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Application News

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Material Testing System

MMB Test of CFRP in Conformance with ASTM D6671

Introduction

Carbon fiber reinforced plastic (CFRP) do not oxidize or rust and have a higher specific strength and stiffness than conventional materials. Applications of CFRP are being investigated, with a focus on applications as aircraft materials that require strength and durability. However, the superior mechanical properties of CFRP laminate are limited to a strengthened direction (parallel to fibers), and the strength of CFRP laminate is reduced significantly in directions that are not strengthened (interlaminar direction, for example.). CFRP laminate are also susceptible to impact, with out-of-plane impacts causing internal damage, such as peeling laminates, to CFRP laminate. The design and product development of CFRP laminate therefore incorporates damage tolerant design, which takes into consideration the effects of internal damage on the strength of the material. Damage tolerant design must determine how resistant a material is to interlaminar crack propagation, which is done by fracture toughness testing.

For homogeneous isotropic materials, only fracture Mode I (crack opening mode) is evaluated normally in fracture toughness testing. Materials that are a composite of a resinous matrix and fibers are anisotropic, and it is important these materials are evaluated not just for fracture Mode I, but also for fracture Mode II (crack sliding mode), fracture Mode III (crack tearing mode), and mixed mode fractures (See Fig. 1). Mixed-mode bending (MMB) tests are used to evaluate fracture toughness in a mixed mode that combines Mode I and Mode II. Features of MMB testing are the mixed mode ratio (hereinafter referred to as mode ratio) can be changed on subsequent tests, and it is almost unchanged by crack propagation. While the stress intensity factor *K* is often used to evaluate the toughness of homogeneous isotropic materials, the interlaminar fracture that occurs in anisotropic composite materials is commonly evaluated using the energy release rate *G*, which is proportional to the square of the stress intensity factor *K*. 1)

MMB testing was performed in conformance with ASTM D6671 and the total mixed-mode fracture toughness G_c was determined at four different mode ratios (proportion of Mode II energy release rate to total energy release rate) of $G_{II}/G = 0.16, 0.30, 0.50$, and 0.70.

Y. Kamei

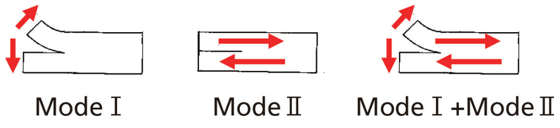


Fig. 1 Mode I and Mode II

ASTM D6671M - 06

Fig. 2 shows a schematic of the jig for MMB testing. By using the jig for MMB testing, Mode I double cantilever beam (DCB) testing (ASTM D5528) and Mode II end-notched flexure (ENF) testing (JIS K 7086) can be performed simultaneously. As shown in equation (1), a variety of mode ratios can be tested by changing the position of ① Yoke and ② Roller holder (values *c* and *L*, respectively). The mode ratio is changed in the course of MMB testing to determine the dependence of the total mixed-mode fracture toughness G_c on mode ratio.

The test load P_c used to analyze the total mixed-mode fracture toughness G_c is calculated as shown in Fig. 3. The points (1) NL, (2) 5 %/max, and (3) VIS are described below.

(1) NL: Point of deviation from linearity in the load-displacement curve

(2) 5 %/max: Point at which the compliance has increased by 5 % or the load has reached a maximum value

(3) VIS: Point at which the delamination is first visually observed to grow on the edge of the specimen

The total mixed-mode fracture toughness G_c can be calculated by the above three methods.

The ASTM standard includes the option of determining the energy release rate *G* at various points during propagation of a crack, and not just at the start of the crack.

$$\frac{G_{II}}{G} = \frac{3(c+L)^2 (a+0.42\,Xh)^2}{4(3c-L)^2 (a+Xh)^2 + 3(c-L)^2 (a+0.42\,Xh)^2} \quad \cdots \text{ Equation (1)}$$

c, L, a, h: See Fig. 2.
X: Crack length correction parameter (See the ASTM standard.)
G_{II}/G: Mode ratio
G_I, G_{II}: Strain energy release rate of Mode I and Mode II (See the ASTM standard.)
G: Total mixed-mode strain energy release rate ($= G_I + G_{II}$)
G_c: Total mixed-mode fracture toughness ($= G|_{Pc,\,a0}$)

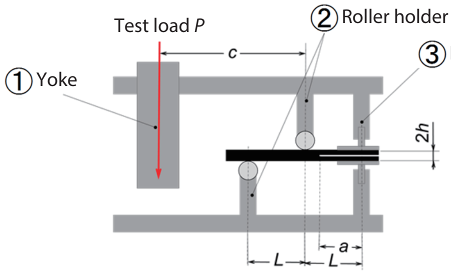


Fig. 2 MMB Test Apparatus

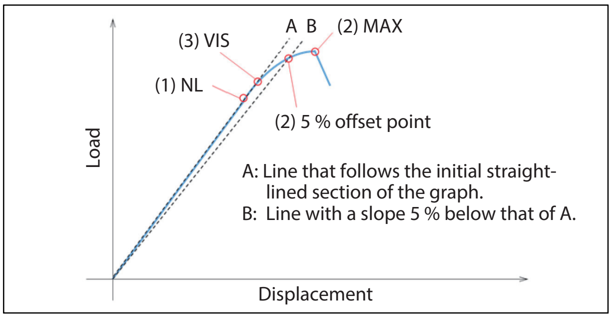


Fig. 3 Test Load Used for G_c Calculation

Measurement System

Fig. 4 is the test specimen used, Fig. 5 shows how the test was set up, Table 1 shows the equipment used, Table 2 provides information about the test specimen, and Table 3 shows the test conditions.

Scale marks were written on the side of the test specimen to confirm crack propagation, and a Mode I test tab was attached to the test specimen. A 13 µm film was also inserted between the laminar layers during preparation of the test specimen to introduce the initial crack into the test specimen.

In testing, crack propagation appearance was confirmed up to 10 mm (delamination length a of 35 mm). A close-up ring was attached to the TRViewX non-contact digital video extensometer to capture video of the scale marks in high resolution and confirm crack propagation on video. Since TRViewX was used to record video, the recorded video could be viewed alongside the test results during data analysis (See Fig. 6).

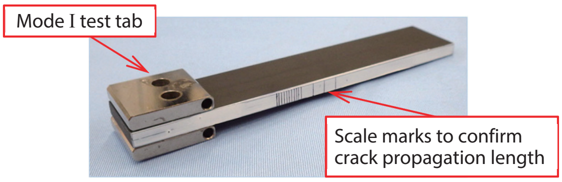


Fig. 4 Specimen

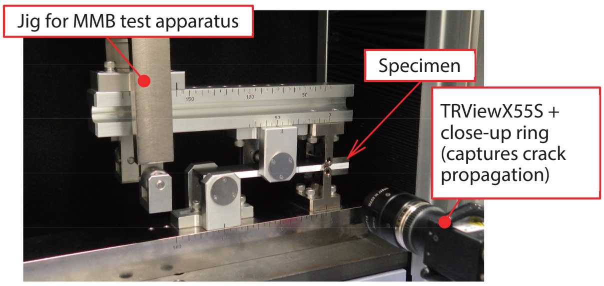


Fig. 5 Test Setup

Table 1 Experimental Equipment

Testing Machine	:	AG-5kNX plus universal testing Instrument
Load Cell	:	5 kN
Measurement Jig	:	MMB test apparatus
Software	:	TRAPEZIUM X (Single)
Crack Length Observations	:	TRViewX55S non-contact digital video extensometer with close-up ring

Table 2 Specimen Information

Prepreg	:	T800S
Lamination Method	:	$[0]_n$
Specimen Thickness	:	5.5 mm
Specimen Width	:	25.2 mm
Specimen Length	:	137 mm
Initial Crack Length	:	50 mm

Table 3 Test Conditions

Test Speed	:	0.5 mm/min
Mode Ratio	:	0.16 (c = 110, L = 50)
		0.30 (c = 60, L = 50)
		0.50 (c = 40, L = 50)
		0.70 (c = 30, L = 50)

A crosshead separation was also used for displacement measurement. When a crosshead separation is used to measure displacement, the effects such as the deformation of the testing machine are included in the measured displacement, so this method cannot be used to measure the strain energy release rate G accurately. Testing system compliance correction is therefore performed as shown below.

Using compliance specimen which is at least as stiff as a steel bar with I=450 mm^4, with a known modulus value, the MMB testing at 75 % of the maximum test load. The slope m_{cal} is then taken from the resulting load-stroke curve and used to calculate the compliance correction value C_{sys} as shown in equation (2). Table 4 shows the compliance correction values for each mode ratio.

$$C_{\mathrm{cal}} = \frac{2L(c+L)^2}{E_{\mathrm{cal}} b_{\mathrm{cal}} t^3}$$

$$C_{\mathrm{sys}} = \frac{1}{m_{\mathrm{cal}}} - C_{\mathrm{cal}} \quad \ldots \text{ Equation (2)}$$

C_{cal}: Calibration specimen compliance
E_{cal}: Modulus of calibration bar
b_{cal}: Width of calibration specimen
C_{sys}: System Compliance
t: Thickness of calibration bar
c, L: See Fig. 2.

Table 4 System compliance

Mode ratio G_{II}/G	Compliance C_{sys} ($\times 10^{-4}$)
0.16	13.15
0.30	5.55
0.50	3.89
0.70	3.33

Test Results

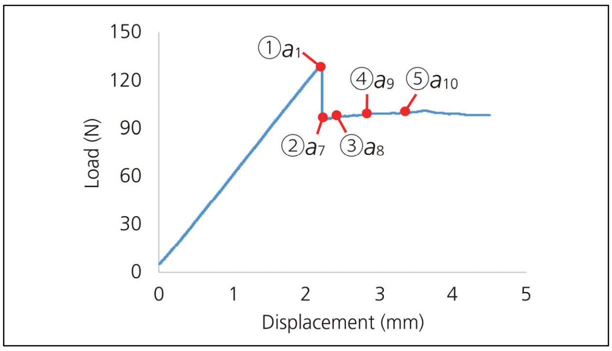
Table 5 shows the test results from a 0.16 mode ratio. This result shows the mode ratio is constant and not dependent on crack propagation. Test results for a_2 through a_6 are not shown as crack propagation occurred extremely rapidly in this area, preventing calculation results as delamination length could not be confirmed on the captured video images.

ASTM D6671 requires the total mixed-mode fracture toughness G_c to be calculated from the value at the crack start point a_0. There are three methods of determining a_0: (1) NL, (2) 5 %/max, and (3) VIS. In general, the value of a_0 increases in order of (2) > (3) > (1).

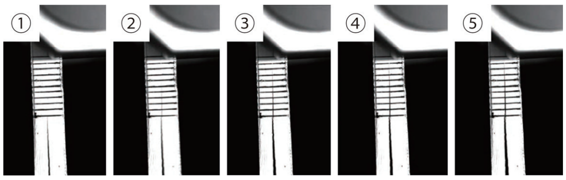
Fig. 6 shows video images captured at each of the crack lengths shown in Table 5. Images (1) though (5) in Fig. 6 (b) correspond with points (1) through (5) shown in Fig. 6 (a).

Table 5 Example Test Results

Crack Delamination Length a (mm)			Load P (N)	G_I (kJ/m^2)	G_{II} (kJ/m^2)	G (kJ/m^2)	Mode Ratio G_{II}/G
a_0	25	NL	113.7	0.232	0.046	0.278	0.165
		5%/max	130.0	0.303	0.060	0.363	0.165
a_0	25	VIS	126.4	0.286	0.057	0.343	0.165
a_1	26	1	97.3	0.664	0.045	1.333	0.157
a_2	27	2	–	–	–	–	–
a_3	28	3	–	–	–	–	–
a_4	29	4	–	–	–	–	–
a_5	30	5	–	–	–	–	–
a_6	31	6	–	–	–	–	–
a_7	32	7	94.6	0.323	0.062	0.385	0.162
a_8	33	8	96.1	0.352	0.068	0.420	0.162
a_9	34	9	97.2	0.379	0.074	0.453	0.163
a_{10}	35	10	98.2	0.407	0.080	0.512	0.164



(a) Load-Displacement Curve



(b) State of Crack Delamination

Fig. 6 (a) Load-Displacement Curve and (b) State of Crack Delamination

Fig. 7 shows test load-displacement curves for results obtained at four different mode ratios, and Fig. 8 and Table 6 show the relationship between the total mixed-mode fracture toughness G_c (NL) and the mode ratio. As seen in Fig. 8, the greater the mode ratio G_{II}/G, the larger the total mixed-mode fracture toughness G_c (NL), and so the greater the fracture toughness.

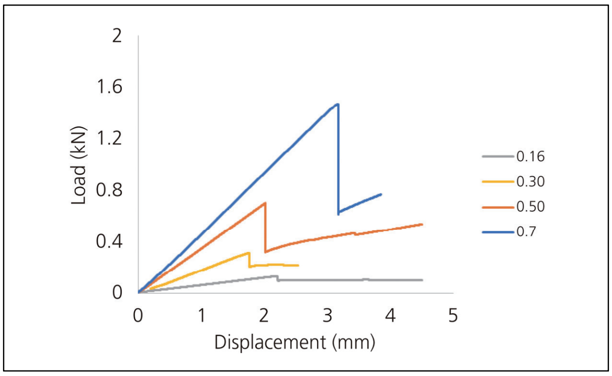


Fig. 7 Load-Displacement Curves

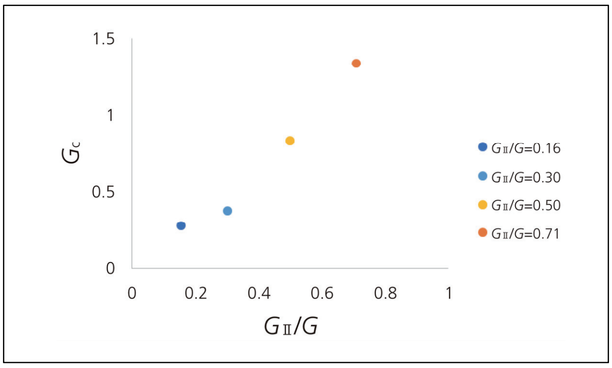


Fig. 8 Relationship Between the Total Mixed-Mode Fracture Toughness G_c (NL) and the Mode Ratio

Table 6 Relationship Between the Total Mixed-Mode Fracture Toughness G_c (NL) and the Mode Ratio

Mode Ratio G_{II}/G	G_c (kJ/m^2)
0.16	0.28
0.30	0.38
0.50	0.84
0.71	1.34

Conclusion

MMB testing was performed in compliance with ASTM D6671 and the total mixed-mode fracture toughness G_c was determined at mode ratio $G_{II}/G = 0.16, 0.30, 0.50,$ and 0.70. The ASTM D6671 standard includes the option to determine change in the energy release rate G against crack propagation up to 25 mm (delamination length of 50 mm), though on this occasion the change in the energy release rate G was determined up to 10 mm (delamination length a of 35 mm).

The TRViewX was used to confirm crack propagation. Using TRViewX allowed the capture of video images of the test specimen synchronized with the test load-displacement curve results (See Fig. 6), which allowed for easy calculation of G_c.

Using the MMB test apparatus in almost no change in the mixed mode ratio of Mode I and Mode II, which allows for mixed mode tests.

References

*1 New Edition: Technical Reference Manual - Composite Materials (2011)

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