Study on the Uniaxial Tensile Fracture of Reinforcement Based on ABAQUS Secondary Development

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Abstract. Taking Chinese HRB400 reinforcement as the research object, the maximum tensile stress criterion was embedded into the VUSDFLD subroutine for secondary development based on the ABAQUS platform. Additionally, the element deletion algorithm was introduced to simulate the uniaxial tensile failure of HRB400 reinforcement. The study found that the numerical results were in good agreement with the experimental results, providing a reference for the numerical model research of reinforced concrete structures.

Keywords: HRB400 reinforcement; VUSDFLD subroutine; ABAQUS platform; Uniaxial tensile failure.

1. Introduction

With the development of modern society, the importance of reinforcement as a key construction material has become increasingly evident. Currently, significant progress has been made in the numerical simulation studies of reinforcement. Liu et al. [1] used open-circuit potential tests, electrochemical impedance spectroscopy, potentiodynamic polarization tests, and Mott-Schottky curve tests to study the passivation behavior, chloride corrosion resistance, and corrosion mechanisms of HRB400 carbon steel reinforcement, 304 austenitic stainless steel reinforcement, and 2304 austenitic-ferritic duplex stainless steel reinforcement in marine environments. Li et al. [2] established a refined finite element model for HB-FRP reinforced RC beams based on the ABAQUS finite element software, investigating the flexural performance of concrete (RC) beams strengthened with hybrid-bonded FRP (HB-FRP). Zhang [3] performed forward simulations of quality detection processes for double-layer reinforced linings using the open-source simulation software gprMax based on the finite-difference time-domain method and a 1500 MHz central frequency antenna, and developed a double-layer reinforced lining model for testing. Wang et al. [4] conducted vertical axial compression simulation tests on one normal concrete column and three UHPC-reinforced concrete columns to study the impact of ultra-high-performance concrete on the axial compression performance of reinforced concrete columns. Liu [5] applied theoretical knowledge in conjunction with finite element software to establish corresponding finite element models to simulate and analyze the failure process of flexible fiber reinforced concrete box girders. Kou et al. [6] performed numerical simulations on damaged RC columns reinforced with different thicknesses of HDC using ABAQUS and analyzed their mechanical behavior. Based on the analysis of experimental and simulation data, they proposed an ultimate bearing capacity calculation method for damaged RC columns reinforced with HDC, considering the influence of the strength utilization coefficient of HDC materials. The research results provide a useful reference for practical engineering applications using this reinforcement method.

Based on these research findings, this paper focuses on HRB400 reinforcement, embedding the maximum tensile stress criterion into the VUSDFLD subroutine for secondary development, and introducing the element deletion algorithm to simulate the uniaxial tensile failure of HRB400 reinforcement. This work provides a reference for the further development of numerical models for reinforced concrete structures.

2. Model establishment

2.1. HRB400 reinforcement model

In this section, the model of HRB400 reinforcement is established (**Fig**. 1). The geometric parameters of the steel bar are determined based on standard dimensions, with the length set to 120 mm and the diameter at 18 mm. The material properties for HRB400 steel reinforcement include a density of 7500 kg/m³, a Poisson's ratio of 0.3, an elastic modulus of 202 GPa, a yield strength of 456 MPa, and a tensile strength of 640 MPa (**Table** 1).

The meshing is performed using a structured method, and the total number of elements generated is 13683, with the element type set as C3D8R, which is an 8-node linear brick, reduced integration element. The boundary conditions are defined by applying vertical constraints at one end of the steel bar model, while the opposite end undergoes displacement-controlled loading at a rate of 0.05 mm/min to simulate the tensile process.

This setup ensures that the HRB400 steel bar's behavior under uniaxial tension can be accurately captured, providing insights into its stress-strain characteristics and fracture mechanics.

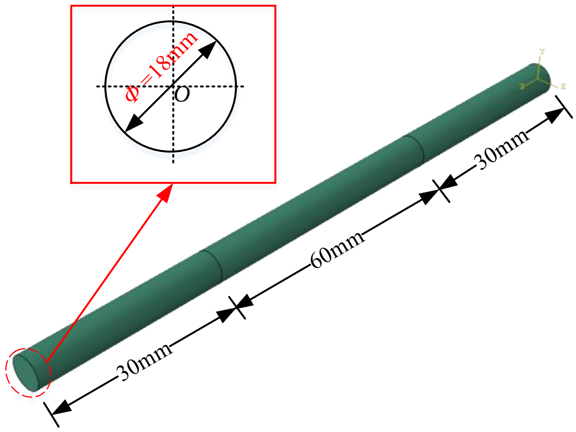


Fig. 1 Numerical simulation of the HRB400 rebar

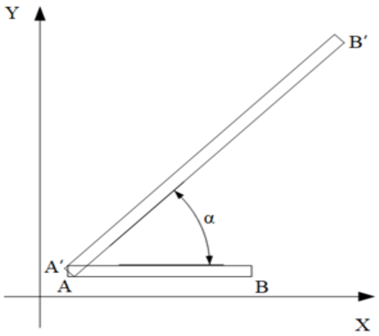
Table 1. Mechanical parameters of HRB400 rebar

HRB400 rebar	ρ kg/m^3	E GPa	μ	f_y MPa	f_t MPa
	7500	202	0.3	456	640

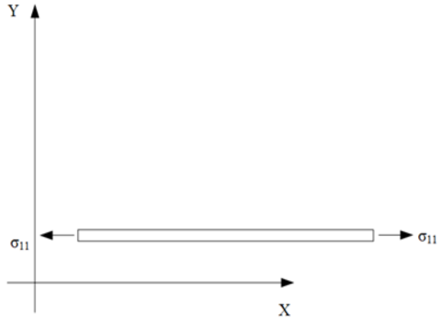
2.2. Element deletion algorithm

The element deletion algorithm is used to simulate the fracture effect of the reinforcement. The element deletion function is a method designed to overcome the inherent limitations of the finite element method (FEM). FEM is based on the mechanics of continuous media, where the objects of study need to be continuous, meaning the material domain is continuous in space. Under this theoretical assumption, elements themselves do not disappear, and their absence is related to damage. Damage mechanisms can generally be summarized into two types: tensile damage and shear damage. However, in real-world scenarios, due to the presence of damage and fractures, some elements inevitably disappear or fail completely. To simulate such fractures, the ABAQUS platform provides an element deletion function.

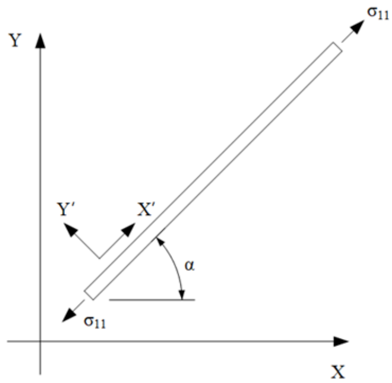
Consider the bar shown in **Fig**. 2(a), which stretches and rotates from its original position AB to the new position A'B'. This deformation can be achieved in two stages: first, stretching the bar, as shown in **Fig**. 2(b), and then rotating it by applying rigid body rotation, as shown in **Fig**. 2(c). The coordinate system that rotates due to rigid body rotation is called the corotational coordinate system. Therefore, the stress tensor and state variables are directly calculated in this framework [7].



(a) Rod displacement



(b) Rod tension



(c) Rod rotation

Fig. 2 Principle diagram of the element deletion algorithm

2.3. Fracture criteria

The maximum tensile stress criterion, also known as the maximum yield stress criterion, is a typical damage criterion used to assess composite materials. The fundamental principle of the maximum tensile stress criterion is that when the stress exceeds a certain value, the material may fail. Therefore, in practice, it is sufficient to ensure that the stress does not exceed a certain threshold to guarantee the safety of the structure.

The maximum tensile stress of the element is given by [8, 9]:

$$f = |\sigma_1| - \sigma_t \tag{1}$$

In the formula, $|\sigma_1|$ represents the maximum principal stress of the material, while σ_t denotes the tensile strength of the material. In this numerical simulation, the value of σ_t is taken as f_t=640MPa.

3. Results analysis

3.1. Model validation

As shown in **Fig**. 3, the numerical simulation curve of HRB400 steel rebar closely matches the experimental curve. The numerical method proposed in this paper effectively reflects the uniaxial tensile performance of HRB400 steel rebar. The stress-strain curve of the rebar can be divided into three stages: (1) the elastic stage, (2) the yield plateau stage, and (3) the strain hardening stage.

In the initial stage of tension, the stress and strain of the rebar exhibit a positive correlation (OA stage). Upon reaching point A (elastic limit), the rebar enters the yield plateau (AB stage). During this stage, the stress level of the rebar develops steadily. After point B, the material enters the strain hardening stage (BC stage). When point C is reached, the material attains its tensile limit and fractures.

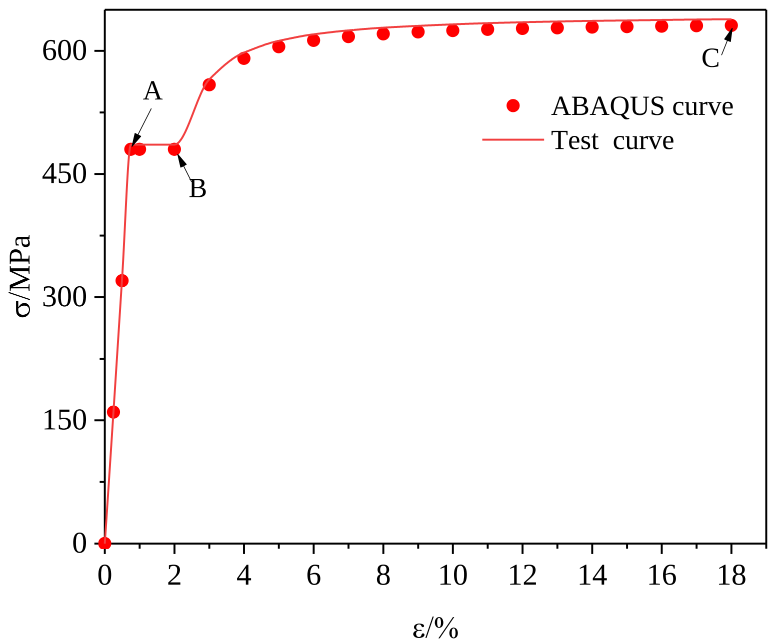


Fig. 3 Stress-strain curve of HRB400 rebar

Based on **Fig**. 3, the numerical stress-strain curve for HRB400 under uniaxial tension closely matches the experimental curve. Additionally, the fracture location in the numerical model is near the end of the model (**Fig**. 4), which aligns with the experimental results. This outcome validates the effectiveness of the numerical method proposed in this paper.

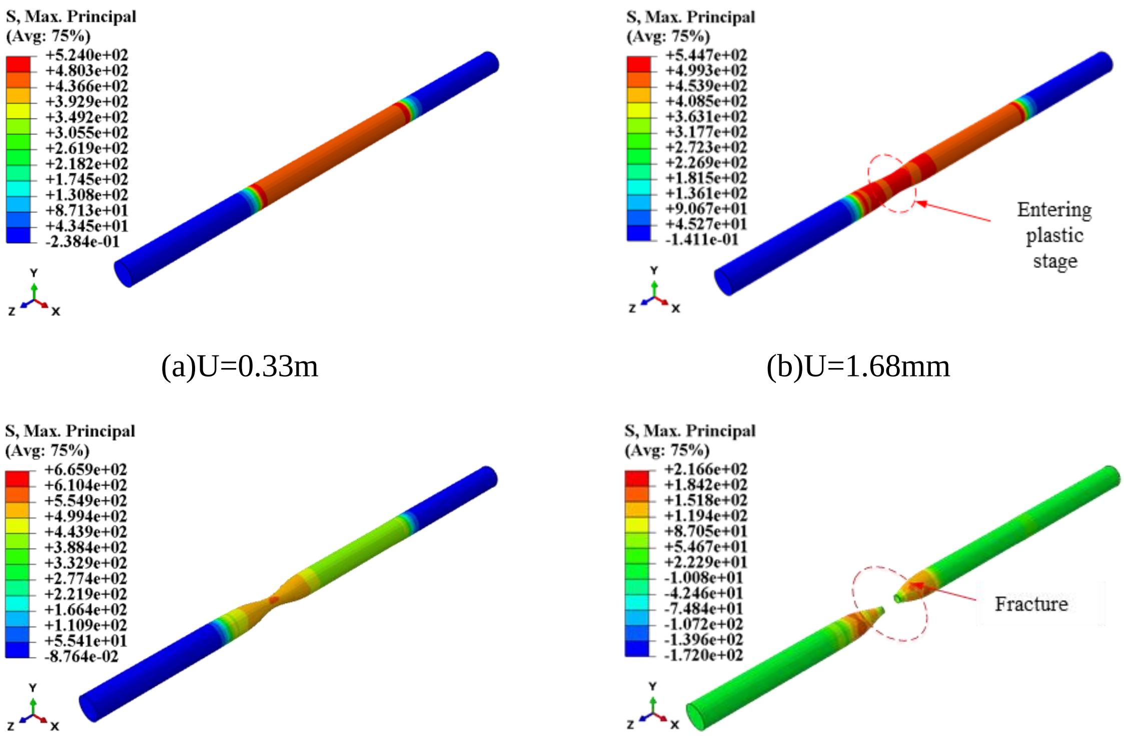
(a) Test result [10]

(b) Numerical result

Fig. 4 Fracture result

3.2. Analysis of reinforcement fracture evolution

As shown in **Fig**. 5, during the initial stage of reinforcement stretching, the material is in the elastic phase, and the stress value of the material continuously increases (U < 0.33 m). As the loading rate increases, the reinforcement enters the plastic phase. At this point, the maximum principal stress of the reinforcement is 544.7 MPa, with a displacement value of U = 1.68 mm. With the material's strengthening ability continuously enhancing, the maximum principal stress of the reinforcement keeps increasing. When the maximum tensile stress reaches f_t=640 MPa, the model element reaches the deletion condition, resulting in fracture of the reinforcement (U = 3.23 mm).



(a)U=0.33m (b)U=1.68mm

(c)U=2.67mm (d)U=3.23mm

Fig. 5 Evolution of Reinforcement Fracture

4. Conclusions

This study utilized ABAQUS as the platform to incorporate the maximum tensile stress criterion into the subroutine VUSDFLD, alongside implementing a unit deletion algorithm to establish a uniaxial tensile numerical model for HRB400 reinforcement. The conclusions are as follows:

(1) The stress-strain curve and fracture results of the numerical model closely align with the experimental results, demonstrating the effectiveness of the proposed numerical method.

(2) During the tensile process, the reinforcement undergoes three phases: the elastic phase, the yield plateau phase, and the strengthening phase.

(3) This research primarily focused on the numerical simulation of uniaxial tensile behavior of the reinforcement, while further studies on dynamic impact numerical simulations of the reinforcement are warranted.

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