frac{h'}{s_h} \right)^{1/2} - 0.002K \).

Here, \( \varepsilon_{cc} \) is the strain corresponding to the peak stress, \( K \) is the increase factor of strength and peak strain caused by stirrups restraint, \( Z \) is the slope of decreasing strain, \( f_{co} \) is the compressive strength, \( f_{cc} \) is the restrained compressive strength of concrete, \( f_{sh} \) is the yield strength of stirrup, \( \rho_V \) is the volume ratio of stirrups in beam-column members, \( h' \) is the width of concrete core, \( s_h \) is the spacing of stirrups.

As shown in figure 1, the strength and peak strain of concrete will be slightly increased when the confinement effect of stirrups is taken into account. At the same time, the ductility of concrete increases significantly, that is, the slope of the descending stage of skeleton curve will be reduced.

In RC shear wall members, the existence of vertical and horizontal distributed bars will also confine concrete, and restrain the development of concrete cracks. When RC shear wall member is simulated by using of the layered shell element, the confinement effect of distributed bars cannot be taken into account in the element configuration, and the bearing capacity and ductility will be underestimated. The confinement effect of distributed bars on concrete in shear wall members should be considered in CDP model. In this paper, the compression skeleton curve of concrete in RC shear wall is also determined by equation (2), (3) and (4). However, \( \rho_V \) in these equations is adjusted to the volume ratio of distributed bars in shear wall members. \( \rho_V \) can be determined by equation (5).

\[
\rho_V = \frac{n \cdot S_v \cdot A_{sv} + n \cdot S_h \cdot A_{sh}}{s_v \cdot s_h \cdot h'}
\]  

In which, \( S_v \) is the spacing of vertical bars, \( S_h \) is the spacing of horizontal bars, \( A_{sv} \) is the area of vertical bars, \( A_{sh} \) is the area of horizontal reinforcement and \( n \) is the number of bar layers.

### 2.3. Determination of compression damage factor

As mentioned above, the compressive damage of concrete in CDP model under reciprocating loading is described by the compressive unloading path of concrete, which is represented by the damage factor \( d_c \) in compressive zone. In CDP model, the unloading path is along a straight line from unloading point F to residual strain point A, as shown in figure 2.

However, the actual unloading path of concrete is along the curve with decreasing unloading modulus. Therefore, the CDP model characterizes the unloading behavior of concrete under compression by a simple path. The damage factor \( d_c \) determined by the Sidoroff energy method cannot reflect the decreasing of the unloading modulus. In this paper, the damage factor \( d_c \) is determined by the
residual strain method. The compression hysteresis rule of the modified Kent-Park model is used to determine the compression residual strain point in the CDP model. Residual strain point A corresponding to the unloading point F is firstly determined, and then the damage factor $d_c$ is calculated, as shown in figure 2.

![Figure 2. Hysteresis law of CDP model.](image)

In the modified Kent-Park model, the unloading path is a straight line from D point to E point to H point, and the reloading path is a straight line from H point to D point, where H point is the residual strain point in compression zone, as shown in figure 3. The compressive residual strain at H point can be obtained as in equation (6).

$$\varepsilon_{c,pl} = \frac{f_{ul}}{E_c} \cdot \frac{(\varepsilon_{ul} - \sigma_{ul})}{E_c \cdot (\sigma_{ul} + f_{ul})} \quad (6)$$

![Figure 3. Hysteretic rule of compression zone in modified Kent-Park model.](image)

For the unloading point F of the CDP model in figure 2, its coordinates are $(\varepsilon_{ul}, \sigma_{ul})$. Residual strain point A can also be obtained as in equation (6) accordingly. Thus, the unloading modulus is $E_f = \frac{\sigma_{ul}}{\varepsilon_{ul} - \varepsilon_{c,pl}}$, and the compression damage factor $d_c = 1 - \frac{E_c}{E_c} = 1 - \frac{\sigma_{uu}}{(\varepsilon_{uu} - \varepsilon_{c,pl})E_c}$. Therefore, the material loading-unloading path in CDP model will be a simplified form of the loading-unloading path of the modified Kent-Park model.
2.4. Tension skeleton curve and tension damage factor

In this paper, the tension skeleton curve is divided into three straight lines, in which the post-failure stress is \(0.01f_t\) and \(\varepsilon_t\) is the peak strain, as shown in figure 4. The tension skeleton curve of concrete ignores the confinement effect of distributed bar.

![Figure 4. Tension skeleton curve.](image)

It is generally believed that the tensile properties of concrete have little influence on the bearing capacity of members. However, there is a process of tensile cracking and closing repeatedly in concrete under reciprocating loading. The crack closure has an important influence on the hysteresis behavior of members under reciprocating loading. The "pinching" of macro load-displacement hysteresis curve of concrete members is largely affected by the crack closure behavior [12]. Therefore, the tension hysteretic relation representing the crack closing behavior in the CDP model is important for the rationality of the simulation results.

Similar to the unloading rules in the compression zone, the tensile unloading path in the CDP model is a straight line from the unloading point (point A or B) to the tensile residual strain point, as shown in figure 4. Under reciprocating loading, when the concrete in figure 2 is tensioned and unloaded from point C (once compressed, i.e. obtained from point F-A-B-C), the unloading path is a straight line from unloading point C to residual strain point D, and the crack closes at point D. If compressive loading occurs subsequently, by default in the CDP model (compressive stiffness recovery factor \(W_c = 1\), i.e. compressive stiffness recovery completely), the compressive reloading will return to point E on the compressive curve along the DE route (DE \(\parallel\) FA), instead of the previous compressive unloading point F. As a result, it exists that the reloading path lags behind the previous unloading path in the CDP model.

The strain difference between point D and point A is an important index to describe the crack closure behavior. When the tension unloading point is fixed, if the strain difference is larger, it means that the closure of cracks and the entry of compression state will occur prematurely, and the lagging of the reloading route in the compression zone will be more serious. The lagging of the reloading path makes the stiffness of the macro load-displacement hysteresis curve from unloading to reverse loading large, so the "pinching" with lower stiffness can not be represented, and the hysteretic curve tends to be chubby.

In the Concrete02 model, the origin-pointing rule is used to represent the tension unloading behavior of concrete. So, there is no lagging of the reloading path. In order to eliminate the lagging of reloading path in the compression zone of CDP model, the strain difference should be small as far as possible to rationally describe the crack closure. However, the strain difference, i.e. the tension residual strain \(\varepsilon_{t,pl}\) and its increment must be greater than 0 in the CDP model. For the sake of simplicity, the tension residual strain is determined by equation (7).

\[
\varepsilon_{t,pl} = \left(\frac{\varepsilon_{i,un}}{E_t}\right)^{1/2} \varepsilon_t
\]

(7)

In which, \(\varepsilon_{i,un}\) is the unloading point strain on the tension skeleton curve.
Similarity to the compressive damage factor, the tensile damage factor $d_t$ can be determined by equation (8) and (9).

$$E_{ri,t} = \frac{\sigma_{t,un}}{\varepsilon_{t,un} - \varepsilon_{t,pl}}$$  \hspace{1cm} (8)

$$d_t = 1 - E_{ri,t} = 1 - \frac{\sigma_{t,un}}{E_c (\varepsilon_{t,un} - \varepsilon_{t,pl}) E_c}$$  \hspace{1cm} (9)

In which, $\sigma_{t,un}$ is the stress corresponding to the unloading strain $\varepsilon_{t,un}$ on the tensile skeleton curve, $E_c$ is the unloading modulus in tension.

2.5. Determination of compressive stiffness recovery factor.

By the tension residual strain determined by equation (7), the lagging of the reloading route in the compression zone still exists when the tensile strain is large. Therefore, the compressive stiffness recovery factor $W_c$ must be adjusted to further eliminate the lagging of the reloading path.

It can be seen from figure 2 that different $W_c$ values will cause different reloading routes. When $W_c = 1$, the reloading path is along DE, and it exists the lagging of the reloading route; when $W_c = 0$, the reloading path is along DG, and it exists the exceeding of the reloading route. Reasonable $W_c$ should make the reloading path is DF.

Because $W_c$ in CDP model is constant, it is impossible to avoid the lagging or exceeding in different loading-unloading cycles. In this paper, the following methods are used: assuming that the compression unloading point is at the peak point of compression, the tension unloading point under is at $10\varepsilon_t$, and the reloading route under compression can come back to the peak point of compression. So, $W_c$ is calculated by equation (10).

$$W_c = \frac{\varepsilon_{in,cc}}{\varepsilon_{in,cc} + \varepsilon_{t,pl10}}$$  \hspace{1cm} (10)

Here, $\varepsilon_{in,cc}$ is the inelastic strain at the peak point of compression, and $\varepsilon_{t,pl10}$ is the residual strain corresponding to the tensile strain $\varepsilon_t$.

3. Constitutive model of rebar

In order to adequately consider the Bauschinger effect of steel under reciprocating loading, a secondary-developed uniaxial constitutive model of steel material is adopted for rebar in shear wall. The skeleton curve of the constitutive model is based on Esmaeily-Xiao model [13], and the loading and unloading curve is based on Légeron model [14], as shown in figure 5, the accuracy verification of the constitutive model and the parameters of the model can be seen in reference [15].

![Figure 5. Stress-strain curve of steel.](image-url)
4. Results and discussions

In order to verify the correctness of the concrete constitutive model, the test of SW1-1 (axial compression ratio is 0.14) and SW1-4 (axial compression ratio is 0.57) in reference [16] are simulated, as shown in figure 6. The layered shell element S4R in Abaqus is adopted in the model. The strength grade of concrete is C30. Yield strength of Φ6 and Φ10 bar are 392 MPa and 352 MPa. The material parameters in simulation are determined strictly according to the experimental conditions, but the number of loading cycles is simplified.

![Reinforcement drawing of specimens set SW1.](image)

**Figure 6.** Reinforcement drawing of specimens set SW1.

![Comparison of test and simulation results of SW1-1.](image)

(a) test result  (b) result A  (c) result B

**Figure 7.** Comparison of test and simulation results of SW1-1.

The results of testing and simulation of SW1-1 are shown in figure 7. It can be seen that the results of simulation without considering the confinement effect of distributed bars (hereinafter referred to as result A) and with considering the confinement effect of distributed bars (hereinafter referred to as result B) are close to the test result. Figure 8 is the skeleton curve comparison between test and simulation results of SW1-1. It can be seen that the calculated skeleton curves are basically in agreement with the test curve and the stiffness is similar when the loading amplitude is smaller than +5 mm. With the increase of the loading displacement amplitude, the deviation between the calculated skeleton curve and the test increases. In the positive loading direction, the skeleton curve of result A reaches the peak value at the displacement amplitude of 8.5 mm, and then decreases. The bearing capacity deviation between simulation and testing is about 15%. The skeleton curve of result B better coincides with the test curve, and the bearing capacity deviation between simulation and testing is about 4.4%. In the negative loading direction, the deviation between the calculated skeleton
curve and the test curve is greater than that of the positive loading. The maximum deviation between the peak bearing capacity of result A and result B is about 23% and 12%, respectively.

![Comparison of skeleton curve of SW1-1.](image-url)

**Figure 8.** Comparison of skeleton curve of SW1-1.

Figure 9 is the comparison of single-loop hysteresis curves of SW1-1. Table 1 shows the error of single-loop calculation results compared with test results. It can be seen that the peak values of positive and negative loads of results A are lower than those of test results, while the peak values of positive and negative loads of results B are close to those of test results. The energy dissipation area of result A is significantly larger than that of test result at 11.5 mm and 20 mm loading amplitude, while that of result B is only slightly higher than that of test result.

The comparison results show that the method of determining damage parameters by residual strain can better simulate the hysteretic behavior of shear walls, and the simulation results with considering the confinement effect of distributed bars are more accurate and reasonable.

![Comparison of Single-loop hysteretic curve of SW1-1.](image-url)

**Figure 9.** Comparison of Single-loop hysteretic curve of SW1-1.

**Table 1.** Single-loop Error between test results and simulation results of SW1-1.

| Displacement amplitude (mm) | Positive load capacity | Negative load capacity | Energy dissipation area | Positive load capacity | Negative load capacity | Energy dissipation area |
|----------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 11.5                       | -16.9%                 | -15.8%                 | +33.1%                 | -4.9%                  | -12.2%                 | +2.0%                  |
| 20                         | -10.9%                 | -10.3%                 | +15.7%                 | +1.9%                  | +5.9%                  | +8.6%                  |

The test results and simulation results of SW1-4 are shown in figure 10. Through the comparison of figure 10(a) and 10(b), it is found that the bearing capacity and hysteretic cycle fullness of the simulation result are close to the test curve. Combined with the analysis results of SW1-1 specimen with low axial compression
ratio shown in figure 6, it is shown that the model in this paper can reflect the influence of different axial compression ratio on the hysteretic behavior of shear walls.

Figure 10. Comparison of test and simulation results of SW1-4.

In order to further verify the constitutive model of concrete, test JLQ-3 (Axial Compression Ratio 0.4) in reference [17] is also simulated, in which the strength grade of concrete is C40. The results of testing and simulation are compared as shown in figure 11. It can be seen that the constitutive model of concrete and reinforcement adopted in this paper can well simulate the pinching of test curve, and the calculated bearing capacity and strength degradation obtained by considering the effect of distributed bars are more consistent with the test results, which further shows that the constitutive model of concrete and reinforcement adopted in this paper is reasonable.

Figure 11. Comparison of test and simulation result of JLQ-3.

5. Conclusions
In this paper, the material constitutive model for simulating hysteretic behavior of RC shear wall members under low cyclic reciprocating loading is studied, and the following conclusions are obtained:

- the confinement effect of distributed bars on concrete in RC shear wall can be considered in the constitutive model of concrete, when the layered shell element is used to simulate RC shear wall member;
- the damage factors of CDP model can be determined based on the residual strain method. The residual strain method can reasonably describe the damage and crack closure behavior of concrete under reciprocating loading, and basically overcome the lagging of the reloading path in CDP model.
- By adjusting the compressive stiffness recovery factor $W_c$, the lagging of the reloading path in CDP model can be further eliminated.
- A secondary-developed uniaxial constitutive model of steel is adopted in the layered shell element, and helpful to simulate the pinching of hysteretic curve under reciprocating loading.
According to the simulation methods proposed in this paper, the hysteretic behavior of RC shear wall members under low cycle reciprocating loading can be simulated accurately and efficiently. These methods can also be applied for dynamic elastic-plastic analysis of RC shear wall structures.

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