

Experimental Study of the Fracture of the Bonding Interface between the EPDM Films

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Abstract. In this paper, the double cantilever sandwich beam (DCSB) specimens were used to study the mode-I fracture behaviour of adhesive interfacial of Ethylene Propylene Diene Monomer film. Simple beam theory, corrected beam theory and experimental compliance method were formulated to calculate the fracture toughness; the obtained experimental results were validated by comparing the obtained experimental results with finite element results, which derived from simulation that based on a cohesive zone model and inverse analysis, it also shows that the corrected beam theory and experimental compliance method calculate the toughness more accuracy than simple beam theory.

1 Introduction

Because of its heat-resistance and good low temperature properties [1], the Ethylene Propylene Diene Monomer (EPDM) is proved to be the best choice for the inhibitor materials of the Solid Propellant Rocket Motor (SRM). In the SRMs, the EPDM film is wrapped on the surface of the solid propellant layer by layer with the help of adhesive. But the EPDM is a kind of low-pole material[2], its adhesive property is very poor, the bonding interface between the EPDM film would fracture easily, thus the adhesive strength of the interface would be one of the key factors that effects the service behavior of the SRMs.

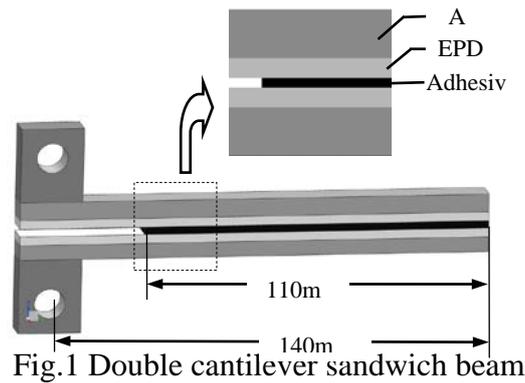
About the adhesive property of the EPDM, there are many researchers studied the factor that could improve its adhesive property. Such as adhesion technology [3], tackifier [4], addition in the EPDM [5]. But there are few study on the fracture behavior of the interface between the EPDM films. As one of the key factors that judge the adhesive property, fracture toughness is very important in both the design of adhesive bonded joints and the simulation of the joints.

Thus, this paper carried out the mode I fracture experiment to study the mechanical property of the interface between the EPDM films. The mode I fracture energy was determined by three linear elastic fracture mechanic (LEFM) methods. Then used the obtained fracture energy as the model parameters of the cohesive zone model (CZM) to simulate the fracture of the specimen. At last, by the means of inverse analysis, we got relatively accurate fracture energy of the interface.

2 Experiment

The double cantilever beam (DCB) specimen is simply made and the reduction of the data is convenient, had been used widely to study the fracture of adhesively bonded joints and lamination of composite materials [6~8].

As the result of its low stiffness, EPDM film can't be used as the cantilever, thus we added a substrate made of aluminum alloy to increase the stiffness of EPDM film and made a double cantilever sandwich beam(DCSB) specimen according to ASTM D3433[9] as shown in fig.1.



The experiment was carried out under the environmental condition of 42% relative humidity and 25°C. The specimens were loaded by an electric material testing system with a constant loading rate of 1mm/min. A CCD was used to observe the propagation of crack and locate its tip so as to record crack length in real time.

The specimen is 150mm in length, 10mm in width, the thickness of the substrate is 5mm. After the surface preparation of the substrate and EPDM film, bonded EPDM film on the substrate with an instant adhesive and then bonded the two cantilevers, the adhesive that used between EPDM films is a kind of two-component polyurethane adhesive. At last, remove the excess adhesives mechanically to leave the specimens with a smooth sides of the specimens and attach a scale to one side of the specimens so as to measure the crack length.

3 Result and discussion

3.1 Load-displacement curve

The load-displacement curves are shown in fig.2 and can be sectioned in three stages:

Linear loading stage (OA section): load increases in a linear way along with displacement continuously. The profile of the specimens are shown in fig.3 (a).

Damage stage (AB section): near the point A, damage appears at the crack tip (fig.3 (b)), at the ending of this stage, damage evolves into macroscopical crack shown in fig.3(c).

Propagation stage (BC section): the crack propagates continuously along with the increase of displacement, fig.3 (d).

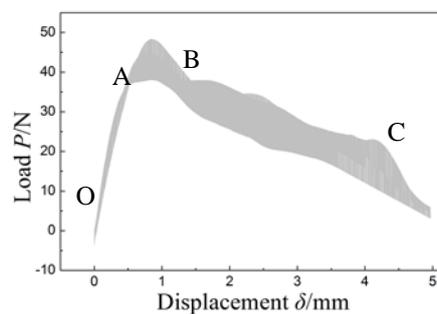
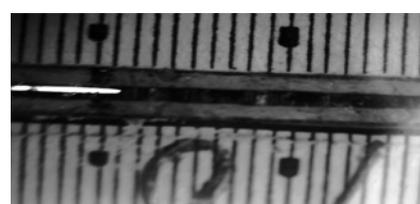


Fig. 2 Load-displacement curve



(a) Loading progress



(b) Damage progress



Fig. 3 The interface in the loading progress

Figure 4 displays the morphology of the interface after the experiments, the morphology are the same of all the specimens. As we can see, there was no adhesive left on the EPDM surface, this means that the failure mode of the interface between the EPDM film is interfacial debonding rather than decohesion of the adhesive and demonstrates that the adhesive strength between EPDM and adhesive is much less than the cohesive strength of the adhesive.



Fig. 4 Morphology of the failure interface

3.2 Methods of data reduction

In the linear elastic fracture mechanic, the mode I fracture energy is determined by the Kies-Irwin equation[10]:

$$G_{IC} = \frac{1}{2B} P^2 \frac{dC}{da} \quad (1)$$

B is the width of the specimen, P is load, C is compliance and a is crack length.

Different formulas of the dC/da lead to different equation for the fracture energy. Thus there exists three methods to determine mode I fracture energy.

(1) Simple beam theory(SBT)

In SBT method, the compliance of the specimen is:

$$C_{SBT} = \frac{8a^3}{E_s B h^3} \quad (2)$$

E is elastic modulus of the specimen, h is the thickness, l is the displacement between the load point and pivot. Thus equation for fracture energy is:

$$G_{IC} = \frac{3P\delta}{2Ba} \quad (3)$$

(2) Correct beam theory(CBT)

Fit the compliance of different crack length and draw a plot of $C^{1/3} \sim a$, the negative intercept is Δ [6]. Use it to correct the crack length and get the equation:

$$G_{IC} = \frac{3P\delta}{2Ba(a+\Delta)} \cdot \frac{F}{N} \quad (4)$$

where δ is the displacement of load point, F is the large displacement correction factor, N is a correction to correct for stiffening by the presence of the end-blocks and the rotation of the block and they are derived by Williams[11].

(3) Experiment compliance method(ECM)

The third method is to fit the compliance-crack length curve and find the relationship as:

$$C = Ae^{at} + y \quad (5)$$

A , t and y are three coefficient. Inserted into Kies-Irwin equation and get:

$$G_{IC} = \frac{P^2}{2B} \frac{A}{t} e^{at} \quad (6)$$

3.3 Fracture energy

Fit the discrete compliance and get the $C \sim a$ curves shown in figure 6. From the plots, we get the correction Δ and the coefficient of equation (7), and then the mode I fracture energy of DCSB specimen can be obtained use the equation (3), (4) and (6).

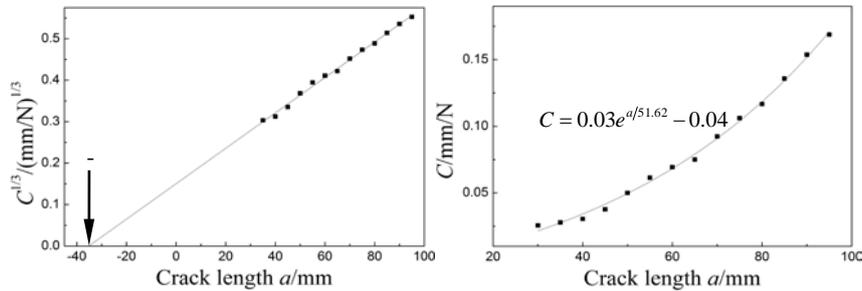


Fig.6 The fitted curves

As shown in figure 7 is the fracture energy of one specimen calculated by three methods. From the figure, we can observe that the fracture energy obtained by SBT decreases along with the increase of crack length but that obtained by CBT and ECM keep steady.

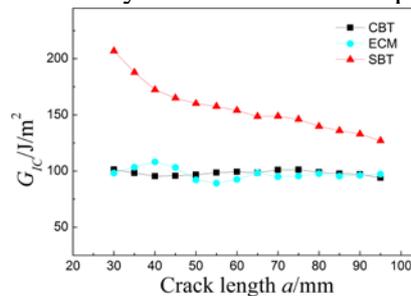


Fig. 7 G_{IC} vs. crack length via three different methods

Figure 8 shows the average fracture energy obtained via different methods for the whole specimens. We can observe that the fracture obtained by CBT and ECM were similar and there exists a large deviation compared with the results from SBT. The most repeatability standard deviation of different methods is 0.056, this means the repeatability of the experimental results is good.

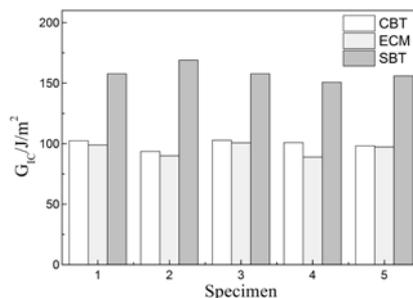


Fig. 8 Average values of fracture energy for specimens

4 Validation

There exists large deviation between the results obtained by three data reduction methods. In this section, we use the CZM to simulate the fracture behavior of the DCSB specimens to validate the availability of the experimental results.

4.1 Cohesive zone model

The CZM, which dates back to the work of Dugdale and Barenblatt, has been widely used in the

simulation of fracture of the materials and adhesively bonded joints. Its essence is the constitutive relation between the traction and separation of the crack surface, named cohesive law. Here we select the widely used bilinear cohesive zone model (fig.9) to simulate the fracture of the specimen.

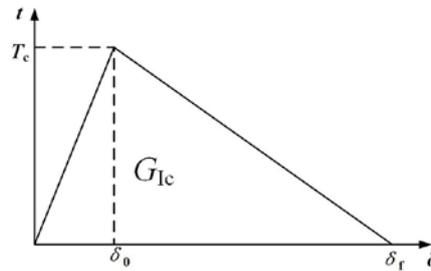


Fig.9 Traction-separation law of bilinear cohesive zone model

where t is traction, δ is separation, T_c is maximum traction named cohesive strength, δ_0 is critical separation, δ_f is maximum displacement, named failure displacement. The area between the x axis and cohesive law is the fracture energy G_{Ic} . Fracture energy and cohesive strength are the two key parameters of the bilinear cohesive zone model.

4.2 Numerical simulation

Another cohesive parameter cohesive strength is unknown, so we carried out an additional experiment to determine it. According to ASTM D2095[12], we determined the cohesive strength by the uniaxial tension experiment. To ensure the accuracy of the cohesive strength, the uniaxial tension specimens should be made in company with the DCSB specimens, and the experiment conditions are the same. The cohesive strength is 0.324MPa.

The finite element code ABAQUS is used to simulate the fracture of the DCSB specimen, and the two dimensional model of the specimen is displayed in fig.10. The geometry is the same with the manufactured specimens. The adhesive layer is modeled with four node cohesive element and aluminium alloy substrate four node quadrilateral solid element which has a elastic modulus of 70,000MPa and Poisson's ratio of 0.33. The material property of EPDM film is given in table 1.

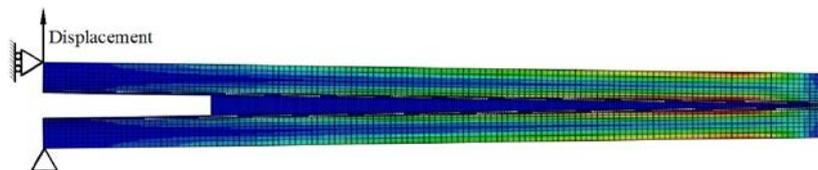


Fig. 10 The model of the DCSB specimen

Table 1: The coefficients of constitutive model of the EPDM

C10	C01	C20	C11	C02	D1	D2
24.82	-20.18	-	62.45	-	0	0

The simulation results are shown in fig.11. From the picture, we can observe that the descending branch of the curves match well except the simulation result of which the fracture energy is determined by SBT. The error of the cohesive strength leads to the large deviation of the increasing branch and peak load between the curves[13], this demonstrates that the fracture energy that determined by CBT and ECM is accurate.

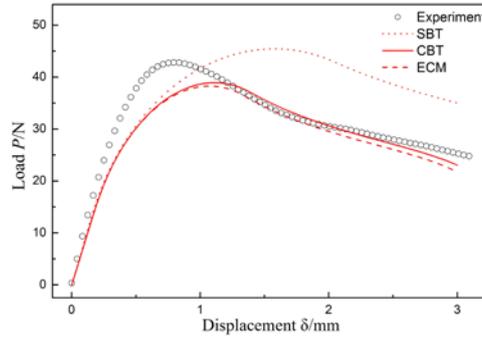


Fig. 11: The comparison of simulation and experiment curves

The cohesive strength of the model is not accurate, we can use another way named inverse analysis[14] to obtain accurate cohesive parameters, its essence is to adjust the parameters until the experiment and simulation curves match well. Figure 12(a) display the comparison of the experiment curve and simulation results of which the parameters are obtained by inverse method and fig.12(b) shows the curves of which the cohesive strength is obtained by the same method. We can observe that the experiment and simulation curves match well. This means the CBT and ECM obtained fracture energy is accurate and can be used to determine the fracture energy of the interface between the EPDM film. And the obtained fracture energy of the DCSB specimen is displayed in table 2.

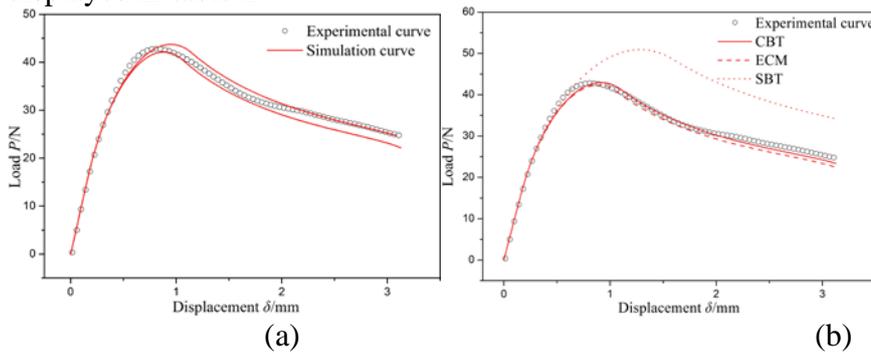


Fig.12: The comparison of experiment and simulation curves with accurate cohesive parameters

Table 2: Fracture energy of the DCSB specimen

	SBT	ECM	CBT	Inverse analysis
Fracture energy J/m ²	158.2	95.2	99.6	99 ± 5

5 Conclusion

In this paper, we studied the mode I fracture of the interface between the EPDM film, observed the propagation of the crack, the failure mode of the interface is interfacial debonding. Mode I fracture energy that obtained by CBT and ECM is much more accurate that of SBT and is very close to the real value, the fracture energy obtained by CBT can be used as the real value of the interface between EPDM film. The mode I fracture energy of the interface is 99.6J/m².

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