Numerical Simulation Analysis of Uniaxial Compression Damage of Reinforced Concrete Columns Based on ABAQUS

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Abstract. Reinforced concrete columns are widely used in construction projects and are mainly damaged by compression. In order to study the characteristics of the damage of reinforced concrete columns under uniaxial compression state, the uniaxial compression damage model of reinforced concrete columns is established by introducing the element deletion algorithm, concrete damage plasticity model (CDP) based on ABAQUS software. The results show that: (1) Under the load, the damage starts at the end of the specimen and expands to the middle, finally forming a through diagonal crack. The diagonal cracks are at 45° to the bottom surface. (2) At the beginning of load loading, the reinforcement has not yet reached the yield strength, and the restraining effect of the hoop on the concrete is not yet obvious. (3) With the increase of load, the hoop reinforcement and longitudinal reinforcement successively yielded. Local damage occurs in the concrete protective layer until the specimen fractures.

Keywords: Reinforced concrete column; Uniaxial compression; ABAQUS; CDP model; Element deletion algorithm.

1. Introduction

Experimental and numerical methods are mainly used for the study of reinforced concrete columns, and numerical simulation analysis is usually available with finite element software such as ABAQUS, Ansys and OpenSEES.

Xu [1] studied the practicality of the finite element reinforcement method using Ansys software, focusing on several key issues in the data transfer process and the optimization of reinforcement analysis, and developed a visual management system for reinforcement design problems, which was applied to the reinforcement design of three major projects. Xiao et al.[2] used ABAQUS software to establish a reinforced concrete column model under proposed static loading, and analyzed in depth the concrete column, the stress-strain characteristics of the reinforcement and the plastic energy dissipation distribution mechanism. Xue et al.[3] established corresponding finite element models for four reinforced concrete columns using OpenSEES, and investigated the effects of material intrinsic parameters, reinforcement ratio and axial compression ratio on the load carrying capacity limit and ductility of reinforced concrete columns. Hu et al.[4] conducted a numerical simulation study for cross-shaped reinforced concrete column axial compression test, and applied ABAQUS to establish a finite element model to investigate the effects of hoop spacing, concrete strength and reinforcement ratio on its performance. Liu et al.[5] To investigate the fire resistance performance of reinforced concrete columns after earthquake damage, the fire resistance limit model after earthquake damage was established and verified using ABAQUS. To investigate the effect of carbon fiber cloth restraint on the flexural performance of reinforced concrete columns, Yingnan Liu [6] compared the results of damage morphology and hysteresis curve of CFRP reinforced concrete columns obtained from finite element simulation with the experimental results, and the calculated results matched well with the experimental results, which verified the feasibility of the finite element software and established a suitable finite element model. Hussain et al.[7] used finite element analysis of SFRP materials (glass and carbon), SFRP thickness (3mm and 5mm), and SFRP structural variables to explain the nonlinear behavior of the externally applied SFRP technology on the enhanced ultimate load carrying capacity of reinforced concrete deep beams. Almusallam et al.[8] established a 3D finite element model of the structure using LS-DYNA to investigate the erosion and damage of the reinforced concrete structure under different explosion scenarios.

However, the above studies have not yet addressed reinforced concrete column damage. In view of this, this paper uses ABAQUS software to introduce the element deletion algorithm, combined with the CDP model to establish the damage model of reinforced concrete columns under uniaxial compression. The numerical method is of guidance for the study of structural safety and reliability.

2. Model building

2.1. Computational model

The reinforced concrete column size is 150mm×150mm×450mm (Figure 1). The model adopts the display dynamic analysis method and divides a total of 10125 grid elements. The model is vertically constrained at the bottom, and the upper surface is loaded by displacement, with a maximum displacement of 80mm and a loading rate of 0.667mm/step (Figure 2). The model is homogeneous in each of the calculation ranges. The samples were designed with reference to the following regulations: GB50010-2010 and JGJ138-2016 [9-10].

C50 concrete with 16mm diameter HRB600 was used as longitudinal reinforcement, with four bars. The hoop reinforcement is HRB400 with diameter of 8mm, the spacing between hoops is 150mm, the protective layer thickness is 20mm, the reinforcement ratio is 3.57, and the hoop ratio is 1.78 (Figure 3).

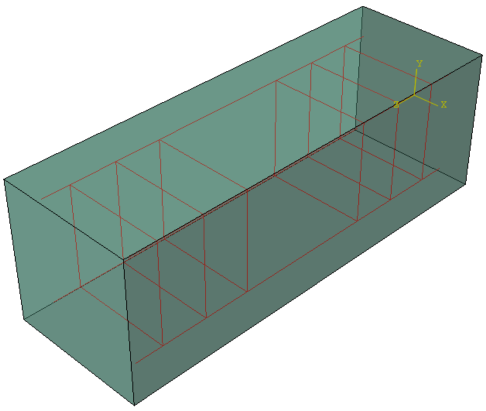


Figure 1 Calculation model

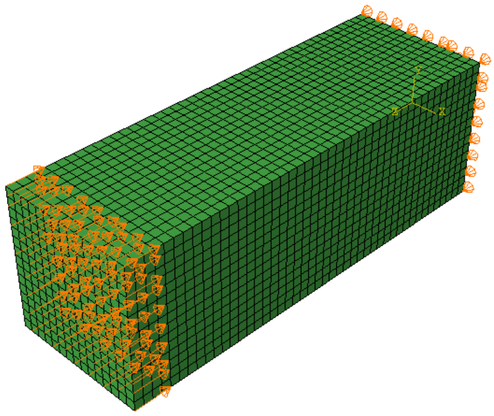
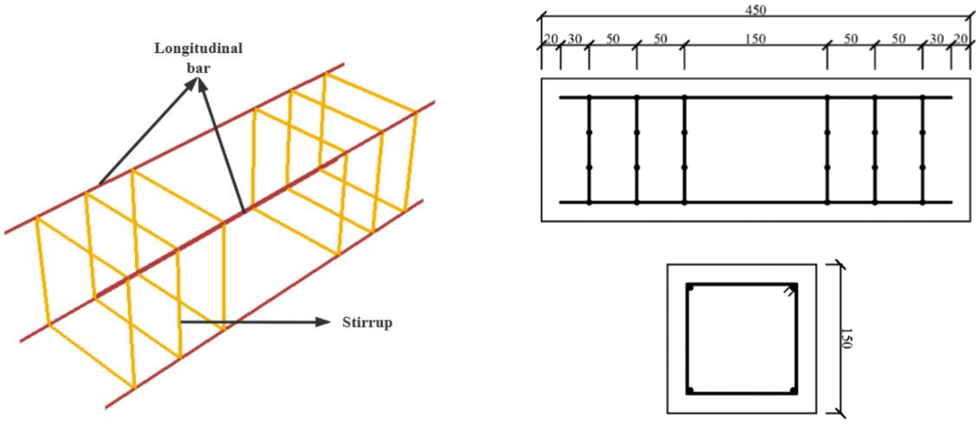


Figure 2 Mesh model



(a) Reinforcing steel model (b) Column size and reinforcement

Figure 3 Reinforcement model

The mechanical properties of reinforcing steel are shown in Table 1. The mechanical properties of concrete are shown in Table 2. Mechanical properties experiments were conducted in accordance with the Standard for *GB/T50081-2019* [11].

Table 1 Mechanical properties of steel bars

Reinforcing Steel Grade	Diameter (mm)	Yield strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
HRB600	16	661.12	3.57	20.4
HRB400	8	426.47	1.78	17.5

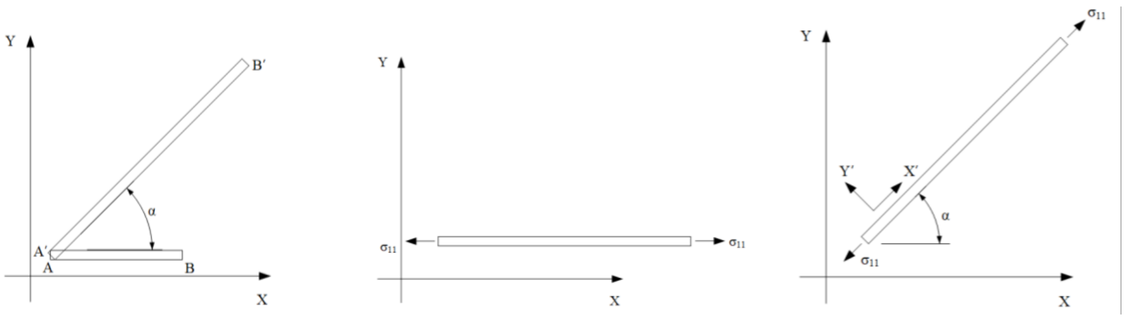
Table 2 Mechanical properties of concrete

Concrete strength grade	Cube compressive strength (MPa)	Modulus of elasticity E/GPa	Poisson's ratio μ	Axial Compressive strength (MPa)	Modulus of elasticity (GPa)
C50	49.30	3.50	0.20	31.64	34.4

2.2. Element deletion algorithm

The element deletion function itself is a method designed to overcome the shortcomings of the finite element itself. Since the finite element itself is based on the mechanics of continuous media, and in the mechanics of continuous media, the object under study needs to be continuous, i.e., the material domain is continuous in space. In the framework of such theoretical assumptions, the element itself does not disappear, and the deletion of the element is associated with damage, the mechanism of which can generally be summarized in two cases, i.e., tensile damage and shear damage. However, in practice, the existence of damage fracture will inevitably make some elements disappear or fail completely, so in order to be able to simulate this situation, ABAQUS software platform provides element deletion function for use.

Consider the rod shown in Figure 4(a), which is stretched and rotated from the original position AB to the new position A'B'. This deformation can be achieved in two stages: first stretching the rod, as shown in Figure 4(b). Then it is rotated by applying a rigid body rotation to it, as shown in Figure 4(c). The stress in the rod after stretching is, which is constant during the rigid body rotation. The coordinate system rotated due to rigid body rotation is a co-rotating coordinate system. Therefore, the stress tensor and state variables are calculated directly.



(a) Rod position transformation Figure 4(b) Rod stretching diagram (c) Rod rotation diagram

Figure 4 Element deletion method schematic diagram

2.3. Failure criterion

In the CDP model, the uniaxial tensile and compressive responses of concrete are characterized by damage plasticity, and the parameters related to the CDP model are calculated using the Standard for *GB50010-2010* [9] (Table 3).

Table 3 CDP model parameters

Compressive strength (MPa)	Inelastic strain ($\times 10^{-3}$)	d_c	Tensile strength (MPa)	Strain of cracking ($\times 10^{-3}$)	d_t
21.06015	0	0	2.11284	0	0
22.68367	1.862E-05	0.0026755	2.64	1.965E-05	0.0611993
24.31216	4.307E-05	0.01009253	2.50677	4.634E-05	0.14635663
25.93727	7.508E-05	0.02192468	2.37329	6.202E-05	0.1958968
27.55771	0.00011767	0.03840388	2.23975	7.65E-05	0.24108453
29.19453	0.00017771	0.06104518	2.10591	9.081E-05	0.28478415
30.82572	0.00027074	0.09364065	1.97307	0.00010528	0.32767213
32.4	0.00055351	0.17846276	1.83938	0.00012046	0.37092191
30.76493	0.00090922	0.2616336	1.70595	0.00013654	0.4145507
29.12673	0.00111615	0.30483303	1.57339	0.00015379	0.45860408
27.48783	0.00130692	0.3431696	1.44038	0.00017283	0.5037065

The CDP model is combined with a element deletion algorithm to delete elements without carrying capacity. When using the element deletion algorithm, the state variable should be set to a value of 1 or 0. A value of 1 indicates that the element is active, while a value of 0 indicates that the element is disabled and deleted.

Failure criterion:

$$\bar{\varepsilon}_c^{pl} \geq 0.05 \tag{1}$$

The damage flow diagram is shown in Figure 5.

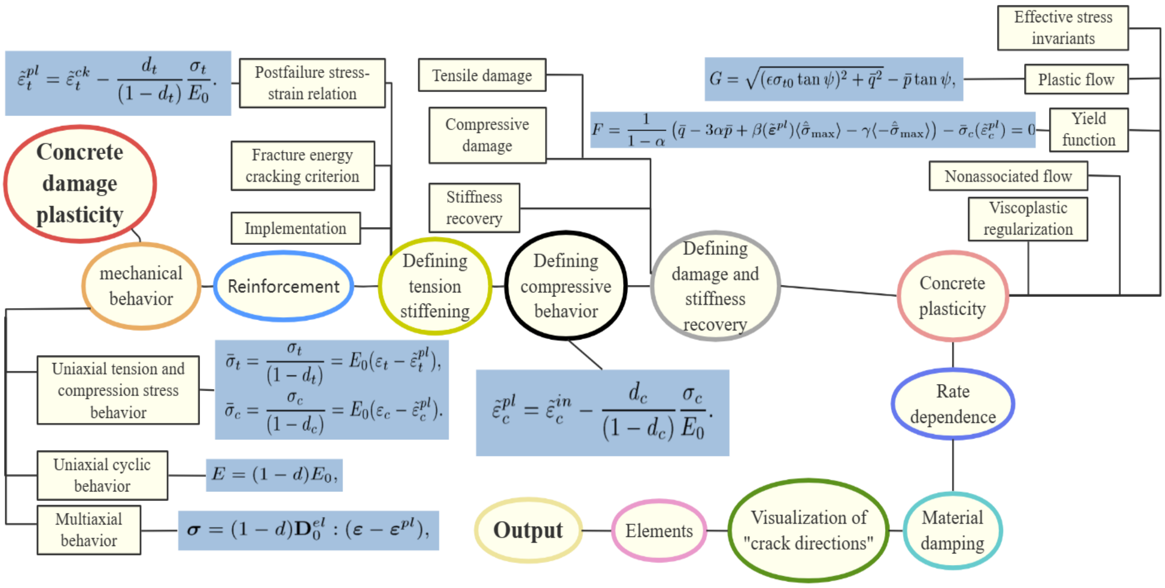


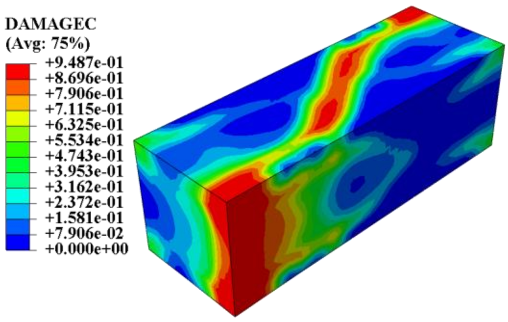
Figure 5 Failure flow chart

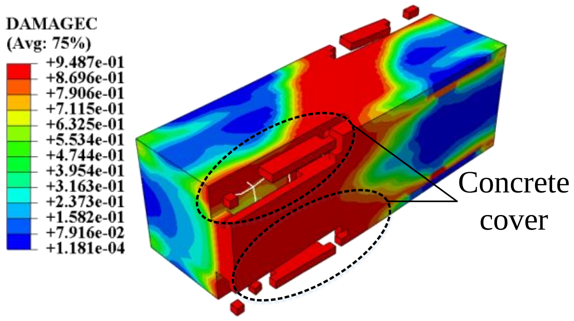
3. Analysis of results

Under vertical loading, when the stress state of a element of the model satisfies the quasi-damage criterion, the element is identified as damaged and deleted, i.e., it is withdrawn from the next load step of the iterative calculation. This iteration is repeated until the calculated residuals of all elements satisfy the convergence criterion, and the stress and deformation results of the elements are output.

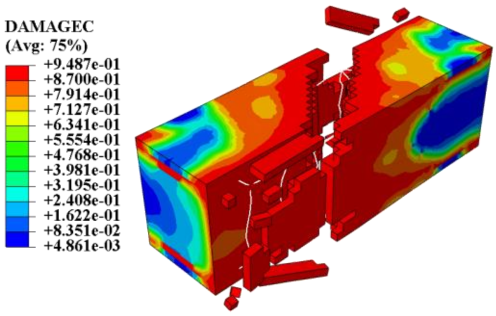
Reinforced concrete column damage begins when the stress in the reinforcement reaches yield strength and ends when the concrete undergoes shear damage. At the early stage of loading (Figure

6(a)), the reinforcement has not yet reached yield strength, the restraining effect of the hoop on the concrete is not yet obvious, and the stresses in the protective layer and the core concrete are basically the same. The stresses at both ends of the specimen keep increasing and stress concentration occurs. With the increasing vertical load, the element at the end of the specimen was the first to reach the damage condition and was removed, and vertical cracks appeared on both sides of the end of the specimen (Figure 6(b)). At this time, the longitudinal reinforcement between the hoop bars is compressed and flexed outward, and the concrete in the middle of the height of the specimen is the main stressed part. The reinforcement reaches the compressive yield strength and the concrete protective layer is damaged. At the later stage of loading, the element in the middle of the specimen reached the damage condition was removed and a through main diagonal crack was formed (Figure 6(c)), and the diagonal crack was at 45° to the bottom surface.





(a) Initial-loading U=6.954×10^{-2} mm (b) Mid-loading U=43.50 mm



6(c) Post-loading U=59.40mm

Figure 6 Damage diagram of reinforced concrete prismatic body

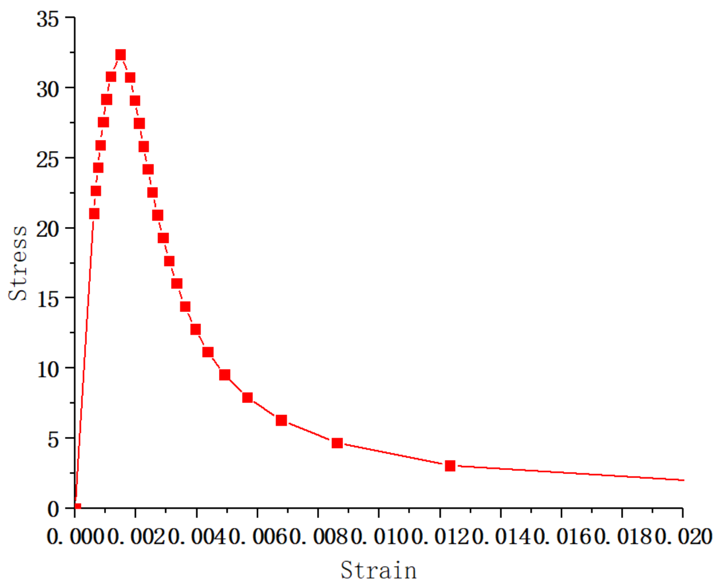


Figure 7 Stress-strain curve

Extracting the concrete stress-strain curve from the model (Figure 7), the peak compressive strength of concrete is 32.52 MPa, and the peak strain at this time is 0.002. The specimen is compressed in the early stage, and the concrete is stressed in concert with the reinforcement, which plays a major role. In this stage, the concrete deformation is small. After the yielding of the reinforcement, the concrete stress increases more, the crack at this stage continues to develop and the internal energy accumulates, when the stress value is greater than the compressive strength of the concrete, the concrete is crushed and the specimen is damaged. After that point, the fissures continue to expand and penetrate, and eventually macroscopic cracks are formed.

4. Conclusion

(1) Under the load, stress concentration occurs at both ends of the specimen, and the damage starts at the end of the specimen and expands to the middle, eventually forming through diagonal cracks. The diagonal cracks are at 45° to the bottom surface.

(2) load loading at the beginning, the reinforcement has not yet reached yield strength, hoop restraint on the concrete is not yet obvious. And with the increase of load, the longitudinal bars between the hoop bars outward compression yield, the concrete in the middle of the height of the specimen is the main part of the force, the reinforcement reaches the compressive yield strength, continue to load, the concrete protective layer occurs local damage.

(3) The results of this paper on the analysis and study of reinforced concrete compressed columns can provide a theoretical basis for the analysis of damage characteristics of the actual specimens.

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