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Fatigue Growth Behavior of Mode I Delamination in Composite Laminates Subjected to Hydrothermal Environments

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Most research results have illustrated that mode I fracture usually take a lager portion (>50%) in damage of composite laminates, and critical energy release rate of mode I interlaminar fracture is the lowest in value compared with that of other two fracture modes. Therefore, The mode I interlaminar fracture behavior of laminates has been widely focused and studied. O'Brien had conducted researches on edge delamination, mode I and mode II delamination growth in composite laminates [1,2]; Bathias studied fatigue growth characteristics of interlaminar delamination and effects of stress ratio and frequencies on the process of interlaminar crack growth of glass/epoxy composite laminates [4]. Hojo had done a lot of works on evaluation and test method of mode I interlaminar crack growth, and established a test approach for determining fatigue growth rate of interlaminar delamination in composites[5-7]. Though many results have been achieved in this research field, less works involved fatigue growth behaviors of delamination in composites under hydrothermal environments. This investigation mainly deal with the influence of hydrothermal environments on behaviors of mode I fatigue delmination growth in composite laminates.

EXPERIEMENTS

Two types of composite laminates were used in this investigation: T300/5405 graphite/bismaleimide laminates and T300/3261graphite/epoxy laminates. The schematic of specimen with $[0°]_{24}$orientation was shown in Fig.1. The width of specimen is 25mm and length is 180mm. A Teflon film was inserted between middle layers to form an interlaminar crack about 40mm at one end of specimen.

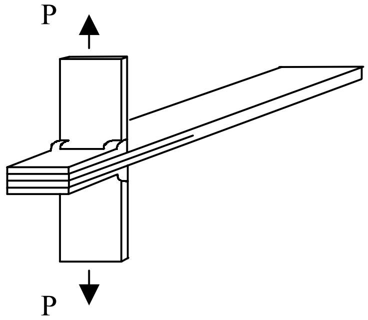

Fig.1 Schematic of Specimen and Loading Condition

Specimens for characterizing mode I delamination under hydrothermal environments were first heated at 80℃ in a oven to a state almost without water content and then immersed into 80℃ water until desired water contents had been reached. The amount of water absorbed was evaluated by the variance of specimen weight as following:

$$m = \frac{w - w_0}{w_0} \times 100 \qquad (1)$$

where m is moisture content, w specimen weight, w_0 specimen weight when there is no moisture inner specimen.

Double cantilever beam (DCB) test was used to determine static mode I fracture toughness and energy release rate during fatigue delamination propagation for both dry and wet laminates. Before mode I fracture test, notch end flexure loads were exerted on specimens in order to form sharp crack tips. The extended crack length by ENF method was limited below 5mm and whole length of precrack was confined to 45mm.

A technique based on photo-electricity and image processing method was developed for monitoring and measuring crack growth length during mode I delamination. Fig.2 is the sketch map of this technique. Crack image appeared at the side of tested specimen is captured

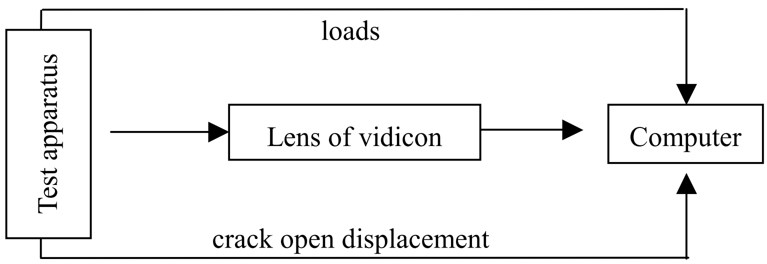

Fig.2 sketch map of delamination crack monitoring and measuring system

by lens of vidicon and input into computer. Computer determines delamination crack length through processing the image with especially developed software and records loads and crack open displacements simultaneously. From length calibration, it is found that the measuring error of this technique is less than 0.1mm for visual field of 25mm.

Static and fatigue tests were conducted on Instron 1253 servo-hydraulic test system. To satisfy the accuracy requirement, a load cell with 300N capacity was employed in whole test process. In fatigue tests, specimens were cycled sinusoidally at a frequency of 3Hz and a stress ratio of 0.4.

MODE I INTERLAMINAR FRACTURE TOUGHNESS

Mode I interlaminar fracture toughness G_{IC} was determined by standardized DCB test method, HB 7402-96, in which G_{IC} is expressed as

$$G_{IC} = \frac{nP_c\delta_c}{2ba} \qquad (2)$$

where P_c and δ_c are critical load and crack open displacement respectively, b is specimen width, and a is interlamiar crack length. n is obtained through crack length - specimen compliance calibration as following:

$$\lg C = A + n \lg a \qquad (3)$$

C is specimen compliance characterized as $C = \dfrac{\delta}{P}$. A and n are related constant which should be determined experimentally.

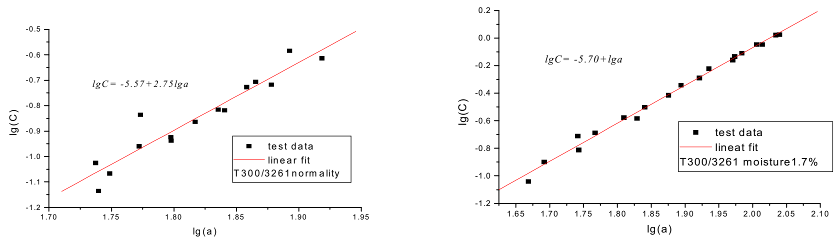

Fig.3 Crack-compliance calibration curve for T300/3261composites

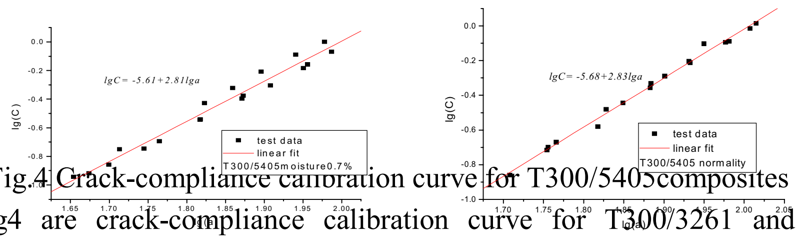

Fig.4 Crack-compliance calibration curve for T300/5405composites

Fig3 and Fig4 are crack-compliance calibration curve for T300/3261 and T300/5405 composites in both state of normality and containing moisture, from which it can be found that there are certain amount of variances in slopes of the curves and lager slope variance is seen after moisture was taken to a content of 1.7% for T300/3261 composites. This phenomenon indicates that moisture in composites may influence the interlaminar fracture performance.

The effective interlaminar crack lengths were limited to avoid nonlinear effects in a range of 45mm to 85mm. Table 1 shows experimental results of mode I interlaminar fracture toughness G_{IC} of T300/5405 and T300/3261 composite laminates in both state of normality and of containing water, from which it can be seen that the increasing of moisture contents improves interlaminar fracture toughness of T300/5405 composites, but decreases the value of

Table 1 G_{IC} of T300/5405 and 300/3261 composite laminates J/m^2

Materials	Material state						
	Normal			Containing water			
	$\overline{G_{IC}}$	S	Cv %	$\overline{G_{IC}}$	S	Cv %	Moisture contents
T300/5405	179	9.62	5.3	202	12.1	6.0	0.7%
T300/3261	290	19.0	6.5	162	8.88	5.4	1.7%

interlaminar fracture toughness of T300/3261 composites. It may be explained that moisture releases the residual stress and plasiticates matrix of composites. Under scan electric microscope, many small cavities were found on fractograph of T300/3261 composites. Theses small cavities may worsen the interfacial behaviors of inter-layers after moisture taken and induce the decreasing of G_{IC}.

Fig 5 Fractograph for T300/3261 composites

FATIGUE INTERLAMINAR CRACK GROWTH BEHAVIOR

With crack-compliance calibration curve and G_{IC} , critical compliance at which interlaminar cracks start to grow can be determined:

$$\delta_c = \sqrt{\frac{2baC}{n} G_{IC}} \qquad (4)$$

DBC fatigue experiments were conducted under displacement control in which the maximum displacements are defined as

$$\delta_{\max} = k\delta_c \qquad (5)$$

where k is called loading parameter.

In displacement controlled DBC fatigue experiments, k and maximum energy release rate G_{Imax} decreases with growth of interlaminar crack as shown in Fig6 and Fing7. O'Brein and his colleagues has indicated, from their research results, that there exists a threshold fracture energy release rate G_{th} at which interlaminar crack will not grow, and G_{th} is about in the range

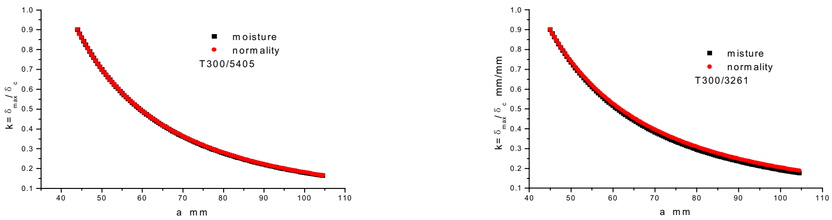

Fig.6 k –a curve at displacement controlled DBC fatigue test

of a sixth to a forth of G_{IC} [1]. It has been found in this experiments that once the growth length of interlaminar cracks reach about 20mm, G_{Imax} will fall into the range of a sixth to a forth of $G_{IC.}$

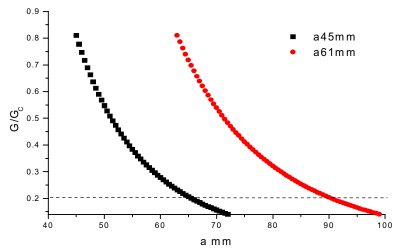

Fig.7 The variation of G_{Imax}/G_{IC} in displacement controlled DBC fatigue tests

This means that the maximum crack growth length will not exceed 20mm in displacement controlled DBC fatigue tests with a constant k value. Therefore, δ_{max} was raised in this research to maintain crack growth rate by increasing k to 0.80 or 0.75 after the crack extended to about 15mm. Initial δ_{max} was selected as 0.90 while start crack length was about 45mm.

Interlaminar crack growth rate can be calculated by

$$\frac{\Delta a}{\Delta N}=\frac{a_{i+1}-a_i}{N_{i+1}-N_i} \qquad (6)$$

where a_i is the crack length related with definite cycle N_i . The smaller $\triangle a$, the more accurate is interlaminar crack growth rate. However, circumscribed by the self-characterization of interlaminar crack and test technique, $\triangle a$ should be kept to a certain value in order to ensure data adaptability. $\triangle a$ was within 2 - 4mm in this research.

Maximum mode I interlaminar energy release rate correlated to crack growth rate is determined by

$$G_{\mathrm{Im}ax}=\frac{n\delta_{\max}^2}{2ba'C} \qquad (7)$$

where $a'=\dfrac{a_{i+1}+a_i}{2}$.

With the data processing method described above, interlaminar crack growth rates and interrelated G_{Imax} were calculated and determined from DBC fatigue tests for composite laminates in both states of normality and containing water. The experimental results for both composites in normality were shown in Fig.8, from which it can be seen that though data scatter is larger in this state, a tendency of proportional increments of logarithmic interlaminar crack growth rates with logarithmic G_{Imax} appears. G_{Imax} interrelated to interlaminar growth rate, 3×10^{-5}*mm/cycle*, is above $100J/m^2$ for T300/3261 composites, but below $100J/m^2$ for T300/5405 composites. this result indicates that the energy needed for driving interlaminar crack to achieve the same growth rate is higher for T300/3261graphite/epoxy composites than that for T300/5405 graphite/bismaleimide composites; T300/3261 is more resistible to mode I interlaminar crack growth in normal state.

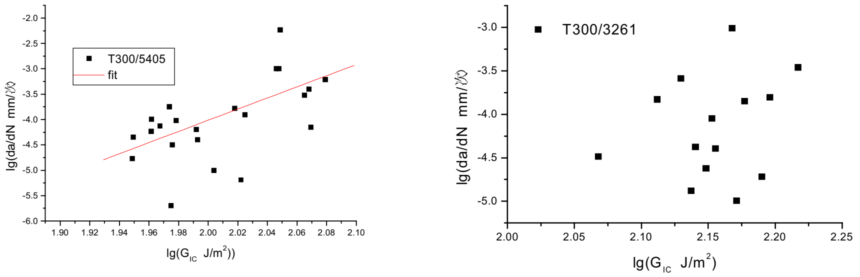

Fig.8 Fatigue growth rate of mode I delamination for composite laminates in normality

Experimental results for T300/3261 with 1.7% moisture content and T300/5405 with

0.7% moisture content were shown in Fig.9. By fitting these data, it is found that following relationship exists for T300/3261 composite laminates:

$$\lg(\frac{da}{dN}) = -7.1 + 2.0\lg(G_{\mathrm{I}max}) \qquad (8)$$

and for T300/5405 composite laminates:

$$\lg(\frac{da}{dN}) = -12.1 + 4.4\lg(G_{\mathrm{I}max}) \qquad (9)$$

this indicates that the process of mode I interlaminar fatigue crack growth follows the rule of $\frac{da}{dN} = AG^{m}_{\mathrm{I}max}$ for composite laminates with inner moisture.

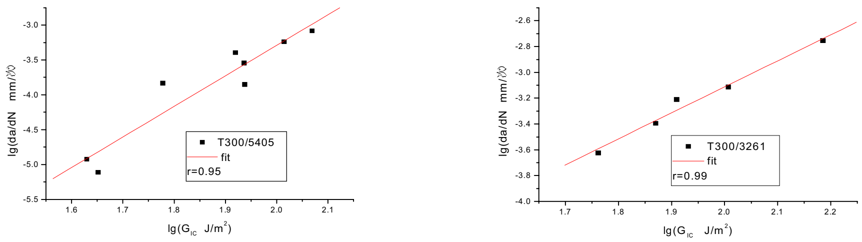

Fig.9 Fatigue growth rate of mode I delamination for composite laminates after subjected to hydrothermal environments

Contrary to the performance of both composites in normality, the value of G_{Imax} needed to reach the same crack growth rate for T300/3261 is less than that for T300/5405 after moisture taken. This phenomenon shows that moisture is more effective on the weakening of interlaminar crack resistance for T300/3261 than for T300/5405 composite laminates. By comparing the experimental results of the same composites with and without water, it was found that, at about the same crack growth rate, the maximum energy release rate G_{Imax} for both composites with moisture content is less than that in normality and the smallest value of G_{Imax} was found for T300/3261 composites with 1.7% moisture content. Thus, it can be concluded that water absorbed from surroundings accelerates fatigue growth rate of mode I delamination in both graphite/epoxy and bismaleimide composite laminates and weakens its abilities to resist fatigue delamination growth.

CONCLUSION

Investigations on fatigue performance of composites with and without water indicated that the process of mode I interlaminar fatigue crack growth roughly follows the rule of $\frac{da}{dN} = AG^{m}_{\mathrm{I}max}$, large scatter of interlaminar fatigue crack growth rate appears in normality for both laminates, while the scatter become small after laminates were subjected to hydrothermal environments and absorbed a certain amount of water; Water absorbed from environments accelerates fatigue growth rate of mode I delamination. in both composite laminates and weakens its abilities to resist fatigue delamination growth.

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