



Numerical simulation of the fiber fragmentation process in single-fiber composites

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ABSTRACT

This paper attempts to simulate the process of fiber break in single-fiber composite fragmentation test (SFCF). The ensued stress redistribution in fiber, matrix and interface after the fiber break is also researched. A new simulation method based on the user subroutine: “User subroutine to redefine field variables at a material point (USDFLD)” in the general finite element method (FEM) software ABAQUS is proposed. The subroutine is used for the definition of the fiber material constitutive model and is programmed in FORTRAN. It is called by ABAQUS. So the damage mode of the fiber break is simulated by the method. The forms of stress redistribution in fiber, matrix and interface are also obtained in the simulation. Then the T300/epoxy single-fiber composite is fabricated and the single-fiber composite fragmentation test is done. The simulation method and results are proved to be appropriate by the comparative analysis with the experiment.

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1. Introduction

Fiber-reinforced polymer matrix composites have been widely used as load-bearing materials in various industries such as aeronautics, astronautics, military defense and transportation due to their superior mechanical properties. However, this kind of materials has a very complicated damage process including fiber break, matrix yield, matrix crack, and interfacial debonding until final failure [1,2]. To ensure the reliability of structures made from these composites, detailed understanding of the damage behaviors is required.

In order to completely understand the damage process in fiber-reinforced composites, many efforts have been made, especially the single-fiber composite fragmentation test firstly proposed by Kelly and Tyson [3]. This test has a significant analogy with practical composites when subjected to uniaxial tension along the fiber direction because it exhibits the fundamental damage modes that are present in the multiple fiber composites in service. So it has been widely used as a powerful tool to conduct micromechanics studies on the interaction between the fiber and its surrounding matrix and characterize the damage process at the constituent level [4–6]. The specimen of the SFCF test is shown in Fig. 1a.

In the SFCF test, with a single fiber embedded in polymer-matrix, the dog-bone specimen is loaded in tension in the axial direction. Once the specimen begins to stretch, tensile load is transferred from the matrix to the fiber through shear stress at the interface and builds up. When the stress exceeds the strength of the fiber, the fiber will break, as shown in Fig. 1b. The process

continues and the fiber breaks into smaller fragments. When the load applied to the specimen can no longer produce a stress in the fiber high enough to reach its breaking stress, the state called as “mechanical saturation” is achieved and the test is finished, as shown in Fig. 1c.

During the SFCF test, the stress in fiber, matrix and interface near the fiber fracture will redistribute. The resulting damage modes such as matrix yield or crack and interfacial debonding will occur depending on interfacial properties. For low interfacial strength, interfacial debonding occurs. For intermediate interfacial strength, matrix yield or crack occurs, which delays interfacial debonding. For high interfacial strength, debonding does not occur and deformation is controlled by matrix yield or crack, as shown in Fig. 2.

The analysis of the SFCF test can be roughly divided into two types: analytical or numerical methods.

In the analytical methods, theory models can be roughly divided into two approaches: one-dimensional analytical models based on the shear-lag theory and two-dimensional analytical models based on an axisymmetric analysis.

The first one-dimensional elastic load-transfer model was developed by Cox [7]. The limitations of Cox’s model have been discussed by Nairn [8]. Then Kelly [9], Piggot [10] have also researched the stress transfer between the fiber and the matrix based on the one-dimensional theory. The typical one-dimensional micromechanics model is presented by Piggot [10].

A relatively early two-dimensional micromechanics model for the SFCF test has been presented by Whitney and Drzal [11]. Then McCartney [12], Nairn [8] and Wu and co-workers [13–16] have respectively developed more complicated ones. The most representative and commonly used model is the Wu’s model.

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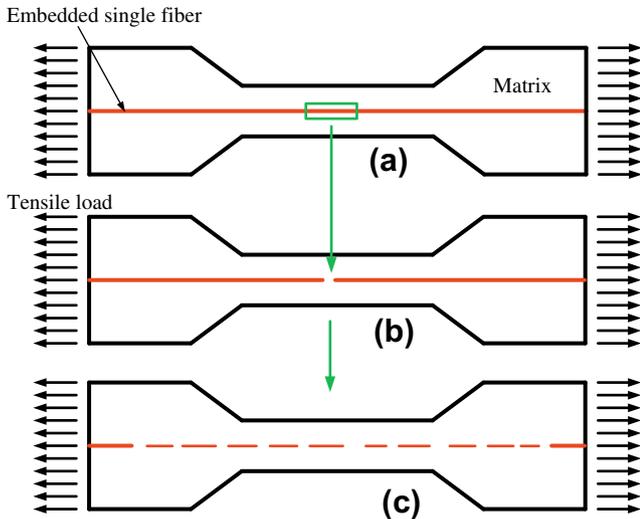


Fig. 1. Specimen and fiber break in SFCF test: (a) typical dog-bone specimen; (b) first fiber break; (c) saturation state of break process.

Based on these models, the stress distribution in the fiber axial direction and at the fiber/matrix interface along the “saturation fragmentation length” can be obtained. And the interfacial strength is thus determined. But the analytical method is difficult for the research of damage process and modes in the SFCF test. So they are appropriate for the analysis of stress state before failure. On the contrary, the whole process of the SFCF test including stress transfer, stress distribution and the mode of damage and failure all can be realized by the numerical method.

In the numerical methods, the general FEM software, such as ANSYS or ABAQUS is often used. Most researches also focus on the numerical solutions of the fiber/matrix stress transfer including elastic stress transfer and plastic stress transfer [17]. In addition, the effect of micro damage modes, such as matrix yield, matrix crack and interfacial debonding, on the stress transfer has been studied [18–25]. But the simulation of damage mode in the SFCF test is seldom done. As for the simulation of the fiber break and the interfacial debonding, the ‘cohesive element’ in ABAQUS is used [26–28]. But the property of such type of element is difficult to determine. So the simulation of these damage modes is difficult to be realized in general FEM software.

Fortunately, in ABAQUS many user subroutines are provided, such as subroutine USDFLD and “User subroutine to define a material’s mechanical behavior (UMAT)”, to solve the user’s own problems easily. For example, “the fiber break process” in the SFCF test is a special phenomenon. So the appropriate subroutine should be chosen to simulate successfully. Our goal is to simulate the process of the fiber breaks and the ensued stress redistribution near the fiber fracture based on user subroutine USDFLD in the general FEM software ABAQUS.

The rest of this paper is organized as follows: In Section 2 the SFCF test is done. In Section 3 we present our numerical model. In Section 4 the simulation results and discussion are presented. In Section 5 we summarize our work.

2. Experiment and results

2.1. Materials and properties

For the SFCF experiment, T300 carbon fiber (provided by Toray Corporation of Japan) was used to fabricate the single-fiber reinforced epoxy composite. The failure strength of fiber is consistent

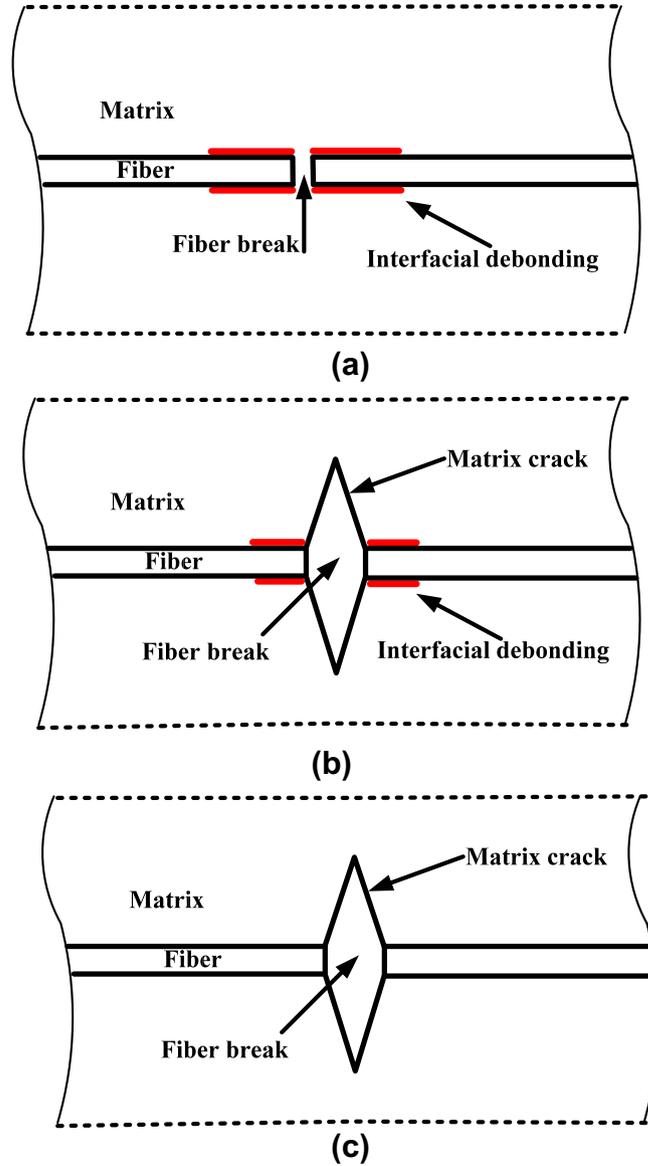


Fig. 2. Typical microscopic damage of different interfacial strength in SFCF test: (a) low interfacial strength; (b) intermediate interfacial strength; (c) high interfacial strength.

with Weibull distribution such that the cumulative failure probability of a fiber of length L is given by

$$F(\sigma) = 1 - \exp[-L(\sigma/\sigma_0)^m] \quad (1)$$

where m , σ_0 are Weibull shape and scale parameters respectively.

Phenol-A epoxy resin (Epikote 128), curing agent triethyleneteramine (TETA) and flexibilizer were used as the matrix system in a 100/30/5 ratio. The experimental stress/strain curve of the present resin matrix is shown in Fig. 3.

The material properties of the fiber and the matrix used in the test were listed in Table 1.

2.2. Specimen preparation

Firstly the single fiber is pulled out from fiber bundle and fixed in the mold by the plastic. During this process the fiber should be kept straight and flat and located in the centre of the mold. Secondly, the resin is injected into the mold and cured in room

temperature. Finally the dog-bone specimen is made by laser beam, as shown in Fig. 4 (the fiber in the specimen is not seen because its diameter is as small as 7 μm).

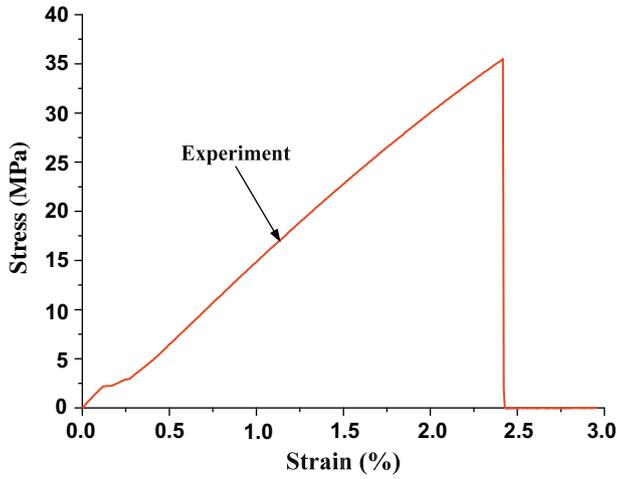


Fig. 3. The stress/strain curve of matrix tension.

Table 1
Material properties for carbon fiber and epoxy matrix.

Parameter	Value
Fiber modulus, E_f (GPa)	232
Fiber Poisson's ratio, γ_f	0.2
Fiber characteristic length, L (mm)	50
Fiber mean strength, σ (GPa)	3.15
Matrix modulus, E_m (GPa)	1.46
Poisson's ratio, γ_m	0.3
Weibull distribution shape parameter, m	3.24
Weibull distribution scale parameter, σ_0 (GPa)	2.34

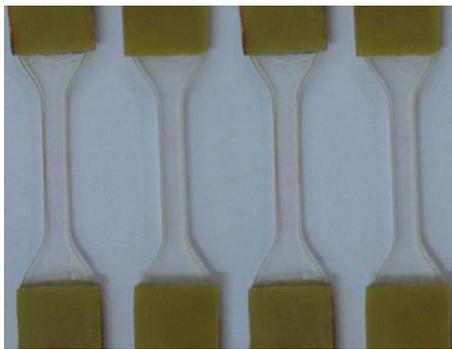


Fig. 4. Dog-bone specimens.

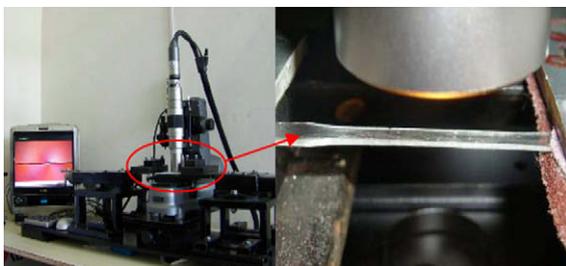


Fig. 5. Test device.

2.3. Experiment and result

The SFCF test was done in the Centre for Composite Materials and Structures of Harbin Institute of Technology. The device is shown as Fig. 5 and the parameters of test device are listed in Table 2.

Table 2
The parameters of test device.

Loading equipment	Load precision	0.02 mm
	Load range	40 mm
	Maximum load	500 N
Polarized micrograph	Spectral range	350–700
	Average projected rate	40%
	Extinction ratio	1/1000

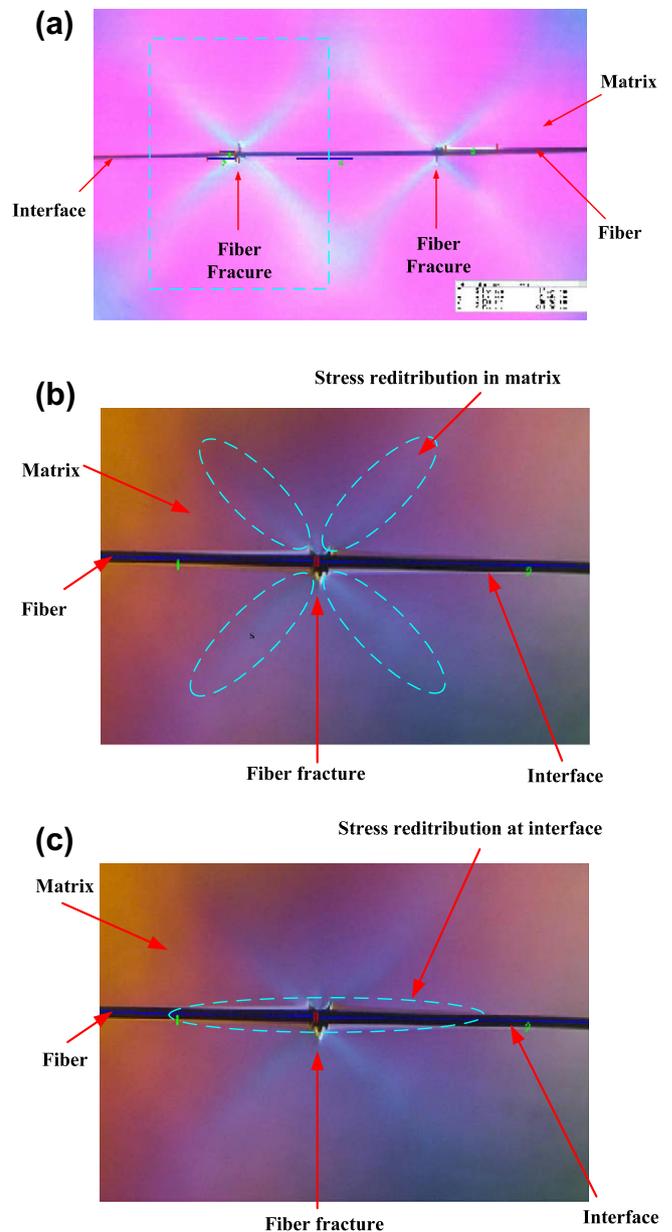


Fig. 6. (a) Polarized micrograph around fiber fracture; (b) the redistribution of stress in matrix; (c) the redistribution of stress at interface.

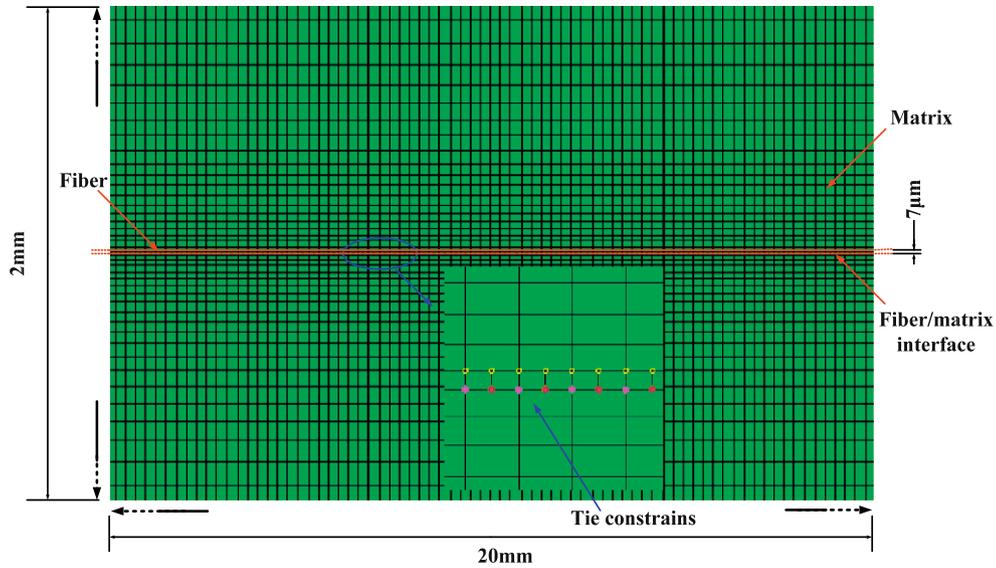


Fig. 7. The finite element model of SFCF.

The displacement load was applied on the end of the specimen. Loaded specimen was periodically stopped to observe the fiber fracture and the stress redistribution in matrix and at the fiber/matrix interface near the fiber fracture under the polarizing microscope.

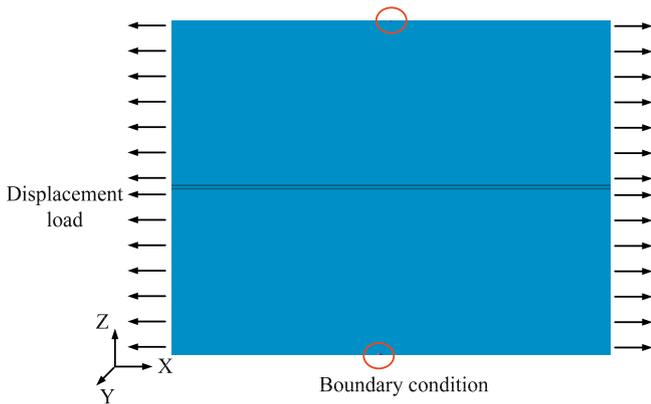


Fig. 8. The displacement load and constrain of SFCF test.

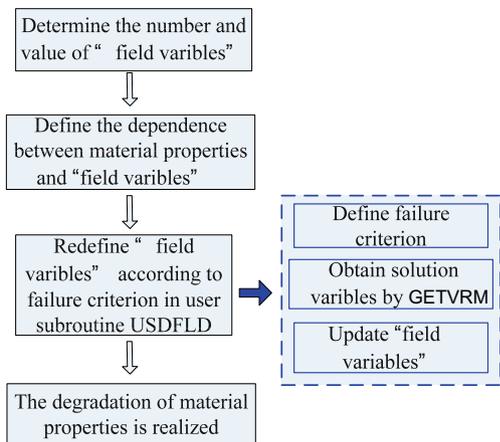


Fig. 9. The realization of the fiber break.

The typical polarized micrograph around the fiber fracture is shown in Fig. 6a. With the fiber break, the stress will redistribute in the matrix and at the interface near the fiber fracture. The redistribution of stress in matrix is shown as Fig. 6b. The cross shape light band is obvious around the fiber fracture, which means stress in these zones of matrix is larger. Similarly the redistribution of shear stress at interface of fiber/matrix is shown as Fig. 6c.

3. Numerical simulation

3.1. SFCF finite element model

The general FEM software ABAQUS is used to create the finite element model. The pre-treatment process including geometry model, material model, mesh, element type, and boundary condition is same to all other general softwares. For every step, the detail information will be described as follows.

A 2D plane finite element model representing the specimen is employed. The fiber diameter is set to be 7 µm; the outer radius of the matrix is 1 mm so that the free-edge does not affect the fiber break process in the embedded fiber. A 4-node bilinear plane stress

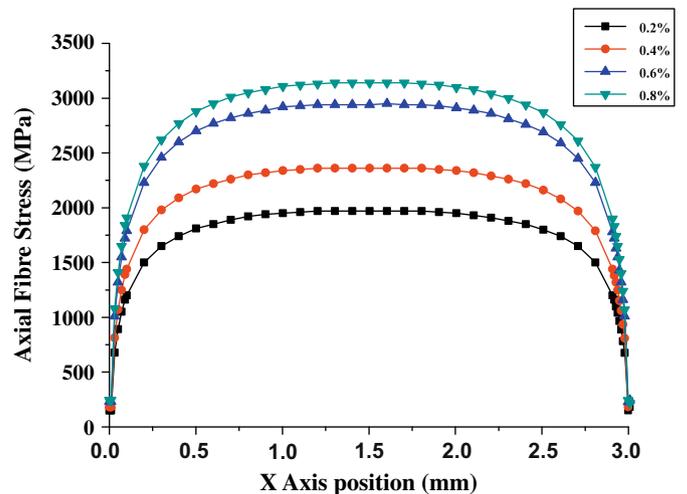


Fig. 10. The axial stress distribution in the fiber before fiber break.

quadrilateral with reduced integration and hourglass control element (CPS4R) is used for the fiber and the matrix. In the axial direction, the number of the fiber element is much larger than that of the matrix. So the “tie constrains” concept should be used at fiber/matrix interface for the different mesh seed number. (Simultaneously it is suit for the hypothesis of perfect bonded fiber/matrix interface.) In the radial direction, one element is enough for the fiber, but biased and gradually reduced elements are used for the matrix, because the radius of the fiber is much smaller than the matrix’s. The finite element model is shown in Fig. 7.

As for material models, the fiber is considered as isotropic-elastic material with “field variable” dependence. “Field variable” is a kind of user defined variable, which can be redefined as the func-

tion of any available solution variables, such as stress or strain, at a material point. This material model is appropriate for the simulation of the fiber break process. The realization of this material constitutive model is done in user subroutine USDFLD of ABAQUS [29]. The detail introduction will be given in the following Section 3.3. (In ABAQUS the user subroutine UMAT can also be used to define this kind of material constitutive model. But it is not adopted in the article because the subroutine USDFLD is easier than the UMAT [29] for the same problem.) The matrix is considered as elastic material.

A tensile displacement load is applied on the end of the specimen. To prevent rigid body motion, the x displacement is fixed along the yz plane, as shown in Fig. 8.

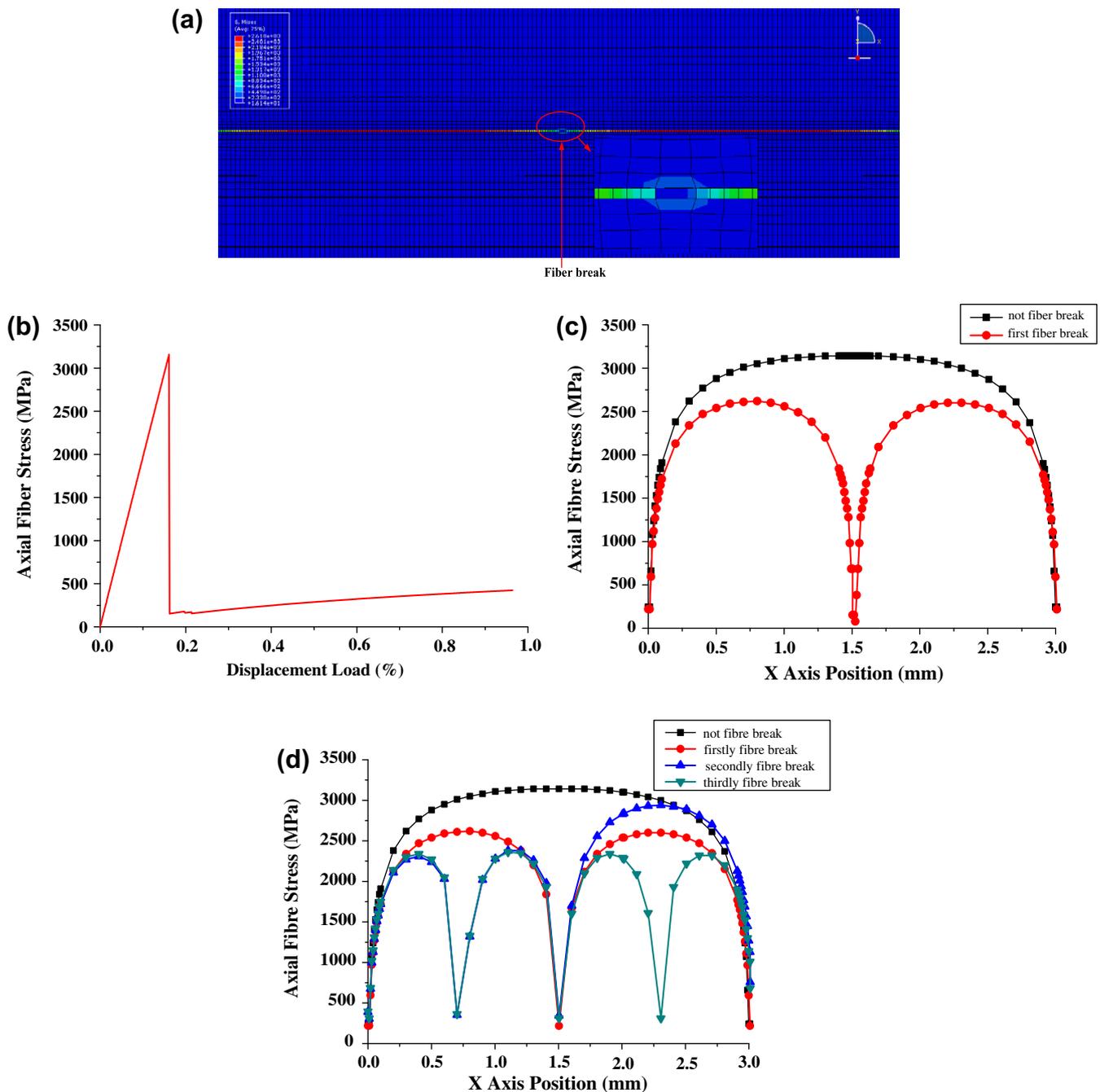


Fig. 11. (a) The contours of fiber axial stress distribution after fiber break; (b) the axial stress of failure fiber element; (c) the curve of fiber axial stress redistribution after first fiber break; (d) the curve of fiber axial stress redistribution after second fiber break.

3.2. Failure criterion and degradation modeling

In the single-fiber composite, the fiber is main load-bearing constituent. When the stress transferred from the matrix exceeds the strength of the fiber, the fiber will break and lose the bearing capacity in the axial direction. So the maximum stress criterion is adopted for the fiber, given by:

$$\sigma_{11} < X_t \quad \text{Fiber does not break} \quad (2)$$

$$\sigma_{11} > X_t \quad \text{Fiber breaks} \quad (3)$$

The Young's modulus of the fiber is reduced after the failure criterion is satisfied, as follows:

$$E_f^d = d_1 E_f \quad (4)$$

The symbols used in above equations are explained now and they will be used repeatedly throughout this paper. X_t is tensile strength of the fiber in axial direction σ_{11} is solving tensile stress in the current load step. E_f is elastic modulus of the fiber without damage. E_f^d is elastic modulus after damaged. The coefficient d_1 is degradation factor; here we used a very little value 0.01 but not zero in order to ensure the non-singular of element stiffness.

3.3. Implementation of the fiber break

In ABAQUS software, many user subroutines are provided to meet the special needs. This kind of subroutines is programmed in FORTRAN and called by ABAQUS. The USDFLD used in this article is a kind of user subroutine. It can be used to define the behavior of material, such as the process of the fiber breaks in the SFCE test. The realization process is described as follows:

- (1) The number and the value of “field variables” are determined. Here the number is “1” and the value is “0” or “1” depending on different conditions (the fiber breaks or not).
- (2) The dependence between the fiber material properties and the “field variables” should be defined. The elastic modular of the fiber changed from E_f to E_f^d after the fiber breaks. The two values of the fiber properties correspond to different “field variables” value “0” or “1” respectively.

- (3) The value of “field variables” is redefined according to the failure criterion. The user subroutine USDFLD should be programmed and called at the material point of element in every incremental step. In USDFLD, three steps are done to complete the definition of the “field variables”. The first step, failure criterion is defined (here the maximum stress criterion is used, which has been mentioned above). The second step, the solution variables included in the failure criterion (σ_{11}) can be obtained by utility routines (in USDFLD the utility routine “Obtaining material point information in an Abaqus/Standard analysis (GETVRM)” is used accordingly [29]). The third step, update “field variables” and end the subroutine.
- (4) The properties of material are changed by the dependence defined in (2), that is, the fiber failure is realized.

The flow chart is shown in Fig. 9.

4. Simulation results and discussion

The elastic load transfer is assumed before the fiber breaks. The axial stress in the fiber increases with the external load, which means more and more external load is transferred to the fiber through the interface of fiber/matrix. In order to reduce the computational cost, the axial dimension is selected to be 3 mm in the simulation. The maximum axial stress is in the fiber centre diminishing toward zero at its end (it is consistent with result of the Wu's model [13–16]), as shown in Fig. 10.

With the load increasing, the axial stress in the fiber will exceed its strength, so the fiber will break, as shown in Fig. 11a. The axial stress of the failure fiber element is almost equal to zero, which means that fiber breaks at this position and loses the load-bearing capability, as shown in Fig. 11b. The axial stress in the fiber will redistribute and the every fiber fragmentation bears load again after the fiber breaks. The stress distribution form in every fiber fragmentation is same as the form before the fiber breaks, as shown in Fig. 11c. But it is clear that the maximum value of fiber axial stress in every fragmentation is reduced. With the load increasing, the fiber will break into more and more fragmentations.

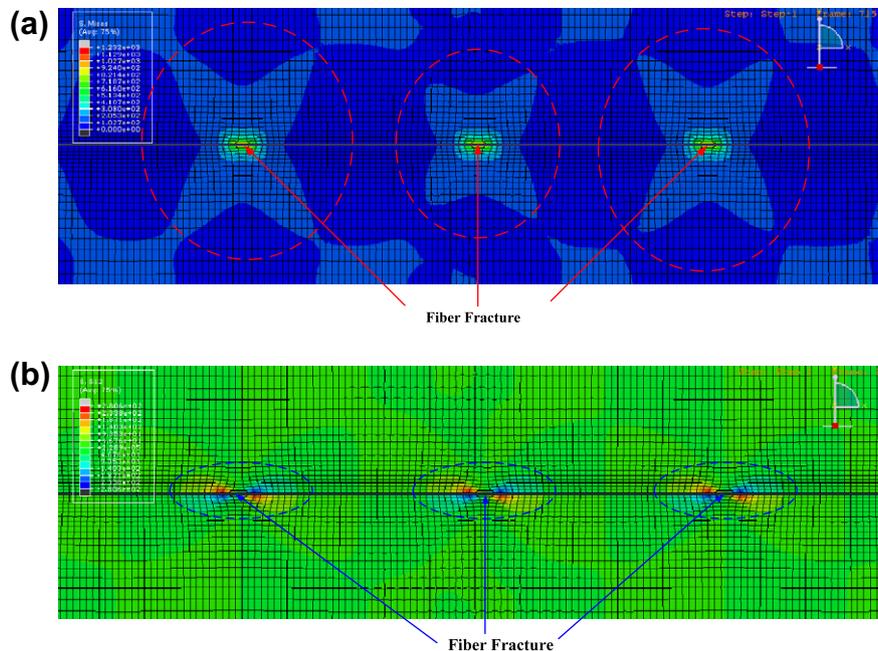


Fig. 12. The contours of stress redistribution after fiber break: (a) the Von Mises stress in the matrix; (b) the shear at fiber/matrix interface.

The curve of the fiber axial stress redistribution after three times of fiber breaks is shown in Fig. 11d [30].

The stress concentration is induced by the fiber breaks, so the stress will be redistributed in the matrix and at the fiber/matrix interface near the fiber fracture. The appropriate analysis step in the simulation is critical for the acquisition of stress redistribution form. By repeated adjustment, the 100 analysis steps are determined. The contours of Von Mises stress distribution in the matrix near the fiber fracture is shown in Fig. 12a. The larger stress in the matrix is located at 45° with the axial direction and form the cross shape obviously. It manifests that the matrix crack or matrix yield will occur in these zones with the load increasing. The shear stress redistribution at fiber fracture is shown as Fig. 12b. The anti-symmetry can be seen clearly and the interface debonding may be located at this position [31].

By the comparison of the Figs. 12 and 6, the resemblance between simulation and experiment is obvious.

5. Conclusion

A new numerical simulation method based on the general FEM software ABAQUS is presented to simulate the process of the fiber break in the SFCF test. The following conclusions can be obtained.

- (1) During the simulation process of the fiber breaks in the SFCF test, the user subroutine USDFLD is appropriate for the definition of material constitutive model of the fiber break.
- (2) The proper analysis step is should be considered to obtain the stress redistribution form in the matrix and at fiber/matrix interface.
- (3) Fiber break induces stress concentration, which lead to the redistribution of stress in the matrix and at the fiber/matrix interface. From the results of simulation and experiment, it is clear that the zone of stress distribution is located at 45° with the axial direction. For brittle matrix, the matrix crack may occur along the direction. This will be done in the following work.
- (4) The stress concentration results in a high interfacial shear stress near the fiber fracture. In this article perfect bonded interface is assumed, but for low interfacial strength the debonding will occur, which should be also considered in future.

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