Seismic damage analysis of RC frames based on La Borderie model

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Abstract. The refined uniaxial La Borderie damage model for concrete is implemented into general-purpose FEA software ABAQUS through the user material subroutine VUMAT. Then, in the platform ABAQUS, the seismic damage analysis of a reinforced concrete (RC) multi-story frame structure is conducted by using the damage model for concrete. The results indicate that the simulation method adopted in the present study can capture the damage and failure process of the RC frame structures. It is effective to identify the weak positions of RC frame structures under earthquake loading.

1. Introduction

The beam-column element model is mostly used to analyze the elastoplastic seismic response of reinforced concrete (RC) frame structures in the practical engineering. With the development of computer software and hardware, fiber beam-column element, as a kind of beam-column element with relatively high accuracy and efficiency, is increasingly studied and applied in the elastoplastic seismic response analysis.

La Borderie damage model is a refined uniaxial elastoplastic damage model for concrete, which can comprehensively describe a variety of typical behaviors of concrete under earthquake or cyclic loading, including tensile cracking, compression plasticity, softening effect, crack closure effect under cyclic load, etc., so it is widely studied [1-3]. In the present paper, based on the interface of user material subroutine VUMAT in ABAQUS, the uniaxial version of La Borderie damage model is embedded in ABAQUS, which enhances the function of ABAQUS in the seismic damage analysis of concrete structures. Then, using the equivalent simulation method of fiber model [4], the elastoplastic damage analysis of a RC multi-story frame structure under the earthquake action is carried out, and the characteristics of the seismic damage evolution process of the structure are discussed in detail.

2. Formulation of the uniaxial La Borderie model

The damage behavior of concrete under tension and compression is described by using the damage variables (i.e. $D_1$ and $D_2$), respectively. The range of damage variable is $[0,1]$ and the damage is irreversible. The total strain of concrete can be expressed as:

$$\varepsilon = \varepsilon' + \varepsilon''$$

(1)

where $\varepsilon'$ and $\varepsilon''$ are the elastic and inelastic strain, respectively. The expressions are given as follows:
\[ \varepsilon^e = \frac{\sigma^+}{E_0(1-D_1)} + \frac{\sigma^-}{E_0(1-D_2)} \]  
\[ \varepsilon^i = \frac{\beta_1 D_1}{E_0(1-D_1)} F'(\sigma) + \frac{\beta_2 D_2}{E_0(1-D_2)} \]

where \( E_0 \) is the elastic modulus; \( \sigma \) is the stress; \( F(\sigma) \) is the crack closure function, describing the special phenomenon of crack closure and stiffness recovery in the process of concrete from tension to compression; \( \beta_1 \) and \( \beta_2 \) are the inelastic parameters; \( \sigma^+ \) and \( \sigma^- \) are simplified as follows:

\[ \sigma > 0, \sigma^+ = \sigma, \sigma^- = 0 \]  
\[ \sigma < 0, \sigma^+ = 0, \sigma^- = \sigma \]  

Unilateral effect is a very important characteristic of concrete. In this model, a function \( F(\sigma) \) is introduced to describe the complex phenomenon. The function and its derivative are defined as follows:

\[ \sigma > 0, F(\sigma) = \sigma, F'(\sigma) = 1 \]  
\[ -\sigma_f < \sigma < 0, F(\sigma) = \sigma \left(1 - \frac{\sigma}{2\sigma_f}\right), F'(\sigma) = 1 - \frac{\sigma}{\sigma_f} \]  
\[ \sigma < -\sigma_f, F(\sigma) = \frac{\sigma_f}{2}, F'(\sigma) = 0 \]  

where \( F'(\sigma) \) is the derivative of crack closure function, \( \sigma_f \) is the crack closure stress, which indicates that the crack is completely closed under this compressive stress.

According to the theory of continuum damage mechanics, the damage evolution of materials should satisfy the thermodynamics law of irreversible process. \( Y_1 \) and \( Y_2 \) are the energy release rates of tensile and compressive damage, respectively. They are defined as:

\[ Y_1 = \frac{\sigma^+}{2E_0(1-D_1)^2} + \frac{\beta_1 F(\sigma)}{E_0(1-D_1)^2} \]  
\[ Y_2 = \frac{\sigma^-}{2E_0(1-D_2)^2} + \frac{\beta_2 \sigma}{E_0(1-D_2)^2} \]

The damage loading function is:

\[ f_i = Y_i - Z_i \]  

where \( Z_i \) is the damage threshold. Before loading, the damage threshold is equal to the initial damage threshold \( Z_i = Y_{i0} \) and damage variable \( D_i = 0 \). During loading, when \( Y_i \) is greater than \( Y_{i0} \), then \( Z_i = Y_i \) and damage increases. The damage evolution is:

\[ D_i = 1 - \frac{1}{1 + \left[ \frac{A_i (Y_i - Y_{i0})}{B_i} \right]^n}, i = 1, 2 \]

where \( A_i \) and \( B_i \) are the material parameters.

The stress-strain hysteretic curve calculated by La Borderie model under cyclic loading is shown in figure 1. It can be seen that the model is very suitable for elastoplastic response analysis of RC structures under earthquake loading.
3. Implementation of the model in ABAQUS

ABAQUS is a general-purpose finite element analysis program. It has user-friendly interface and powerful solvers. It also provides user material subroutine interfaces UMAT and VUMAT, which make the software open and extensible. The uniaxial La Borderie damage model is embedded in ABAQUS, through the corresponding material subroutine VUMAT developed in Fortran. Then in the analysis platform ABAQUS, the seismic damage analysis of RC structures based on fiber beam-column element model can be realized. In VUMAT, the numerical implementation procedure of the uniaxial La Borderie model is as follows.

According to the flow chart (figure 2), under the initial assumption, we calculate $D_1$ and $D_2$. Then use the new value of $D_1$ and $D_2$, and perform the above steps again to test the initial assumption. If the verification is passed, the stress is updated according to the sign of the stress. The flow chart of stress updating is shown in figure 3. However, if the verification is not passed, the iteration continues.

4. Example study

4.1. Analytical model

Taking a 4-story and 3-span RC frame structure as the analysis object, the height of each story of the frame is 4m except that the height of the first floor is 4.5m. The planar layout of the frame is shown in figure 4. The beam and column reinforcement are calculated in the structure design software YJK and imported into the ABAQUS through the built-in tool in YJK. The finite element model of the frame is shown in figure 5. The rigid diaphragm assumption is adopted for simplicity. And the section
discretization of beams and columns in the model is shown in figure 6. C30 is used for concrete and HRB400 is used for reinforcement (according to Chinese Code). The uniaxial La Borderie damage model is used for concrete, and the confinement effect is not considered; the kinematic hardening plastic model is adopted for the reinforcement. Both concrete and reinforcement are simulated by B32 beam element in ABAQUS.

In order to study the characteristics of seismic damage of RC frame structures, the whole process of seismic damage evolution of the frame under the action of El Centro wave was simulated. The bi-directional horizontal seismic wave was input at the base of the structure and the PGA is about 0.34g. The waveform of El Centro earthquake wave recorder is shown in figure 7.
4.2. Result and discussion.
The tensile or compressive damage value of each concrete fiber can be obtained in ABAQUS. However, in the example, the damage contour of the typical fiber is selected to show the tensile damage evolution process of the whole frame. As shown in figure 8(a), the frame was damaged for the first time at 2.3s under the earthquake loading. The damage occurred at the northeastern and southeastern corner columns, mainly. At 3.3s, the damage of the corner columns became relatively serious, as shown in figure 8(b). The damage zone developed rapidly, and most of the beam ends and column ends of the structure in the first floor are damaged at 5.5s, as shown in figure 8(c). It can be observed that the distribution pattern of structural damage zone was basically unchanged from 5.5s to 15.0s (figure 8(d)), however, slight damage in some northern columns still occurred eventually. Therefore, the weak parts of the RC frame are the corner columns in the northeast and southeast, and some strengthening measures will be taken in the detail design of the columns.

![Seismic damage contour of the RC frame](image)

**Figure 8.** Seismic damage contour of the RC frame

5. Conclusions
By using ABAQUS and the interface of user material subroutine VUMAT, the subroutine module of the refined uniaxial La Borderie damage model for concrete is implemented. Then in the platform ABAQUS, the seismic damage evolution process of a RC frame structure is simulated. In view of the evolution of seismic damage, the weak positions of the structure under earthquake loading can be identified quickly.
References

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