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EFFECT OF SPECIMEN SIZE ON INTERFACIAL BEHAVIOR FOR FIBER PULL OUT TEST

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SUMMARY: The paper studies the effect of specimen size on interfacial behavior in the fiber pull out test by a numerical simulation method. The effect of the embedded length of the fiber in the matrix and the wrapped thickness of the matrix around the fiber is considered. For a perfect interface between fiber and matrix, finite element analysis for interfacial shear stress and normal stress of the test specimen with different dimensions were performed. The energy release rates are obtained for the whole process of crack growth. All materials used here are assumed to be linear elastic solids. It is shown that the size of the test specimen can influence the distribution of the interfacial stresses and the fracture properties dramatically.

KEYWORDS: composite material**,** interface, distribution of stresses, energy release rate, numerical simulation.

INTRODUCTION

Properties of interface between the fiber and matrix have important influence for the damage behaviors of fiber-reinforced composite materials. But people are not very clear to the mechanical characterization of fiber/matrix interface. The basic method to study bonding characterization of fiber/matrix is examination of some important physical parameters for various bond situations by micro-mechanical experiments. Therefore, many experiments to test or study bonding characterizations, such as the single-fiber pull-out test, micro-drop debonding test and so on, had been developed, although there are many difficulties in preparations of test specimens and change of some physical parameters (especially the dimensional parameters) because of the small size of the tests. One of typical examples is the single-fiber pull-out test, which was introduced several decades ago, and had been a subject of numerous fundamental experimental and theoretical investigation [1]. Despite its simple geometry, a closed analytical solution to the stress and strain distributions has not been found and approximate approaches on a shear-lag basis have been shown to provide a coarse qualitative description. In this test, one of the most obvious difficulty is the very inhomogeneous stress state induced on the interface, showing strong gradients at the entry point of the fiber into the matrix drop (named the upper end point) and at the embedded fiber end (named the lower end point). In an ideal elastic model, the maximum interfacial stresses are even infinite, although in reality the interfacial stresses remain limited owing to large strain and plasticity effects, the actual maximum value is very complex and not easy to be obtained by a simple analytical approach. The common data reduction schemes for interpretation of the experimental results rely on very simplistic theoretical ideas, mostly based on the assumption of constant shear stress distributions along the fiber length, and provide an interfacial shear value. On an inadequate theoretical basis, this value can only be an even value of the interfacial shear stress, and it can not reveal the reality of the interfacial shear stresses' distributions along the fiber length. In addition, during the course of the fiber debonding from

the matrix, crack growth is even more complicated, because of the singularity of the stress field and the high stress concentration at the tip of the crack. In this case, the common elastic mechanical parameters can not well describe the whole process of crack growth. However, it is convenient to apply the fracture mechanics analysis method to interpret the interfacial debonding, using concept of the energy release rate. Many scholars have applied the fracture mechanics to many micro-mechanics tests such as fiber pull-out test and micro-drop debonding test in order to simulate the whole process of material interface damage. These test results can explain experimental data very well [2-5]. Thermal residual stress, friction of crack in the interface and material non-linearity may have effects on the debonding between the fiber and the matrix. A micro-size and a complicated analysis may bring difficulties to the experiments. However, numerical simulation and analytical method provide powerful tools for these problems.

It is very difficult to consider a non-linear material case and simulate interfacial coarseness. So in this paper, with assumption of linear elastic material, we study the effect of specimen size on interfacial behavior in the fiber pull out test, considering the effect of the varied embedded fiber length in the matrix and of the varied wrapped matrix around the fiber. For an ideal case (fiber and matrix in perfect bonding), numerical analysis distribution of interfacial shear stress and normal stress under the effect of dimensions are performed. For the whole course of crack growth, we studied the effect of dimension changes on the law of energy release rate.

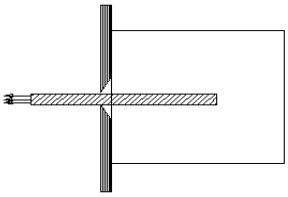

Fig.1. Geometry model of the fiber pull-out test

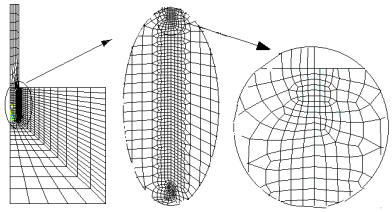

Fig.2. Finite element meshing graphs

FINITE ELEMENT MODEL

In present numerical simulation, commercial finite element software ANSYS is used. Fig.1 shows the simplified form of the fiber pull-out test. Consider an axial symmetry model. The finite element model takes a 2-D model, and 8-node quadrilateral element PLANE82 was used. Choose axial symmetry item in the element key options. The fiber radius is $r_f = 5\mu\mathrm{m}$, When the effect of the embedded fiber length in the matrix is considered, we select a fixed wrapped thickness of the matrix around the fiber $r_m = 10r_f$, while the embedded fiber length in the matrix l_f varies between $2r_f$ and $40r_f$. To consider the different effects of the wrapped thickness of the matrix around the fiber is considered, we select a fixed the embedded fiber length in the matrix $l_f = 10r_f$, while the wrapped thickness of the matrix around the fiber r_m varies between $2r_f$ and $30r_f$. When simulating the whole process of the debonding, crack length c is varies between $0.05l_f$ and $0.95l_f$. Material is of a linear elasticity. Elastic modulus of the fiber is $E_f = 64\mathrm{GPa}$, Poisson ratio is $\nu_f = 0.2$; Elastic modulus of the matrix is $E_m = 3\mathrm{GPa}$, Poisson ratio is $\nu_m = 0.35$ [5]. Load is an even distributed tensile force $p = 1\mathrm{MPa}$. When simulating the whole process of the debonding, load is an even distributed tensile force $p = 1\mathrm{GPa}$.

STRESS ANALYSIS OF PERFECT INTERFACE

In the shear-lag model, interfacial shear stress is assumed to be even distribution along the fiber length. In fact, interfacial stress distributions are very complex, especially around the upper-end point and the lower-end point of the fiber, where high level of stress concentration exists. To get more precise interfacial stress distributions, element local refinement is applied in the meshing of the finite element

model. At the zone of the stress concentration, element sides are less than 1/10 of the fiber's radius. A typical element mesh is shown in Fig.2.

It is shown that concentration of the shear stress along the interface is not the only factor for the interfacial layer damage. There is another factor, that is normal stress concentration vertical to the interface. For different value of the fiber's embedded length and the matrix's wrapped thickness, we can obtain a series of distributions of interfacial shear stresses and normal stresses along the fiber axis as shown in Fig.3~Fig.6. It is showed that the maximum of interfacial shear stress changes with fiber's embedded length (Fig.7) and with matrix's wrapped thickness (Fig.8).

Fig.3 shows that the shear stress reaches its maximum at the upper end point. Along the fiber, it decreases rapidly till it almost reaches zero near the center part of the fiber. Then, the shear stress increases very fast, it is shown that there is high level of stress concentration near the end points, while a nearest-to-zero value at the center of length of the fiber. In Fig.4, Maximum of normal stress occurs at the upper-end points, it causes debonding of the interface. Even at those points that are very near to the upper-end point, the normal stress may decrease to zero and this tendency continues until another stress concentration occurs at the lower-end points. When embedded length of the fibers is relatively small, maximum of interfacial shear stress and normal stress is greater and the lower-end points have a relatively higher level of stress concentration. As embedded length of fiber increases, the maximum of the interfacial stresses decrease. At the same time, stress concentration at the lower-end points also decreases (see Fig.3 and Fig.4), but this decreasing tendency will stop at a certain point even though the embedded length of fiber continues to increase. When the embedded length of fiber amounts to more than 20 times the fiber radius ($20r_f$), stress concentration will not decrease any more (see Fig.7). For fixed fiber embedded length, when wrapped length of the matrix is relatively small, maximum of interfacial shear stress and normal stress (at the upper-end points) are relatively great. As the wrapped length increases, maximum of interfacial stresses decreases. Of course, this decreasing tendency will stop at a certain point even though the embedded length of fiber continues to increase. When the embedded length of fiber amounts to more than 12 times the fiber radius ($12r_f$), decreasing rate is not obvious (see Fig.8). In the process of changing the wrapped length, stress concentration at the lower-end points changes little (see Fig.5 and Fig.6). This demonstrates the fact that only the fiber embedded length attributes to the stress concentration near the lower-end points. When embedded length is small, stress concentration near the lower-end points is relatively high. Stress concentration near the lower-end points is relatively low when embedded length is great. Something interesting is that for fiber with a fixed embedded length, there is a fixed point in interfacial shear stress distribution figure. Graphs for different wrapped length of matrix share this point. That is to say, wrapped length has nothing to do with this point.

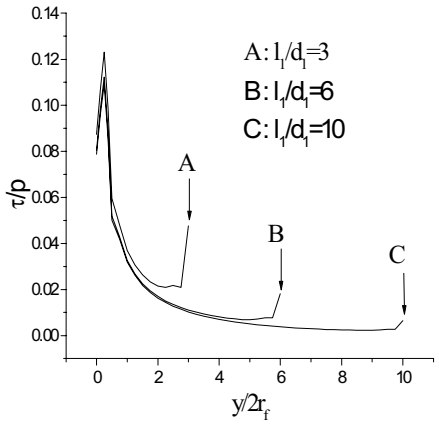

Fig.3: Shear stresses along fiber for the different

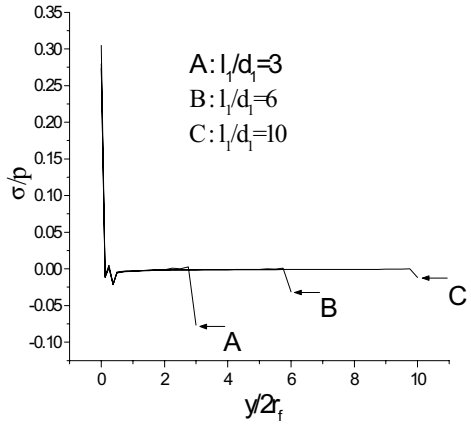

Fig.4: Normal stresses along fiber for the different

embedded fiber length in the matrix

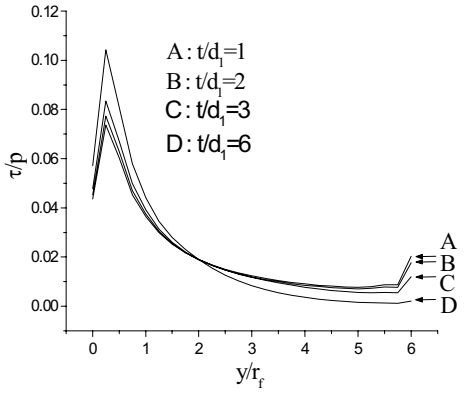

Fig.5: Shear stresses along fiber for different wrapped matrix thickness around the fiber .

embedded fiber length in the matrix.

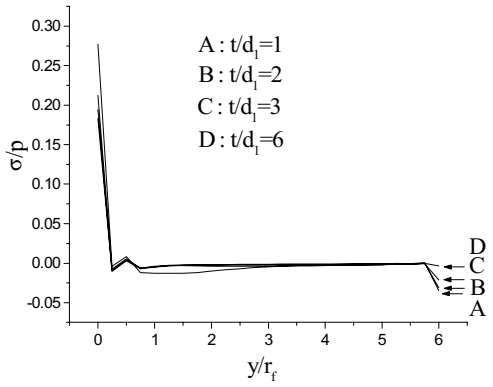

Fig.6.Normal stresses alone fiber for different wrapped matrix thickness around the fiber .

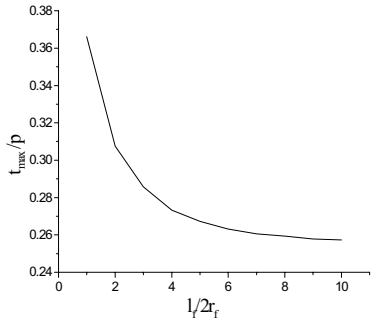

Fig.7: The maximum shear stress against depth.

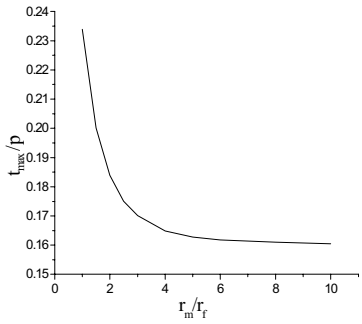

Fig.8: The maximum shear stress against thickness

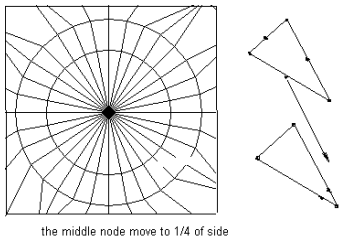

Fig.9. Singularity element arranged at the tip of crack

ENERGY RELEASE RATE OF INTERFACIAL CRACK

Because of the singularity of the stress field and the high level of stress concentration at the tip of the crack, singularity elements have to be arranged around the tip of the cracks. Element meshes around this point may be refined so that minimum element side at the tip of the crack is only 1% the fiber radius. The same refinement is also applied to the lower-end points. Local element meshes at the crack tip is shown in Fig. 9. For small crack length, free part of the fiber contributes the greatest to the energy release rate. For energy release rate of this part, Outwater and Marphy have offered an analytical expression:

$$G_0 = \frac{P_0^{\,2}}{4\pi^2 R_f^{\,3} E_f}.$$

Where P_0 is a tensile force at the fiber tip, R_f is fiber radius, E_f is elastic modulus of the fiber [6]. So in energy release rate figure, we use G_0 to normalize the energy release rate G. Results of finite element analysis indicate that energy release rate is related to the crack length. When crack length is very small (the very beginning of the crack growth), energy release rate decreases as the cracks increase. As the crack length continues to rise up (further growth of the crack), energy release rate will increase instead of decreasing, but first period of the increase is not obvious, a 'plateau range' is being indicated. When the crack reaches a point near the lower-end point, the increment of energy release rate is pronounced and incremental rate is very great. For the case of a relatively small fiber embedded length, the 'plateau range' can not be seen, and the 'plateau range' is elongated as the fiber embedded length increases. In addition,

if crack length is fixed, a high-energy release rate may occur when fiber embedded length is relatively small, the rate will decrease as the embedded length goes up. When embedded length is 30 times over the fiber radius, this tendency becomes inapparent (Fig.11). Keep the fiber embedded length while let the wrapped thickness of the matrix changes, we find that the same occurs for energy release rate. For a fixed crack length, a high-energy release rate may occur when fiber embedded length is relatively small. The rate will decrease as the embedded length goes up. When embedded length is 20 times more than the fiber radius, energy release rate almost will not decrease (Fig12 and Fig.13). At the points near the upper-end, energy release rate goes down gradually until it reaches its minimum. This indicates a mechanics rule of the growth of the debonding cracks: in area of stress concentration, any small interfacial pre-crack will develop itself steadily to a certain degree (i.e. minimum point of the energy release rate). Passing this point, crack will develop unstably and this unstability continues until the fiber is completely debonded from the matrix.

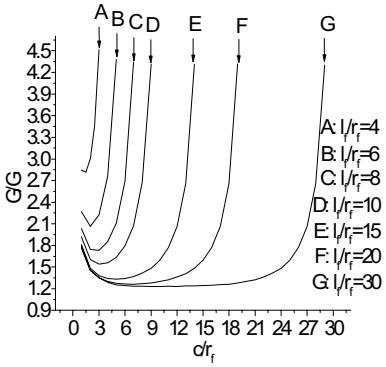

Fig.10. The energy release rate of interfacial crack for different embedded fiber length .

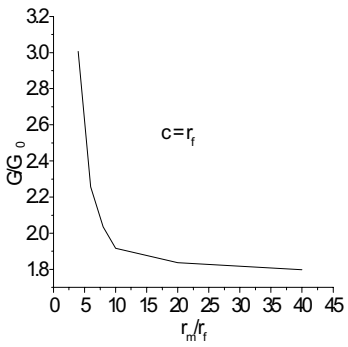

Fig.11.Relations between the energy release rate and the embedded fiber length

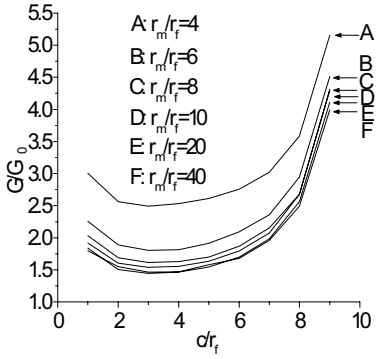

Fig.12. The energy release rate of interfacial crack for different wrapped matrix thickness

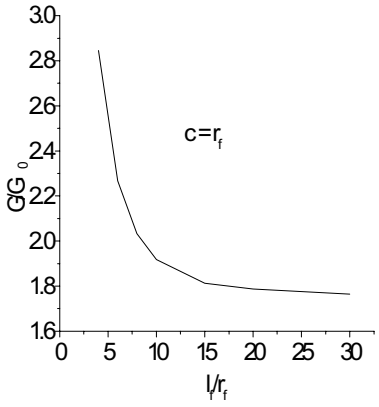

Fig.13. Relations between the energy release rate and the wrapped matrix thickness .

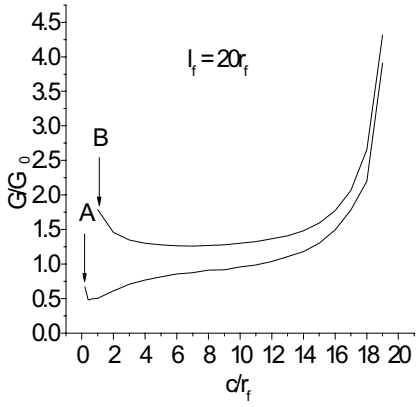

Fig.14.The energy release rate for the different displacement constraints.

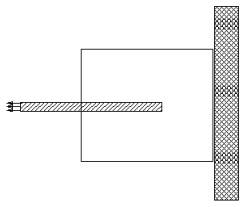

Fig.15.Another geometry model.

EFFECTS OF DISPLACEMENT CONSTRAINTS ON THE ENERGY RELEASE RATE

Now replace the displacement constraints in Fig.1 with constraints in Fig.15. In the process of the crack growth, the energy release rate will change to another case as compared with the former case, if the lower-end points are constrained by a stiff board bonding system. Then, near the upper-end points, energy release rate decrease gradually and it will reaches its minimum rapidly. After that, energy release rate

begins to go up and we can see a pronounced increment. As the crack grows, increment decreases, energy release rate changes little and a 'plateau range' exists. When the crack goes near the lower-end points, the energy release rate suddenly goes up till the fiber is completely pulled out (see Fig.14). For the case when fiber embedded length is relatively small, this plateau is so inapparent that sometimes it is nonexistent.

CONCLUSIONS

The effect of specimen size for the fiber pull-out test was studied by numerical method. The distributions of interfacial shear and normal stresses were obtained. And the influence of specimen size on the energy release rate of interfacial crack was discussed. The research can be concluded as follows:

(1)The interfacial shear and normal stresses is smaller while the embedded fiber length or the wrapped matrix thickness is bigger. After a certain point, the interfacial stresses do not decrease. For different wrapped matrix thickness, the interfacial shear stresses have a same value at some point of the fiber.

(2) For a fixed interfacial crack, the energy release rate is small while the embedded fiber length or the wrapped matrix thickness is bigger. After a certain value, it does not decrease. During the whole process of the interfacial crack growth, the energy release rate passes a ' plateau range '. But if the length of embedded fiber is short, the ' plateau range ' does not visible.

(3) The displacement constraints can influence considerably the energy release rate, when the interfacial crack is small. And during the whole process of crack growth, a large difference for the energy release rates appears near the upper-point.

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