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Analysis and determination for the parameters of "cohesive element" in the numerical model of single fiber composites: the elastic parameters

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Abstract

In the fiber-reinforced resin matrix composites, the "interphase" is an important component. And the "cohesive element" is usually used to characterize the mechanical properties of "interphase" in numerical models based on the general finite element software ABAQUS. But the corresponding parameters of it are difficult to be determined. So the single-carbon fiber-reinforced resin matrix composites are used as the main research object and the method combining resistance experiment and numerical analysis is adopted. Then in the numerical models of three different single-carbon fiber composites (CCF/epoxy128, CCF/epoxy5228, CCF/Bismaleimide5428), the parameters of the "cohesive element" are analyzed and determined. It turned out that in CCF/Bismaleimide5428, the parameters are much higher (they are 10–12 GPa). It is also demonstrated that the ability of transferring load of "interphase" is much stronger in it than the other single fiber composites. What's more, these parameters will be used for the numerical analysis of macroscopic mechanical properties of composites in future.

Keywords

Cohesive element, interphase, single fiber composites, resistance experiment, numerical analysis, stress transfer

Introduction

Fiber-reinforced resin matrix composites are widely used in aviation, aerospace and transportation etc., because of its excellent mechanical properties such as high specific strength and high specific modulus. It is well known that in composites the "interface" between the fiber and the resin matrix is an important component. The load imposed on the composites is transferred to the reinforced fiber through the "interface," so it can be seen that in composites the fiber is the main component to bear the load.

It is shown that the formation process of the "interface" experienced two phases: the first one is the contacting and infiltrating stage between the resin and the reinforced fiber, and the second one is the curing stage of the resin matrix itself. During these processes, the complicated physical and chemical reaction occurred. With further research, the "interface" is no longer simply to be considered as a common boundary without thickness between the reinforced fiber and the resin matrix but to be considered as a zone with certain thickness i.e. "interphase." It is researched that the thickness of the "interphase" is approximately dozens to hundreds of nanometers. And the property of it is different from the fiber and the resin matrix. Much

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more than this, the formation of ''interphase'' is a result of the complicated reaction that is mentioned above. It is thus clear that the mechanical properties of ''interphase'' are very difficult to be obtained through the conventional mechanical test methods. And it is always one of the difficult points to characterize the performance of ''interphase'' in the field of the composites research.

Now, the experimental testing methods such as ''carbon elements distribution method,'' ''nano-indentation method'' etc. are used to characterize the performance of the ''interphase.''[1–3] But the experimental results obtained by different experimental method are different from each other. In addition, the theoretical analysis method is also used. In order to describe the mechanical properties of the ''interphase,'' a lot of mechanical models are proposed; especially, the model based on the ''cohesive theory'' is used widely.[4,5] In this model, the constitutive relationship of traction-separation for materials located at the both sides of the ''interphase'' is established, so the mechanical properties of the ''interphase'' can be described.

With the wide application of the finite element numerical method for analyzing the mechanical properties of composites, a type of element based on the ''cohesive theory'' is developed and used to describe the mechanical behavior of ''interphase'' of composites in numerical model. In general finite element software such as ABAQUS, this type of element is called as ''cohesive element.'' But, the related parameters of it are difficult to be determined because of the particularity of material properties of the ''interphase'' described above. As for this problem, single-carbon fiber composites are used as the main research object and the method combining experiment and numerical analysis is adopted in this article. The parameters of ''cohesive element'' in the numerical model of different single-carbon fiber composites are analyzed and determined. This will provide the necessary parameters for the numerical analysis of composites macroscopic mechanical behavior in future.

The rest of this paper is organized as follows: In the experiment section, the resistance test for different single-carbon fiber composites is done. In the numerical simulation section, we present our numerical model of single-carbon fiber composites based on ABAQUS software. In the determination of parameters section, the parameters of ''cohesive element'' in numerical model are determined. In the conclusion, we summarize our work.

Experiment

It is researched that there is a certain linear relationship between resistance and strain load for the single-carbon fiber when it is loaded. So the stress along the fiber axis in different single-carbon fiber composites that is under the same load can be measured indirectly by using the linear relationship. And the measurement result is different, it is reflected that the difference of the ability of ''interphase'' to transfer load in different single-carbon fiber composites.

Materials and properties

Carbon fiber (CCF) provided by Weihai Tuozhan Fiber Corporation of China with average diameter 7 μm was used as conductive reinforced material in single fiber composites. The linear relationship between the resistance of single-carbon fiber and the strain load is shown in equation (1).[6]

$$\varepsilon = \frac{dl}{l} = K_R \Delta R \tag{1}$$

The coefficient K_R is the resistance sensitivity coefficient of the single-carbon fiber. There is a big difference for different single-carbon fiber. So the calibration of K_R is necessary in order to use this linear relationship.

The principle and the device of the test for the calibration of the coefficient K_R is shown as Figure 1(a) and (b). The screw-thread micrometer is the core component of the test device. It is used to apply displacement load to the single-carbon fiber. The process of the test is described here briefly. First, the single-carbon fiber is taken out from fiber bundle and fixed on the conductive flake (it is connected to the resistance measurement instrument) of the test platform by conducting resin. Then the displacement load is applied to the single-carbon fiber by rotating the screw-thread micrometer. And the variation of the resistance of the single carbon fiber during the process of loading is recorded by resistance measurement instrument. Finally, the resistance-strain curve of the single-carbon fiber during the test is shown as Figure 2. So the resistance sensitivity coefficient K_R of the single-carbon fiber CCF used in the single fiber composites is determined as $K_R \approx 1.26$.

Epoxy resin-128, epoxy resin-5228 and bismaleimide resin-5428 are used as the matrix materials of the single-fiber composites. So, three types of single-carbon fiber composites including CCF/Epoxy128, CCF/Epoxy5228 and CCF/bismaleimide5428 are researched in this article. The material properties of the fiber and the resin matrix used in the test are listed in Table 1.

Specimen preparation

Different methods are needed to prepare the three different single-carbon fiber composites because of the different state that the three kinds of resin matrix show at room temperature. Generally, at room temperature the

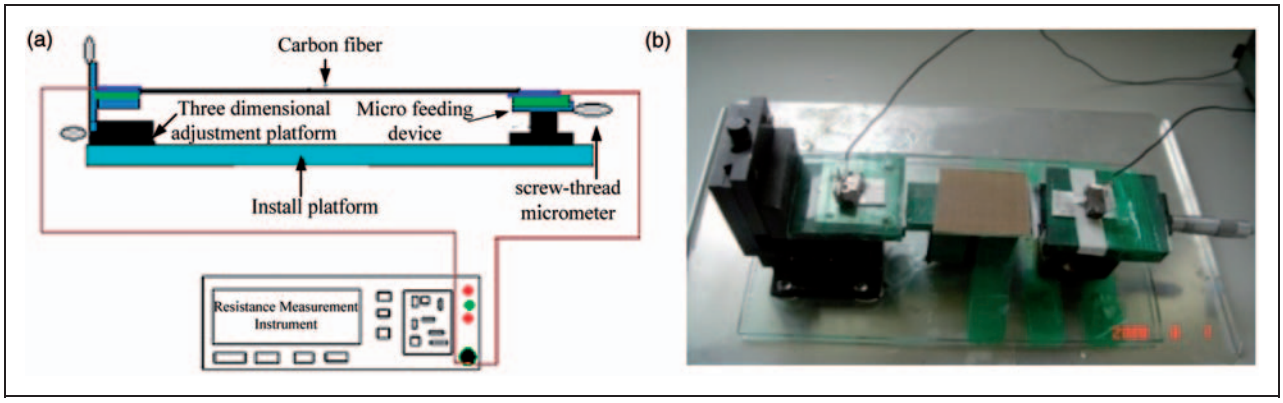

Figure 1. The calibration of K_R: (a) the test principle and (b) the test device.

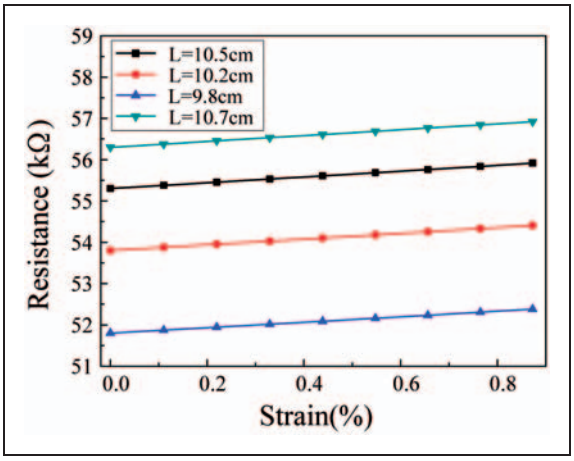

Figure 2. The resistance–strain curve of the single carbon fiber CCF.

Table 1. The property parameters of fiber and resin material

	Elastic modulus (GPa)	Poisson's ratio
CCF	252	0.279
Epoxy 128 resin	2.1	0.31
Epoxy 5228 resin	3.5	0.33
Bismaleimide 5428 resin	3.5	0.35

epoxy 128 is liquid state but the epoxy5228 and bismaleimide5428 are solid state. Moreover, the latter is very viscous in heating conditions. The preparation process for CCF/epoxy128 single fiber composites is described in detail as follows:

First, two pieces of copper sheets (4 mm × 4 mm) used as conductive terminals are pasted on the bottom of the mold with stripping cloth in it. Between the two copper sheets, the single carbon fiber taken out from fiber bundle is fixed by conductive adhesive. During this process, the carbon fiber should be kept in straight state without stress and be located in the middle of the mold. Then the mold is put into drying oven and the proper temperature is adjusted in order to make the conductive adhesive cure. Secondly, the matrix system composed with epoxy resin128, curing agent and flexibilizer in a 100/30/6 ratio is stirred evenly by magnetic stirrers and is poured into the mold with single-carbon fiber in it. Finally, the whole mold is put into drying oven. The process of vacuumization should be done firstly at room temperature followed by the process of curing. The curing cycle of CCF/epoxy128 single fiber composites is as follows: The drying oven is heated to $100 \pm 2^{\circ}$C and is preserved 1 hour, then heated to $150 \pm 2^{\circ}$C and is preserved 2 hours. During this process, the heating rate is kept always at 0.5–2°C/min. Finally, the drying oven is cooled down to the room temperature naturally.

Compared with the CCF/Epoxy128 single-fiber composites, the resin matrix epoxy5228 and bismaleimide5428 are all difficult to be poured into mold because of the solid state and the viscidity they have at room temperature. So different preparation method suited to the CCF/epoxy5228 and the CCF/bismaleimide5428 single fiber composites is used and the process is shown as follows:

Firstly, the device shown as Figure 3 is used during the process of preparation. Together with mold they are all put into drying oven (The process of single fiber fixed in the mold is the same as the process used for CCF/Epoxy128). Then the solid resin epoxy5228 (bismaleimide5428) is knocked into small pieces that are put into the steel funnel. Finally the process of heating and curing is done according to the curing process of different resin. (The melting process will appear before the resin cures. So at that moment, the resin will flow

into the mold, infiltrate fiber and fill in the mold slowly through the steel funnel.)

The curing cycle of CCF/epoxy5228 single-fiber composites is as follows: The drying oven is vacuumized at room temperature. Then it is heated to $130 \pm 2^{\circ}C$ and is preserved 1 hour. It is continued to be heated to $180 \pm 2^{\circ}C$ and be preserved 2 hours. During this process, the heating rate is kept always at 0.5–2/min. Finally, the drying oven is cooled down to room temperature naturally.

The curing cycle of CCF/bismaleimide5428 single fiber reinforced composites is as follows: The drying oven is vacuumized at room temperature. Then it is heated to 135–140°C and is pressure to 0.62 MPa simultaneously. It is continued to be heated to $150 \pm 2^{\circ}C$ and be preserved 1 hour, $180 \pm 2^{\circ}C$ and be preserved 2 hours and 203°C and be preserved 4 hours, respectively. During this process, the heating rate is kept always at 0.8–1.2/min. Finally, the drying oven is cooled to the room temperature naturally.

The dumbbell-shaped specimen is obtained by the method of laser cutting. After that, the strain gages are pasted on the top and the bottom surface of the specimen in the field of gauge length. But the reinforced pads are pasted on the specimen in the field of clamping length. Finally, the leading wires connected with copper sheet are linked. The specimen for the resistance experiment is shown in Figure 4.

Experiment and results

The resistance experiment of the single-carbon fiber composites is shown in Figure 5. The displacement load is applied through the loading device. During the

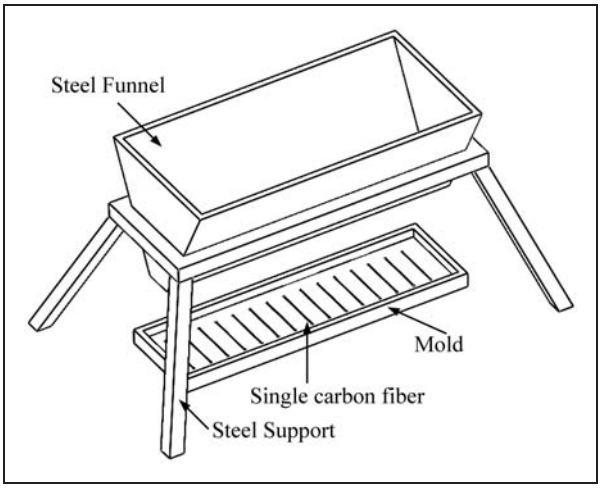

Figure 3. Schematic of CCF/epoxy 5228 (bismaleimide 5428) specimen produced.

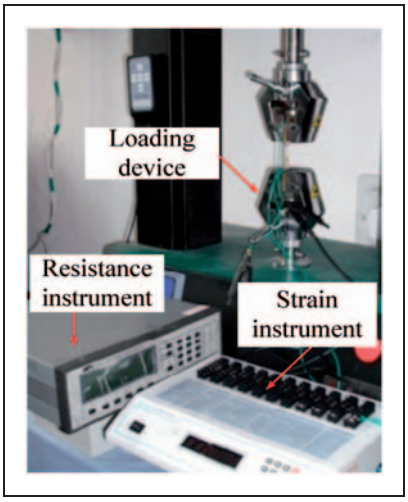

Figure 5. The resistance experiment.

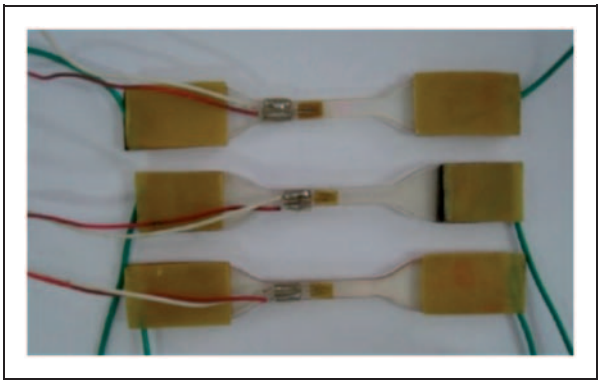

Figure 4. The specimen of resistance experiment.

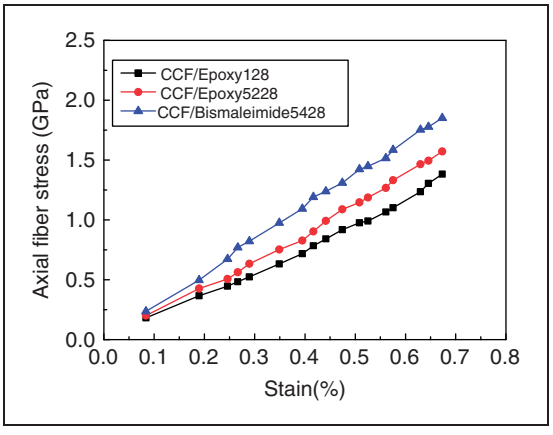

Figure 6. The results of resistance experiment.

process of loading, the deformation of specimen is recorded by the strain instrument and the variation of resistance of the single carbon fiber in the composites is recorded by the resistance instrument. According to the linear relationship between the resistance and the strain of the single-carbon fiber that is mentioned above, the experimental result is shown as Figure 6.

It is clear that the maximum fiber axial stress is generated in the CCF/bismaleimide5428 composites at the same loading. It is manifested that much load is transferred to the reinforced fiber through "interphase" in the CCF/bismaleimide5428 composites than that in the other single-fiber composites during the process of loading, that is, the much ability of transferring load that the "interphase" has in CCF/bismaleimide5428 composites.

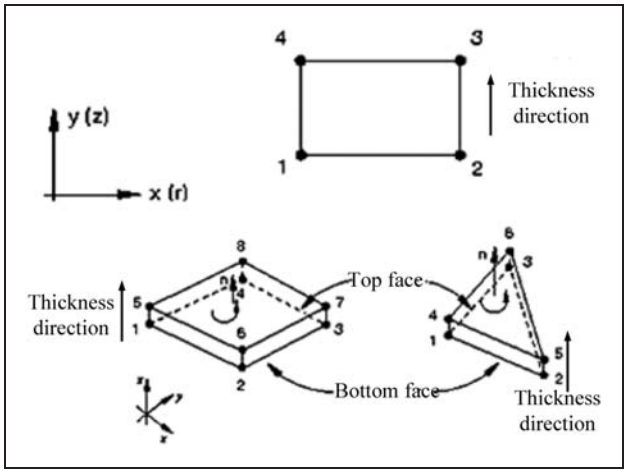

Figure 8. Default thickness direction of "cohesive elements.".

Numerical simulation

Cohesive element

The interaction force between the atoms or the molecules of materials is called as the "cohesion force." The mechanical model based on "cohesive theory" is a kind of simplified model and is called the "cohesive model." The "Needleman cohesive model," "Embendded Process Zone cohesive model" and "Bilinear cohesive mode" are all frequently used cohesive models. The detail description of these models can be referred to in literatures.[4,5]

The "cohesive element" is developed based on the "cohesive theory" in general finite element software ABAQUS. It is often used to model the behavior of adhesive joints, "interphase" in composites, and other situations where the integrity and strength of interfaces may be of interest. The detail introduction on the "cohesive element" can be referred in ABAQUS user

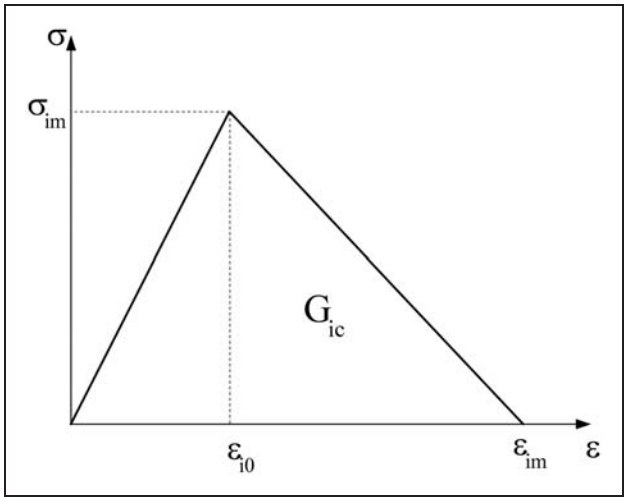

Figure 9. The traction–separation curve of "cohesive element.".

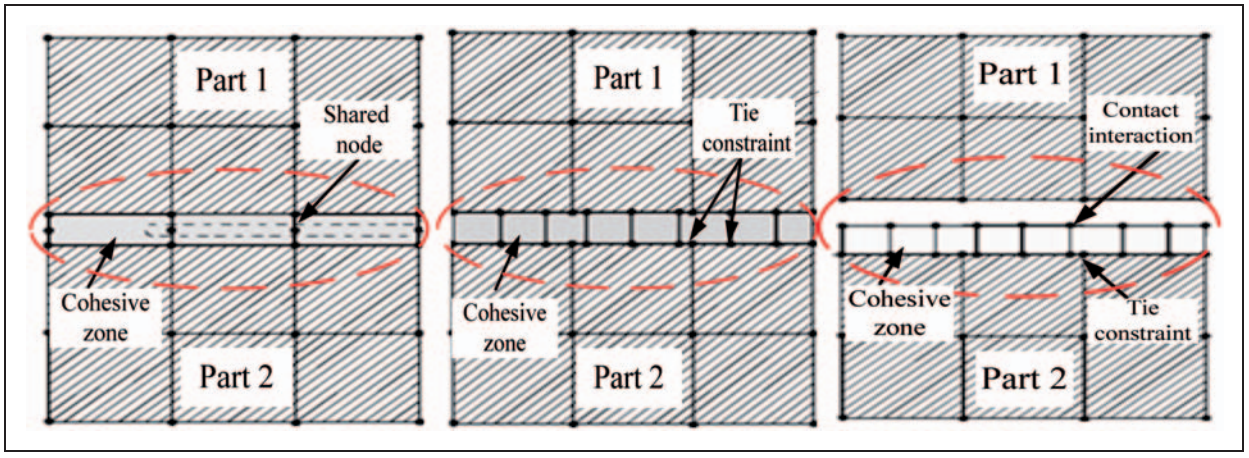

Figure 7. Connection types of cohesive element.

manual 28.5.[7] Here, a simple description on the usage of "cohesive element" is done.

When the numerical model including "cohesive element" is created in ABAQUS, three key questions such as the type of connection, the initial geometric shape and thickness direction and the mechanical behavior should be resolved. According to the grid density between the cohesive element zone and the adjacent components, three types of connection style such as shared node, tied constrain and contacted interaction shown as Figure 7 can be used in the numerical models.

The initial geometry shape of "cohesive element" is defined by the nodal connectivity of the element and the position of these nodes or by the stack direction and the magnitude of the initial constitutive thickness. It is important to define the orientation of "cohesive elements" correctly. By default, the top and the bottom faces of "cohesive elements" are as shown in Figure 8 for three-dimensional and two-dimensional "cohesive elements."

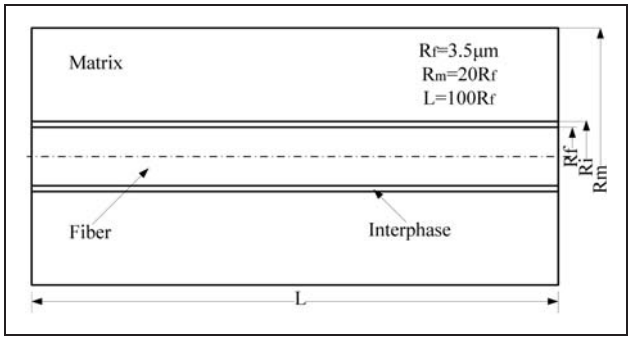

Figure 10. Geometry model for single fiber composite.

The mechanical constitutive behavior of the "cohesive elements" can be defined with a continuum-based or a uniaxial stress-based constitutive model. And they also can be defined by using a constitutive model specified directly in terms of traction versus separation. The latter one is often used. The common traction-separation curve is shown in Figure 9, and the constitutive model of the elastic stage is as equation (2):

$$t = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{nt} & K_{tt} \end{bmatrix} \begin{Bmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_t \end{Bmatrix} \quad (2)$$

The symbols K_{nn}, K_{ss} and K_{tt} are parameters of the "cohesive element," which will be determined later and

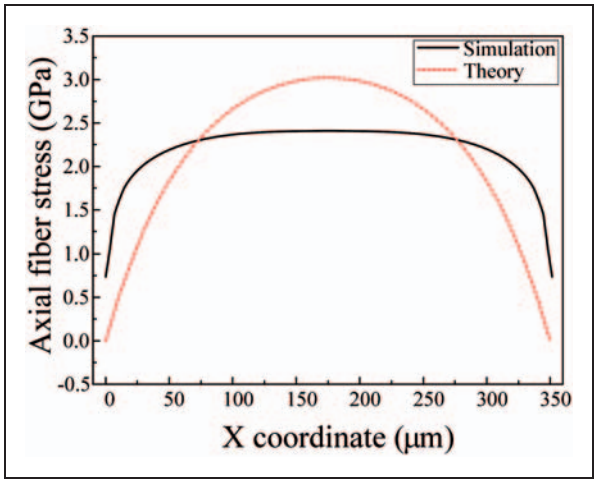

Figure 12. Comparison between the simulation and the theory.

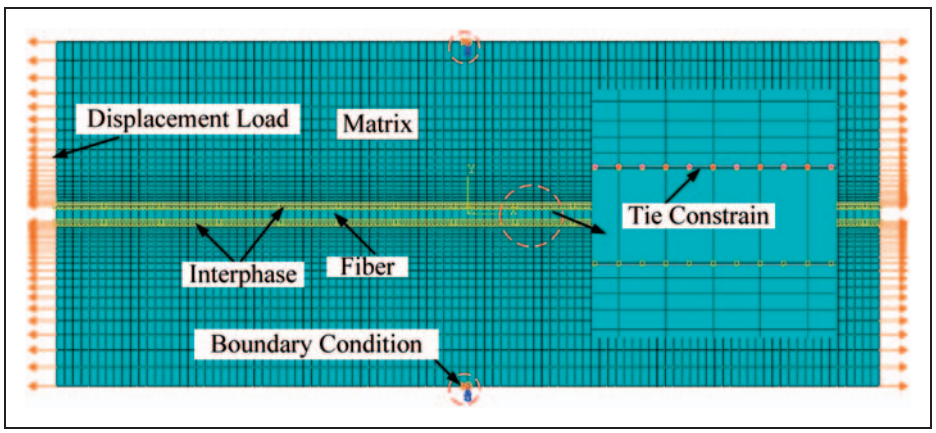

Figure 11. The finite element model based on ABAQUS.

be used to reflect the mechanical behavior of "interphase" in composites.

Numerical model

The numerical model of single-fiber composites is created based on the general finite element software ABAQUS. The pre-treatment process including geometry model, material model, mesh, element type and boundary condition is same as to all the other general software. For every step, the detail process will be explained as follows.

A 2D plane model is employed. In the part module, three parts representing fiber, "interphase" and matrix of single fiber composites are created first. Then they will be assembled to single fiber composites according to the corresponding location in the assembled module. So far the geometry model of the specimen is created and is shown in Figure 10. (The symbols R_f, R_i and R_m are the radius of fiber, "interphase" and matrix, respectively. And the symbols $R_i - R_f, L$ represent the thickness of "interphase" and the axial dimensions of single fiber composites, respectively.)

As for the definition of material models, the fiber and the matrix are both considered the isotropic elastic material as usual and the properties of them are listed in Table 1. It is key point that the definition of "interphase" material. The constitutive model of traction-separation, which corresponded to "cohesive element," is used, and the value of the correlative parameters K_{nn}, K_{ss} and K_{tt} are supposed here. (These parameters will be analyzed and determined later.)

A 4-node bilinear plane stress quadrilateral with reduced integration and hourglass control element (CPS4R) is used for the fiber and the matrix. But the "interphase" is divided with 2D "cohesive element"

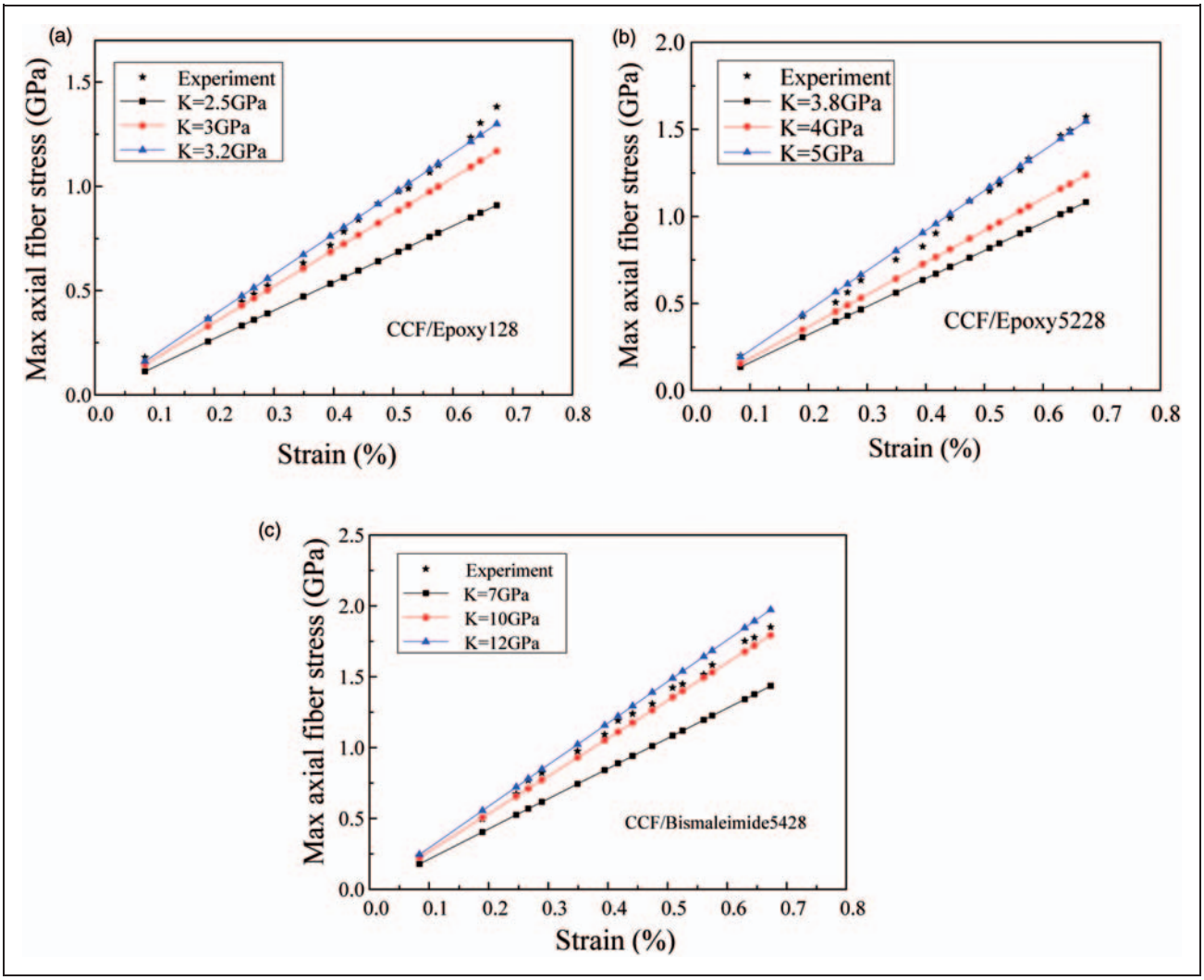

Figure 13. Determination of the parameters of "cohesive element."

(COH2D4) by the sweep mesh technique and it is worth noting that the thickness direction of the ''cohesive element'' must be defined correctly. The radial direction is appropriate for it in single-fiber composites.

In order to obtain the better computing results with the less computing time the following mesh density is adopted. In the radial direction, one element is enough for the fiber and the ''interphase,'' but biased and gradually reduced elements are used for the matrix. In the axial direction, the mesh density ratio among the three parts of fiber, ''interphase'' and matrix is 1:2:1, and the connection type of ''tied constrain'' is applied to the ''cohesive element'' with the surrounding elements.

At last, a tensile displacement load is applied on the specimen. To prevent the rigid body motion, the x displacement is fixed along the yz plane. The finite element model of single-fiber composites is shown in Figure 11.

Simulation results and discussion

The static-general step is created and the ABAQUS/Standard solver is adopted based on the ABAQUS software. Then the strain load $\varepsilon = 1\%$ is applied to the numerical model created above. Thus, the stress distribution along the fiber axial in single-fiber composites is extracted. It is compared with the results based on shear-lag theory.[8] The comparison is shown in Figure 12.

It can be seen clearly that the maximum axial stress appears in the fiber centre and diminishes gradually at the both ends. This trend is consistent between the simulation and the theory. What is more, the maximum value of fiber axial stress obtained by the two methods is comparatively approximate and that value is useful for us and will be extracted later. So it is manifested that the numerical model will be used for later research.

Determination of parameters for ''cohesive element''

It is worth pointing out that the suppositious parameters value is used for ''cohesive element'' in the above numerical model during the analysis process. Here, the parameter $K(K_{nm} = K_{ss} = K_{tt} = K)$ of ''cohesive element'' in different single-fiber composites will be analyzed and determined based on the numerical model and the results obtained by the resistance experiment. Then they will be used to characterize the mechanical properties of ''interphase'' in different single-fiber composites. During the process of computing, the value of the parameter K is adjusted repeatedly until the maximum axial stress in fiber is close to the experimental results at different load. That is shown as Figure 13.

From Figure 13, the parameters of ''cohesive element'' in the three different single fiber composites CCF/epoxy128, CCF/epoxy 5228 and CCF/Bismaleimide5428 are list in Table 2.

Table 2. The parameters of ''cohesive element'' in different numerical models

	Parameters K of ''cohesive element'' (GPa)		
	K_{nn}	K_{ss}	K_{tt}
CCF/epoxy 128		3–3.2	
CCF/epoxy 5228		4–5	
CCF/bismaleimide 5428		10–12	

Conclusion

It is proposed in the article that the method used for analyzing the parameters of ''cohesive element'' in the numerical model is created based on the general finite element software ABAQUS and is used for analyzing the process of stress transfer in different single-carbon fiber-reinforced resin matrix composites. The following conclusions can be obtained.

1. According to the linear relationship between the resistance and the strain of single-carbon fiber, the stress along fiber axial direction under the same load in different single-fiber composites is obtained by the resistance experiment. It is manifested that much load is transferred to the fiber in CCF/Bismaleimide5428 single fiber composites, that is, the ability of transferring load of ''interphase'' in it is much stronger than the other single-fiber composites.
2. The numerical model of single fiber composites is created based on the general finite element software ABAQUS. It is important that the ''cohesive element'' characterizing the mechanical properties of ''interphase'' in single-fiber composites is included in the model. Then, the analysis of the process of stress transferring in single fiber composites is done based on the numerical model. It is proved that the numerical analysis method is appropriate by the comparison of results between the theory and the numerical simulation.
3. The parameters of ''cohesive element'' in the numerical model of different single-carbon fiber composites are determined by the method of numerical analysis combining with resistance experiment. It will provide necessary parameters for the numerical analysis of macroscopic mechanical properties of composites.

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