PREDICTION FOR THE TRANSVERSE TENSILE STRENGTH OF UNIDIRECTIONAL COMPOSITES CONSIDERING INTERPHASE

Boming Zhang[1*],Changxi Liu[2,3] , Xiaohong Wang[3*], Zhong Yang[2]
[1]Materials science &engineering school, Beijing University of Aeronautics & Astronautics, Beijing, China
[2]School of Astronautics, Harbin Institute of Technology, Harbin, China
[3] Mechanical and electronic engineering department, Heilongjiang Institute of Technology, Harbin, China
* Corresponding author (zbm@hit.edu.cn,wangxiaohong422@126.com)

Abstract: The transverse tensile strength of unidirectional composites considering interphase is forecasted by means of finite element method based on the general software ABAQUS/Explicit. Two damage models such as interphase debonding and matrix damage are considered during the process of simulation. The interphase debonding is modeled using the "cohesive element" provided by the software ABAQUS. The related elastic and strength parameters of the "cohesive element" are determined by the method of carbon fiber monofilament resistance test and micordroplet debonding test combined with numerical analysis respectively. The damage model for matrix failure is realized by the user subroutine VUMAT in ABAQUS. It found that the simulated fracture patterns are shown to be in good agreement with experimental result and the predicted transverse tensile strength of unidirectional composites is close to the result reported in the literature. In addition, the effect of the interphase parameters on the transverse tensile properties is analyzed. It demonstrates that the transverse tensile strength decreases with the interphase modulus increasing. On the contrary, it increases with the increasing interphase strength when it is less than a certain value.

Keywords: *interphase debonding, matrix damage, cohesive element, transverse tensile strength.*

1 General Introduction

It is well known that fiber reinforced resin matrix composites are widely used in aviation, aerospace and transportation etc, due to their excellent mechanical properties such as high specific strength and high specific modulus. And in order to fully and effectively play the potentiality of these materials, the mechanical property from the micro level must be understood. So many research methods for predicting the performance of composites are emerged. But only two phase material such as fiber and matrix are considered during the earlier studies. Some experience and results are accumulated and used for providing some guidance for the understanding and the development of composites.

With the further research the "interface" in fiber reinforced resin matrix composites is no longer simply to be considered without thickness but to be considered a region with certain thickness i.e. "interphase". The "interphase" is an important part of the composites. It determines the mechanical performance of composites. So the prediction method of composites performance considering "interphase" is needed urgently. The numerical method for predicting the transverse tensile strength of unidirectional composites considering "interphase" is established in this article.

2 The analysis and determination of "cohesive element" parameters

Interfacial debonding is one of the most important damage modes of composites. In earlier, the interface mechanics method based on the fracture mechanics theory is used to analyze the interfacial debonding damage. But the complex analytical process limits this method further development. At present, the relatively simple cohesive zone model (CZM) based on cohesive theory is widely used in the analysis of composites mechanical properties. The “cohesive element” is a special element type developed based on CMZ in the general finite element software and used to simulate the phenomenon of the “interphase” damage. But the related parameters for it are difficult to be determined because of the “interphase” itself feature. So in this article, the method of the carbon fiber monofilament test combined with numerical analysis is adopted to determine the module and strength parameters of “cohesive element”.

2.1 The analysis and determination of modulus parameters for “cohesive element”

2.1.1 The resistance experiment of carbon fiber/resin single fiber composites

There is a liner relationship between the resistance of single carbon fiber and the strain load, that is, $\varepsilon = dl/= K_R \triangle R$[1]. The coefficient K_R is the resistance sensitivity coefficient of single carbon fiber. So it can be used to measure indirectly the variation of stress in reinforced fiber when the carbon fiber/resin single fiber composite is loaded.

There is a big difference about the coefficient K_R in different carbon fiber filament. So the calibration of K_R is needed. The experiment principle is shown in Fig.1. The displacement load is applied to the single carbon fiber fixed on the installation platform though the micro-feed device. At the same time, the variation of resistance in single carbon fiber during the loading process is measured by resistance measuring instrument (HM2541/HM2541A). So the coefficient K_R can be achieved (Fig.2) $K_R \approx 1.26$.

Now, the variation of stress in reinforced fiber in single fiber/resin composite system when it is loaded can be measured indirectly. And the abality of transfering load of “interphase” in the single fiber composite system is characterized.The experimential priciple is shown as Fig.3. The variation of resistance in fiber can be measured and the datum can be collected by the Labview software when the composite system is loaded. The variation of stress in reinforced fiber can be obtained by the linear relationship mentioned aboved.

The materials used in the experiment are list in table 1 and the experimental results of three different single fiber/resin composites are shown as Fig.4.

2.1.2 Numerical analysis and the determination of modulus parameters

The numerical analysis for the process of stress transfer in the single fiber/resin composite system when it is loaded is completed based on the general finite element software ABAQUS.

In numerial model,the zone of the fiber and the resin matrix in the single fiber/resin composite system is divided with plane stress element (CPS4R),but the “interphase” zone is divided with two-dimension “cohesive element” (COH2D4). And the “tie constrain” is used to connect the different zone because of the difference of element density. The displacement load is applied along the direction of the fiber axis. In order to prevent rigid body displacement, the Y axis symmetry constrain is applied on the middle place of the model. So the numerical model is shown as Fig.5.

The modulus parameter of “cohesive element” can be determined by combing the numerical results and the experimental results mentioned above. The elastic parameter of “cohesive element” is adjusted repeatedly until the numerical results of the max axial stress in reinforced fiber is equal to the experimental results during the calculation process.(Only the CCF/epoxy 128 single fiber composite system is calculated) The results are shown as Fig.6.

2.2 The analysis and determination of strength parameters for “cohesive element”

2.2.1 The microdroplet debonding experiment

The microdroplet debonding test is one of the kinds of micromechanical tests used to measure the interfacial bonding strength [2]. The experimental principle is shown as Fig.7. The single fiber is fixed and the external load is applied on the resin microdroplet through scraper. When the load reaches the some value the resin microdroplet is debonded from the single fiber. Then the interfacial bonding strength of “interphase” is obtained according to the micromechanical model $\tau = F / 2\pi rl$ .The symbol F is the debonding load, r is the radius of fiber, l is the length of microdroplet. The experimental materials are listed in table1and the experimental result is shown as Fig.8.

It can be seen clearly that large discreteness is demonstrated in the experimental results. So the effective experimental result should be determined by the numerical analysis as followed.

2.2.2 Numerical analysis and the determination of modulus parameters

The numerical model is created based on the general finite element software ABAQUS. The zone of the fiber and the resin matrix is divided with plane stress element (CPS4R),but the "interphase" zone is divided with two-dimension "cohesive element" (COH2D4).The load exerted on the microdroplet is realized by the contact between the scrape and the surface of microdroplet. The numerical model is shown as Fig.9.

The relative position between the scrape and the resin microdroplet is difficult to be controlled in the test because the size of the microdroplet is very small. The interfacial shear stress is changed with the change of the relative position and it is shown as Fig.10.So it is the main reason of resulting the discreteness of experimental results. And the minimum critical load F=0.057N (the length of microdroplet is 60μm) in the experimental results is the effective experimental data and it is used to determine the strength parameters of "cohesive element".

The bilinear respond model based on load—displacement is used as the damage model of "cohesive element"[3]. The maximum stress criterion and the linear damage propagation criterion based on displacement are used as damage initiation and propagation criterion respectively [4]. The determination of strength parameters are shown as Fig.11.

3 Prediction for the transverse-tensile strength of unidirectional composites

The damage modes of composites are different from the homogeneous materials such as metal because of the complex microstructure. Firstly, the transverse damage process of representative element (RVE) of unidirectional composites is analyzed based on Abaqus/Explicit. Then the transverse-tensile strength of unidirectional composites is predicted.

3.1 Numerical model

The fiber is distributed randomly in the unidirectional composites. So the geometry microstructure reflecting true random distribution should be built in order to predict the macro-performance of unidirectional composites truly. The true geometry microstructure is obtained with SEM shown as Fig 12(a) which is transferred to be CAD format and lead into ABAQUS. The numerical model of is shown as Fig 12(b).

The zone of fiber is divided with CPS4R element and the hypothesis is made that the fiber material is not fracture under the transverse load. The matrix is also divided with CPS4R element and the damage of the matrix material is described with the strength criterion of Mohr – Coulomb because the tensile and compressive strength of the matrix material is not only different but also the latter is greater than the former. The realization of damage criterion is done by the user define subroutine VUMAT provide by ABAQUS[5].The "interphase" zone is divided with COH2D4 element and the parameters used are determined by the method mentioned above.

3.2 Results and experimental verification

The symmetry boundary condition is adopted and the analysis module ABAQUS/Explicit is used. The stress of every component element in RVE is increasing with the load increases. The damage judgment for each component is done according to the corresponding failure criterion at every load. The element satisfied failure criteria will begin to damage evolution until to be deleted. When enough elements have been deleted the structure will lose carrying ability.

The simulation result obtained by the method established above and the experimental result obtained by the SEM in situ measurement is shown as Fig.13. The crackle expands along "interphase", that is, the "interphase" debonding is the main failure mode. The minor failure mode is the plastic failure of resin matrix. It found that the simulated fracture patterns are shown to be in good agreement with experiment result.

The predicted transverse tensile strength of unidirectional composites is shown as Fig.14. It is close to the result reported in the literature. (The experimental result is 27MPa in [6]). So it manifests that the simulation method put forward in this article is to be true.

In addition, the effect of the "interphase" parameters on the transverse tensile properties is analyzed. It demonstrates that the transverse tensile strength decreases with the interphase modulus increasing shown as Fig.15. On the contrary, it increases with the increasing interphase strength when it is less than a certain value shown as Fig.16.

4. Conclusion

1、The method combining experiment and numerical analysis can be used to determine the parameters of "cohesive element"

2、The numerical method established in this article can be used to predict the transverse tensile strength of unidirectional composites.

3、The performance of "interphase" have an great impact on the macroscopic mechanical properties of composites.

References

[1] M. Kupke, K. Schulte, R. Schuler. "Non-destructive of FRP by d. c. and a. c. electrical methods". *Science and Technology*, Vol.61, No. 6, pp 837-847, 2001.

[2] B. Miler, P. Muri, L. Rebenfeld. A microbond method for determination of the shear strength of a fiber/resin interface. Composites Sci Technol. 1987, 28(1): 17-32

[3] Y. Mi, M. A. Crisfield, G. A. O. Davies. Progressive delamination using interface elements. Journal of Composite Materials. 1998, 32:1246-1272

[4] Hibbit, Karlson, Sorensen, Inc. Section 27.5.6: Defining the constitutive response of cohesive elements using a traction-separation description. ABAQUS Analysis User's Manual Vol. VI: Elements, Ver.6.8.

[5] Hibbit, Karlson, Sorensen, Inc. Section 1.1.34: User subroutine to define a material's mechanical behavior;1.1.43:User subroutine to redefine field variables at a material point. ABAQUS User Subroutines Reference Manual .Ver.6.8.

[6] P. D. Soden, M. J. Hinton, A. S. Kaddour. "Lamina propertites, lay-up configurations and loading conditions for a range of fiber-reinforced composite laminates". *Composites Science and Technology*, Vol. 58, No. 7, pp 1011~1022,1998.

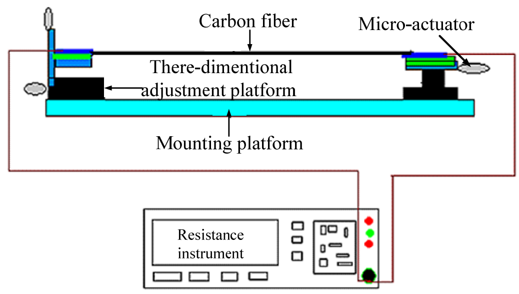


Fig.1. Experiment principle of the K_R

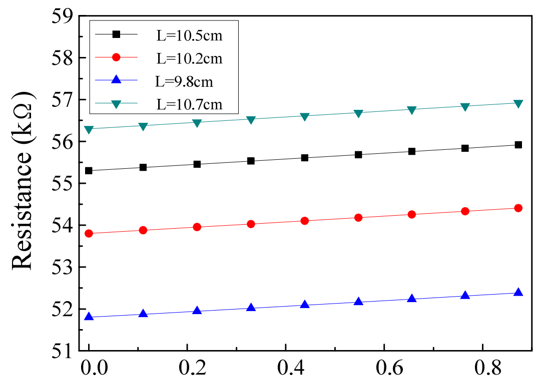


Fig.2.The experimental result of the K_R

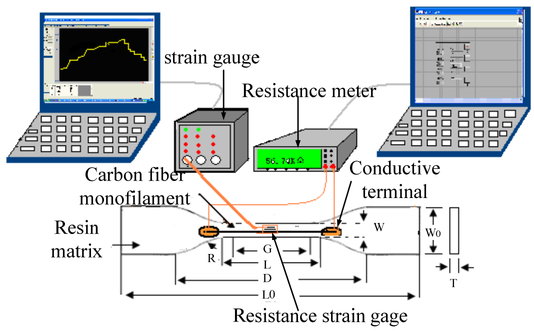


Fig.3. Experiment principle of resistance test

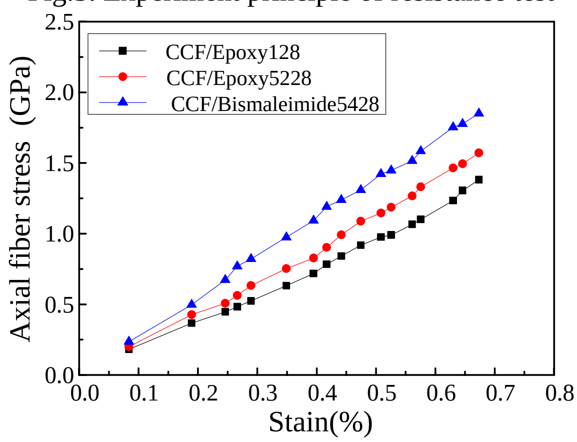


Fig.4. The result of resistance test

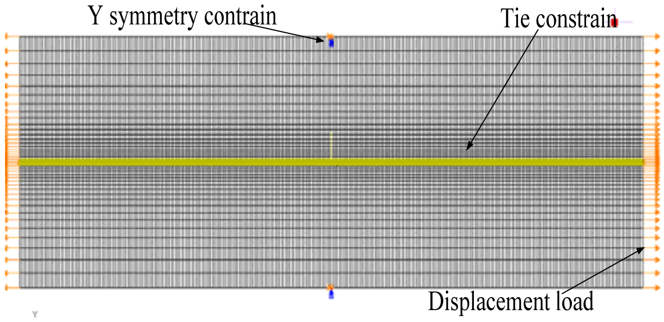


Fig.5.The numerical model of stress transfer

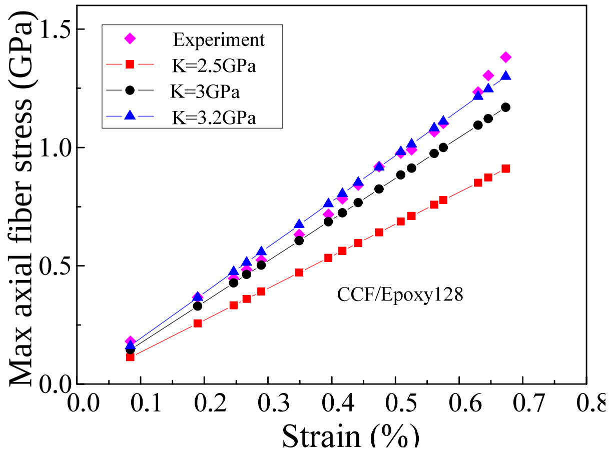


Fig.6.The result of “cohesive element” modulus parameters

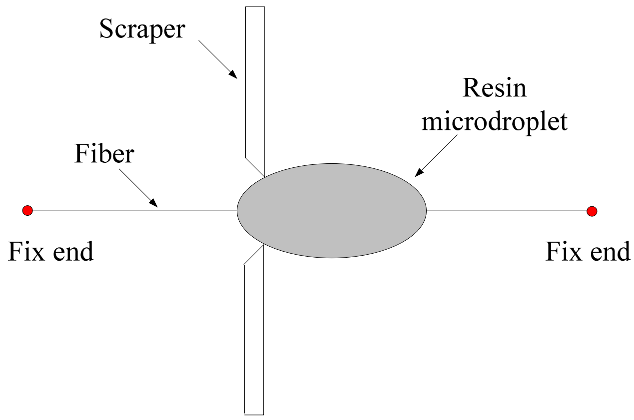


Fig.7.Schematic diagram of microdroplet debonding test

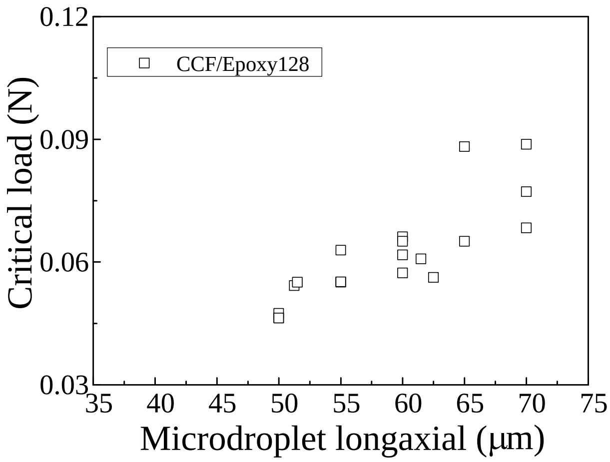


Fig.8 The result of microdroplet debonding test

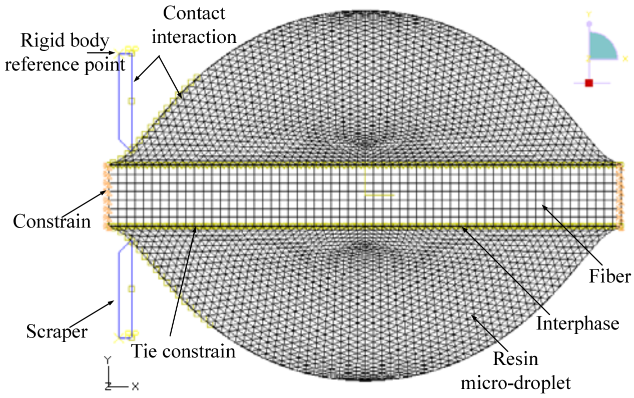


Fig.9. The numerical model of microdroplet debonding

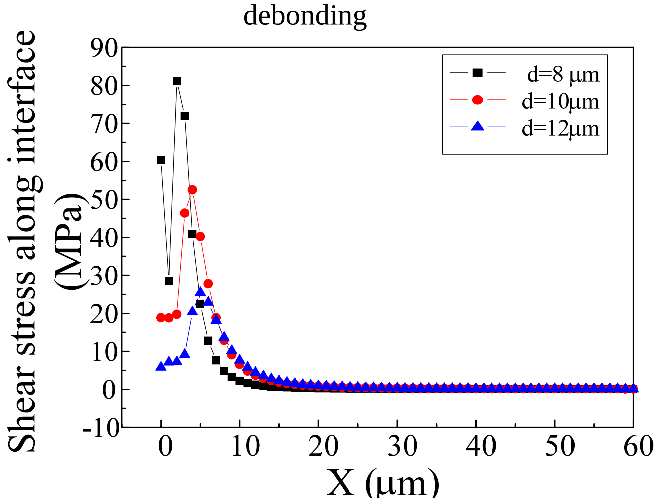


Fig.10.The distribution of interfacial shear stress under different displancement between scrape and microdroplet

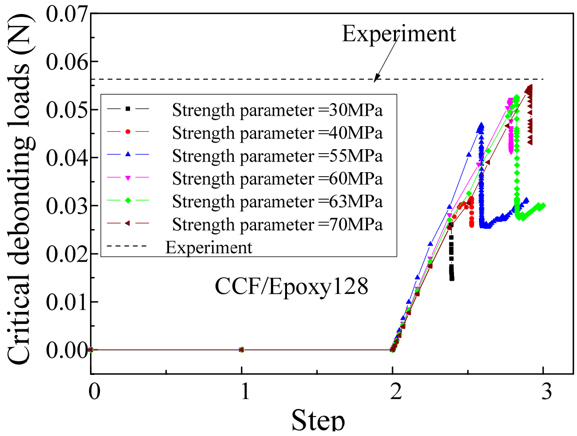
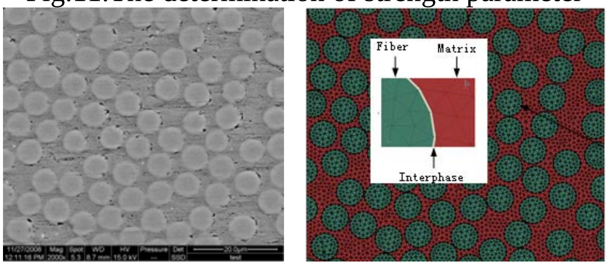
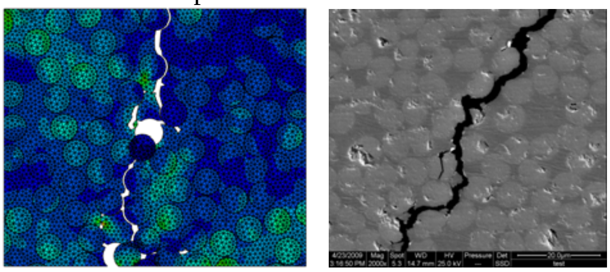


Fig.11.The determination of strength parameter



(a) (b)

Fig.12. The SEM(a) and the numerialc model(b) of representative element



(a) (b)

Fig.13. The result of damage model (a) the numerical result and (b) the experimental result

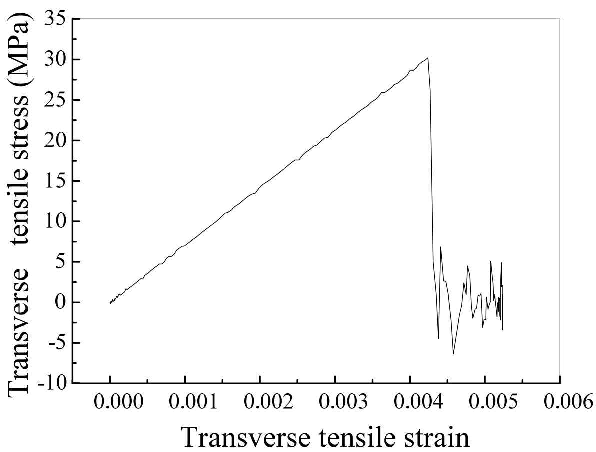


Fig.14.The transverse stress-strain curve

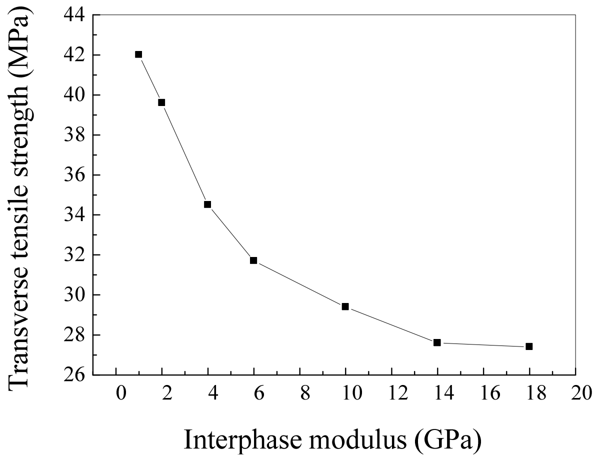


Fig.15. Effect of interphase modulus on transverse tensile strength

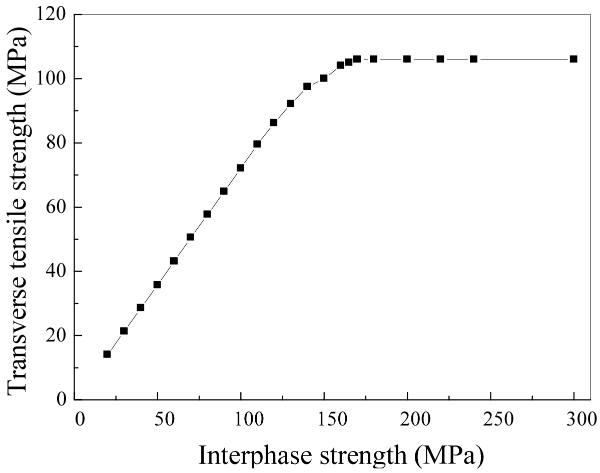


Fig.16.Effect of interphase strength on transverse tensile strength

Table.1 Property parameters of material property

	Elasticity modulus （GPa）	Poisson ratio
CCF	252	0.279
Epoxy 128	2.1	0.31
Epoxy 5228	3.5	0.33
Bismaleimide5428	3.5	0.35