Available online at www.sciencedirect.com

SCIENCE DIRECT®

Composites Science and Technology 63 (2003) 155–159

COMPOSITES SCIENCE AND TECHNOLOGY

www.elsevier.com/locate/compscitech

A study on dynamic fracture toughness of composite laminates at different temperatures

Han Xiaoping[a,*], Han Shenliang[b], Yu Liang[a]

[a]The State Key Laboratory of Mechanical Structural Strength and Vibration, Xi'an Jiaotong University, China
[b]Department of Civil Engineering and Mechanics, Xi'an Jiaotong University, China

Received 4 July 2001; received in revised form 14 June 2002; accepted 26 July 2002

Abstract

The fracture toughness of glass-cloth/epoxy laminates has been determined under different temperatures and strain rates by means of the WEK fracture mode. To determine the parameters of WEK model, two groups of experiments must be conducted. One is the tensile experiment of smooth specimens (there is not a crack). Another is the tensile experiment of specimens with a crack. The tensile strengths are measured and the certain curves are drawn by means of the two experiments. Then, the characteristic length *a* for the laminates is obtained. Finally, from the values of *a*, the fracture toughness of the laminates is determined. The experimental results show that there exist clear effects of temperature and strain rate for the fracture behaviour of glass-cloth/epoxy laminates. Some problems of failure process and damage for the laminates have also been discussed. It is found that different damages are formed in the laminates under different temperatures and strain rates.

© 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Composite laminates; B. Fracture toughness

1. Introduction

Several attempts have been made in recent years to investigate the effect of strain rate on the fracture behaviour of composite laminates. Aliyu and Daniel [1] have observed the rate dependent Mode I fracture behaviour in graphite/epoxy composites. The result indicated that the fracture toughness of graphite/epoxy increased with loading rate increasing within a range of crosshead speeds from 0.5 to 500 mm min^{-1}. In contrast, Smiley and Pipes [2] reported that graphite/epoxy and graphite/PEEK showed strong negative rate dependence (i.e. fracture toughness decreased with loading rate increasing) under a speed of 0.25–40,000 mm min^{-1}. Mall et al. [3] also reported that woven carbon–fiber/PEEK showed negative rate dependence within a range of crosshead speed from 0.005 to 1000 mm min^{-1}, where the crack grew unstably. Gillespie et al. [4] examined the rate dependence of fracture behaviour in graphite/epoxy and graphite/PEEK. Their experiments showed that PEEK composites exhibit highly rate dependence. They suggested that the rate dependence is attributed to plastic and viscoelastic effects in the process zone. Hiley et al. [5] described results of tests on single-lap shear specimens of carbon/epoxy and carbon/PEEK laminates at both quasi-static and impact rates of loading. Examination of the interlaminar failure surfaces by optical and scanning electron microscopy revealed no significant effect of strain rate. Kusaka et al. [6] reported that the fracture toughness of carbon/epoxy laminates decreased with loading rate increasing. The crack growth behaviour changed from an unstable stick-slip manner to a stable continuous manner with loading rate increasing. In addition, Kander and Siegmann [7] studied changes in damage mechanisms in glass/polypropylene composites by varying the strain rate (1.67×10^{-6} to 1.67×10^{-2} s^{-1}). The changes were reflected in the mechanical response (σ–ε curve), the acoustic emission signature, and the morphology of the fracture surfaces as observed by SEM and optical microscopy.

The temperature dependence of fracture toughness of a composite is another important topic. Some investigators [8,9] found that the fracture toughness of mode increases with temperature. But others [10,11] test results showed that the the behavior of a composite at

---

* Corresponding author at: Department of Applied Mechanics, Northwestern Polytechnical University, China.

0266-3538/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0266-3538(02)00207-5

different temperatures is complicated. The temperature dependence of fracture toughness of a composite depends on its fiber/matrix interface bond and micro structure, and mechanical properties of matrix. So there still has been much controversy about the mechanism of temperature dependence of a composite.

Although there are many results about rate dependence of fracture behaviour in fibre reinforced composite laminates, very few systemmatic studies have been carried out on the fracture response under from quasi-static to impact loading. In particular, there is very little information on the dynamic fracture behaviour for composite laminates at moderate strain rate (1×10^{-4} to 10 s^{-1}).Our purpose here is to study the effects of strain rate on the fracture behaviour of composite laminates and dynamic fracture toughness under different temperatures and strain rates. Furthermore, the failure process and damage growth for the laminates under different conditions have been discussed.

2. Fracture toughness determination

Waddoups and coworkers [12], proposed a model of fracture toughness, i.e. WEK model. They suggested that the damage zone in the crack tip can be described by assuming a characteristic length a. The length a stands for the damage zone in the crack tip. The fracture toughness, K_c, is calculated by the following expression:

$$K_c = \sigma\sqrt{\pi(L+a)} \tag{1}$$

where L is the original crack length. The critical values of the stress (i.e. fracture strength), σ_c, at the onset of crack growth, was given by

$$\sigma_c = \frac{K_c}{\sqrt{\pi(L+a)}} \tag{2}$$

For $L=0$, σ_c becomes the tensile strength of the laminates, σ_0, which is estimated by

$$\sigma_0 = \frac{K_c}{\sqrt{\pi a}} \tag{3}$$

Combining Eqs. (2) and (3), the ratio of σ_c/σ_0 can be obtained by

$$\frac{\sigma_c}{\sigma_0} = \sqrt{a/(L+a)} \tag{4}$$

Rewriting Eq. (4), the characteristic length, a, can be calculated from the slope of the curves of original crack length versus parameter $\left[(\sigma_0/\sigma_c)^2-1\right]$

$$L = a\left[(\sigma_0/\sigma_c)^2-1\right] \tag{5}$$

The WEK model depends upon two parameters, i.e. the tensile strength σ_0 and characteristic length a. From the values of a, the fracture toughness K_c can be calculated by Eqs. (2) or (3). To measure the characteristic length a, two groups of experiments have to be conducted. Tensile tests of laminates were performed to obtain tensile strength σ_0. In fracture toughness tests, the critical stress σ_c of specimens with different initial crack length can be measured. From the values of σ_0 and σ_c, the parameters $[(\sigma_0/\sigma_c)^2-1]$ can calculated $[(\sigma_0/\sigma_c)^2-1]-L$ curves are drawn for different original crack length of specimens. The characteristic length a, i.e. the slope of the curves, can be determined by means of least-square fit.

3. Experiment

The composite laminates were composed of 18 plies of 0.14 plain-weave glass cloth and CYD-128 epoxy. The weight fraction of glass was 55%.

Fig. 1 shows the geometry of a specimen with aluminium end tabs. Original crack length L was varied from 6 to 12 mm. A 0.3-mm wide saw cut was introduced at the bottom of a 1-mm wide notch machined by a grinding cutter. Then a 6-mm diameter hole was drilled at the two ends of every specimen and a loading pin was installed in every hole.

Experiments have been carried out using a servo hydraulic material test machine system. The two loading rates (10^{-5}/s and 1/s) were adopted. The environment temperatures were selected as room temperature, 45 and 65 °C.

4. Results and discussion

The curves of stress versus strain for glass-cloth/epoxy were recorded at different temperatures and strain rates.

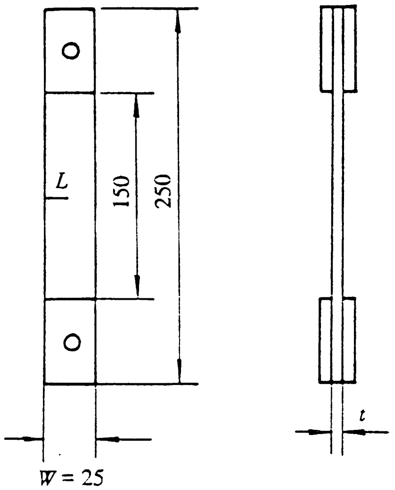

Fig. 1. Schematic diagram of specimens.

The tensile strength σ_0 and fracture strength σ_c (σ_0 varing with initial crack length) were measured. Typical $[(\sigma_0/\sigma_c)^2-1]-L$ curves are shown in Figs. 2, 3 and 4. The slopes of the curves, i.e. characteristic length *a*, were obtained by the least square method. The values of *L* can be regarded as an independent value of the initial crack length.

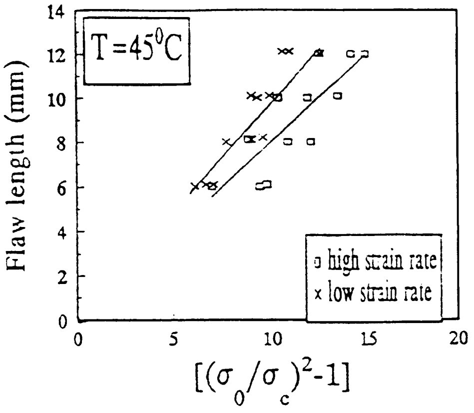

Fig. 2. $[(\sigma_0/\sigma_c)^2-1]-L$ curves.

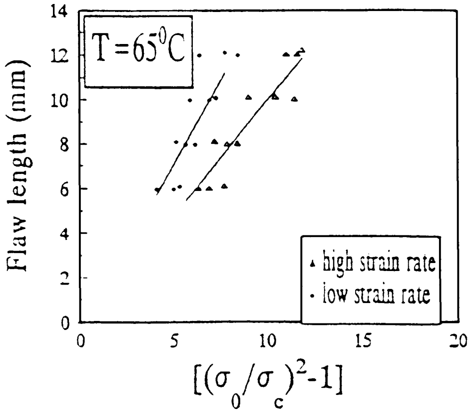

Fig. 3. $[(\sigma_0/\sigma_c)^2-1]-L$ curves.

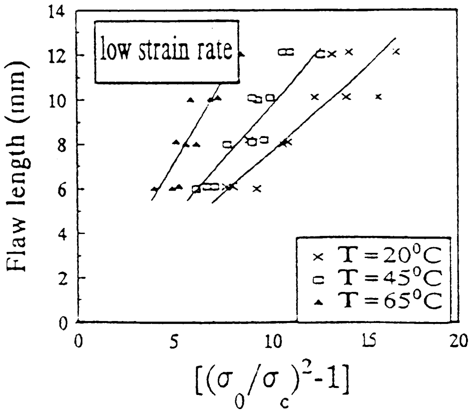

Fig. 4. $[(\sigma_0/\sigma_c)^2-1]-L$ curves.

Table 1
Fracture toughness for glass-cloth/epoxy laminates

Strain rate	10^{-5}/s			1/s		
Temperature	20 °C	45 °C	65 °C	20 °C	45 °C	65 °C
Tensile strength (MPa)	310.11	225.15	166.26	408.93	362.07	292.82
Characteristic length (mm)	0.76	0.97	1.42	0.88	0.78	0.96
Fracture toughness (MPa $\sqrt{m}$)	15.15	12.43	11.10	21.49	17.92	16.08

Table 2
Fracture work for glass-cloth/epoxy laminates

Strain rate	10^{-5}/s			1/s		
Temperature	20 °C	45 °C	65 °C	20 °C	45 °C	65 °C
Fracture work (Kg/mm)	3.40	2.71	2.12	6.20	5.31	4.56

The trend for the values of characteristic length a with changing loading rate and temperature can be found from the Table 1. The values of a increased with loading rate increasing at room temperature. On the contrary, there is a clear decreasing tendency with loading rate increasing beyond room temperature (i.e. at 45 and 65 °C). There is an increasing tendency with temperature rising for the values of *a*.

The fracture toughness K_c, tensile strength σ_0 and characteristic length a at three temperatures and two strain rates are shown in Table 1. At a given loading rate, the values of K_c decreased with temperatures increasing. And at a certain temperature, the values of K_c increased with loading rates increasing.

The fracture works r_F of the laminates under different temperatures and loading rates were also measured. The fracture works r_F is calculated by the following expression:

$$r_F = \frac{U}{2t(W-L)} \tag{6}$$

where *W* and *t* are, respectively, the width and the thickness of the specimen, and *L* is the original crack length. The deformation energy *U* corresponds to the load and the displacement when the crack develops.

Table 2 shows that, the faster the loading rate is, the larger the value of r_F is, and the higher the temperature is, the smaller the value of r_F. This is compatible with the dependency of fracture toughness on loading rate and temperature.

5. Features of damage and failure mechanisms

The damage area and failure pattern of glass-cloth/epoxy laminates under different loading rates and temperatures were shown in Figs. 5 and 6. From Fig. 5, it can roughly be found damage accumulation inside crack tip and failure process. It was observed in the

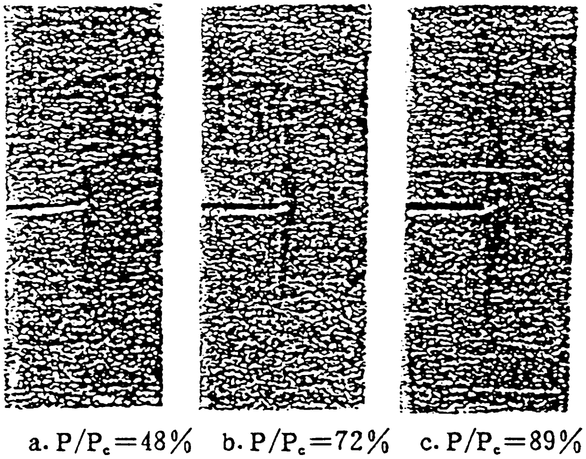
a. $P/P_c=48\%$ b. $P/P_c=72\%$ c. $P/P_c=89\%$

Fig. 5. Damage area and failure shape (temperature = 65 °C).

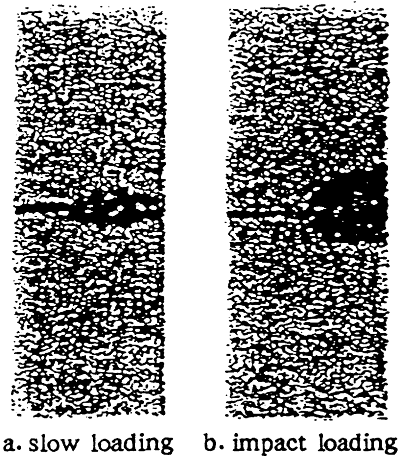
a. slow loading b. impact loading

Fig. 6. Damage area and failure shape (temperature = 23 °C).

experiments that a small white damage zone emerged near the crack tip when one third to one half of the peak load was applied. Then increasing load, the damage area gradually spreads and the voice of the crack split can be heard. Finally, the damage rapid increases and the whole specimen failed with approaching the peak load.

The extent of damage was different with changing loading rate. Fig. 6 shows that, at room temperature, the damage area at impact loading is much larger than that at quasi-static loading. These observations suggest that, the material could be adiabatic if the loading rate is high enough to neglect the heat condection, a substantial temperature rising emerges at localized region near crack tip, the heat transformed from the region leads to debonding between the fiber and matrix, matrix area spreads and finally a larger damage occurs. In contrast to this, at the elevated temperature (65 °C), damage became more extensive at slow loading than impact loading. The elevated temperature causes thermal softening of matrix resin. And with increasing load slowly, the damage accumulation process extend and finally it leads to deteriorate.

The shapes of damage are also different with changing temperature and loading rate. At room temperature, the direction of damage growth is along with transverse fiber (being consistent with the direction of initial crack). But at elevated temperature, the damage growth is starting from the crack tip and then spread simultaneous vertically and horizontally. The rough sketch for the damage area is similar to an isosceles triangle, as shown in Fig. 5.

In addition, the failure mode of specimens is transverse fracture along crack at room temperature. A failure mechanism is expected, that is, shear failure in matrix occured firstly, then debonding along interfaces and fiber fracture took place with crack growth, and finally the failure of a test specimen is mainly attributed to fibre fracture. The damage areas and fracture surfaces are different for different loading rates. The fracture surfaces are smooth at slow loading, and broom-like region under impact. At elevated temperature, the damage growth is along longitudinal direction and the failure mechanism could be related to crack along interfaces, delamination and other processes. The damage acculumation process accompanied probably by matrix resin softening, debonding along interfaces, fiber failure and delamination.

Acknowledgements

The present work was supported by Visiting Scholar Foundation of Key Laboratory in University and the Aeronautics Science Foundation of China.

References

[1] Aliyu AA, Daniel IM. Effects of strain rate on delamination fracture toughness of graphite/epoxy. ASTM STP 1985;876:336–48.

[2] Smiley AT, Pipes RB. Rate effects on mode I interlaminar fracture toughness in composite materials. J Comp Mat 1987;21:670–87.

[3] Mall S, Law GE, Katouzian M. Loading rate effect on interlaminar fracture toughness of a thermoplastic composite. J Comp Mat 1987;21:569–79.

[4] Gillespie JW, Carlsson LA, Smiley AJ. Rate-dependent mode I interlaminar crack growth mechanisms in graphite/epoxy and graphite/PEEK. Comp Sci Tech 1987;28:1–15.

[5] Hiley MJ, Dong L, Harding J. Effect of strain rate on the fracture process in interlaminar shear specimens of carbon fiber-reinforced laminates. Composites 1997;28:171–80.

[6] Kusaka T, Hojo M, Mai YW, Kurokawa T, Nojima T, Ochiai S. Rate dependence of mode I fracture behaviour in carbon-fiber/epoxy composite laminates. Comp Sci Tech 1998;58:591–602.

[7] Kander RG, Siegmann A. The effect of strain rate on damage

mechanisms in a glass/polypropylene composite. J Comp Mat 1992;26:1455–73.

[8] Hunston DL, Bascom WD. Effects of lay-up temperature and loading rate in double cantilever beam tests of interlaminar crack growth. Composites Technology Review 1983;5:118–9.

[9] Hine PJ, Brew B, Duckett RA, Ward IM. Failure mechanisms in continous carbon-fiber reinforced composites. Comp Sci Tech 1989;35:31–51.

[10] Jiang LH, Rowlands RE. Fracture behaviour of extren at room temperature and 77K. J Comp Mat 1990;24:326–44.

[11] Hartwig G, Kneifel B, Pohlmann K. Fracture properties of polymers and composites at cryogenic temperatures. Advances in Cryogenic Engineering Materials 1986;32:169–77.

[12] Waddoups ME, Eisenmann JR, Kaminski BE. Macroscopic fracture mechanics of advanced composite materials. J Comp Mat 1971;5:446–54.