Application News

Precision Universal Testing Machines AGX™-V

DCB Tests on CFRP in Accordance with ASTM D5528

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User Benefits

- It is possible to measure the interlaminar fracture toughness, which is necessary for designing CFRP.
- The delamination length can be observed after testing by video recording delamination growth using TRViewX.

Introduction

Applications of carbon fiber reinforced plastics (CFRP), which do not corrode and have high specific strength and specific stiffness compared to conventional materials, are being investigated primarily in regards to aerospace materials, which must be both strong and durable. However, CFRP laminates are known to exhibit excellent mechanical properties only in the reinforced direction (fiber direction), in contrast to the strength in the unreinforced directions (interlaminar direction, etc.), which is significantly lower. Also, CFRP laminates are not impact-resistant, and damages such as delamination can occur on impact. Therefore damage-tolerant designs, which take into consideration the effect of internal damage on the strength of the material, are incorporated in design and product development. In order to implement damage-tolerant designs, it is necessary to determine the resistance to delamination growth, so fracture toughness tests are performed.

For homogeneous isotropic materials, normally only Mode I (opening mode) fracture toughness tests are performed. However, composite materials consisting of fibers in a plastic matrix are anisotropic, so it is important that they be evaluated not only in Mode I, but also in Modes II (in-plane shear) and III (out-of-plane shear). (Fig. 1) The Double Cantilever Beam (DCB) test evaluates the properties in pure Mode I. The stress intensity factor K is frequently used to evaluate the toughness of homogeneous isotropic materials. However, for composite materials that are anisotropic, the strain energy release rate G is generally used to evaluate interlaminar fractures. The strain energy release rate G is proportional to the square of the stress intensify factor K.

In this article the Mode I interlaminar fracture toughness G_{Ic} was obtained by performing DCB tests in accordance with ASTM D5528.

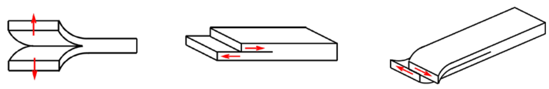

Fig. 1 Schematic Diagram of Modes

Mode I Interlaminar Fracture Toughness G_{Ic}

Fig. 2 shows the method for determining the test force P, which is used to calculate the Mode I interlaminar fracture toughness G_{Ic}. The definitions for (1) NL, (2) 5 %/max, and (3) VIS are as follows.

(1) NL: Point of deviation from linearity
(2) 5 %/Max: 5 % offset point or maximum test force point
(3) VIS: Point at which delamination is visually observed

The Mode I interlaminar fracture toughness G_{Ic} can be obtained from the above three methods.

There are four methods for calculating G_{Ic}: ① No correction, ② MBT, ③ CC, and ④ MCC. ASTM D5528 states that "Because G_{Ic} values determined by the three different data reduction methods differed by no more than 3.1 %, none of the three were clearly superior to the others. However, the MBT method yielded the most conservative values of G_{Ic}." Accordingly, the MBT method is recommended. (Refer to the Supplementary section on page 4 for the method of calculating G_{Ic}.)

Measurement System

Fig. 3 shows the test specimens used. ASTM D5528 prescribes that a scale be marked on both edges of the test specimen every 1 mm up to a delamination length of 5 mm, as well as every 5 mm from 5 mm to 25 mm. However, in these tests a scale for confirming the delamination growth was marked on one side of the test specimen, while on the other side a crack gauge was installed for confirming the delamination length. In addition, loading blocks were bonded to the test specimens for applying the loads in the Mode I direction. Also, during production of the test specimens, a thin film was placed between the laminations to form an initiation site for the delamination.

In these tests, the extent of delamination growth was monitored up to a length of 50 mm from the tip of the initial delamination. A close-up ring was installed on a video-type non-contact extensometer (hereafter referred to as TRViewX). The scale was photographed at high magnification, and the delamination length was confirmed using the camera. Using TRViewX to save the video made it possible to perform the calculations while reviewing the video synchronized with the results after the tests.

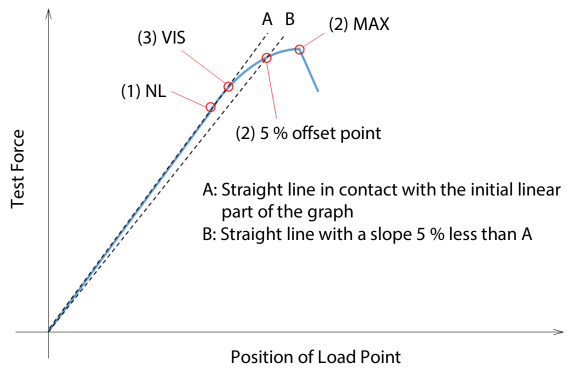

Fig. 2 Position of the Test Force for Obtaining the Mode I Interlaminar Fracture Toughness G_{Ic}

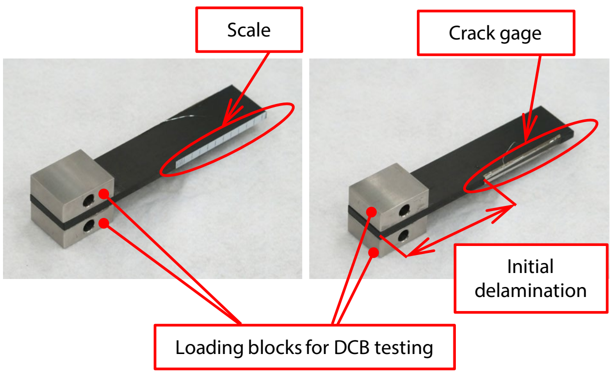

Fig. 3 Test Specimen
(Left: Scale Side, Right: Crack Gauge Side)

Tests

Fig. 4 shows a view of the test. It was not possible to track the full extent of delamination growth in the test specimen within the field of view of the TRViewX when set to high magnification for precision measurement. Accordingly, a slide rail was installed to move the camera in the direction of delamination growth, and the position was adjusted manually so that the delamination tip stayed within the field of view during the test. Table 1 shows the configuration of the instrument and the test conditions, and Table 2 shows information about the test specimens.

For the tests, loading was applied so that the initial delamination length was 3 to 5 mm, and the delamination length was checked on both sides of the test specimen. If the difference in delamination lengths on the two sides was 2 mm or more, the test was stopped. In these tests, the delamination length according to the TRViewX and the crack gauge were compared, and if the difference was no larger than 2 mm, the test was performed. After checking the delamination length, the test was restarted at a constant speed, and the Mode I interlaminar fracture toughness G_{Ic} was calculated for each delamination length.

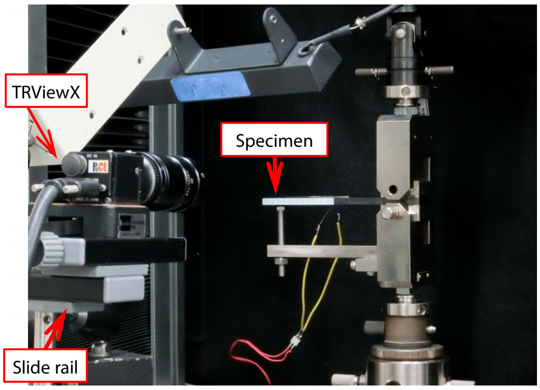

Fig. 4 View of the Test

Table 1 Instrument Configuration and Test Conditions

Testing Machine:	Precision Universal Testing Machine AGX™-1kNV
Load Cell:	1 kN
Measurement Jigs:	Jigs for Interlaminar Fracture Toughness Evaluation
Software:	TRAPEZIUM™ X-V (Control)
Observation of Delamination Length:	Video non-contact extensometer TRViewX 55S + extension tube
Test Speed:	1 mm/min (to delamination length 4 mm) → Unloading speed 25 mm/min (to test force 5 N) → 1 mm/min (to fracture)

Table 2 Test Specimen Information

Prepreg:	T800S
Lamination Method:	[0]n
Thickness:	5 mm
Width:	25 mm
Length:	137 mm
Initial Delamination Length:	Approximately 50 mm

Test Result

Fig. 5 shows an example of the test results. In the specimens tested, delamination growth was initially unstable, with the force dropping suddenly at point A. Subsequent delamination growth was stable, with fracture occurring at 45 to 50 mm.

Table 3 shows the test results, and Fig. 6 shows the relationship between G_{Ic} and delamination length. The initial fracture toughness was 0.3-0.4 kJ/m^2, and as the delamination propagated, the value increased to 0.5-0.6 kJ/m^2 due to fiber bridging.

Fig. 7 shows each point with the test results linked to the TRViewX images. With the combination of camera and lens used in these tests the maximum field of view was 20 mm. However, by using the slide rail it was possible to check the full extent of delamination growth.

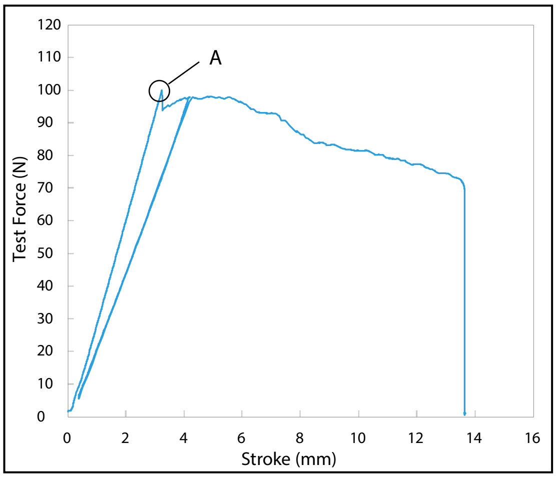

Fig. 5 Test Results

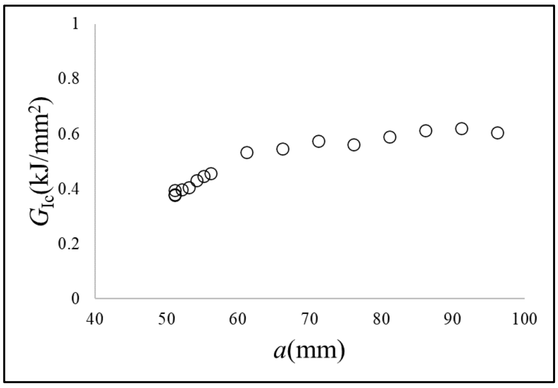

Fig. 6 Relationship between Delamination Length and G_{Ic}

Table 3 Test Results

a (mm)	δ (mm)	P (N)	δ/a	G_{Ic} (kJ/m^2)			
				Eq. (1)	Eq. (2) MBT	Eq. (3) CC	Eq. (4) MCC
51.17 (NL)	3.23	99.6	0.063	0.38	0.32	0.34	0.33
51.17 (VIS)	3.55	95.3	0.069	0.40	0.34	0.35	0.33
51.17 (5 %/MAX)	3.25	99.9	0.064	0.38	0.33	0.34	0.33
52.17	3.60	95.9	0.069	0.40	0.34	0.35	0.34
53.17	3.73	96.3	0.070	0.40	0.35	0.36	0.35
54.17	3.99	97.4	0.073	0.43	0.37	0.38	0.37
55.17	4.20	97.8	0.076	0.45	0.39	0.40	0.39
56.17	4.39	97.5	0.078	0.46	0.40	0.41	0.40
61.17	5.55	97.9	0.090	0.53	0.47	0.47	0.47
66.17	6.44	93.7	0.097	0.55	0.48	0.49	0.49
71.17	7.63	89.1	0.107	0.57	0.51	0.51	0.51
76.17	8.50	83.7	0.112	0.56	0.50	0.50	0.50
81.17	9.80	81.5	0.121	0.59	0.53	0.52	0.53
86.17	11.1	79.0	0.129	0.61	0.56	0.54	0.56
91.17	12.4	75.9	0.136	0.62	0.57	0.55	0.57
96.17	13.6	71.4	0.141	0.61	0.55	0.54	0.56

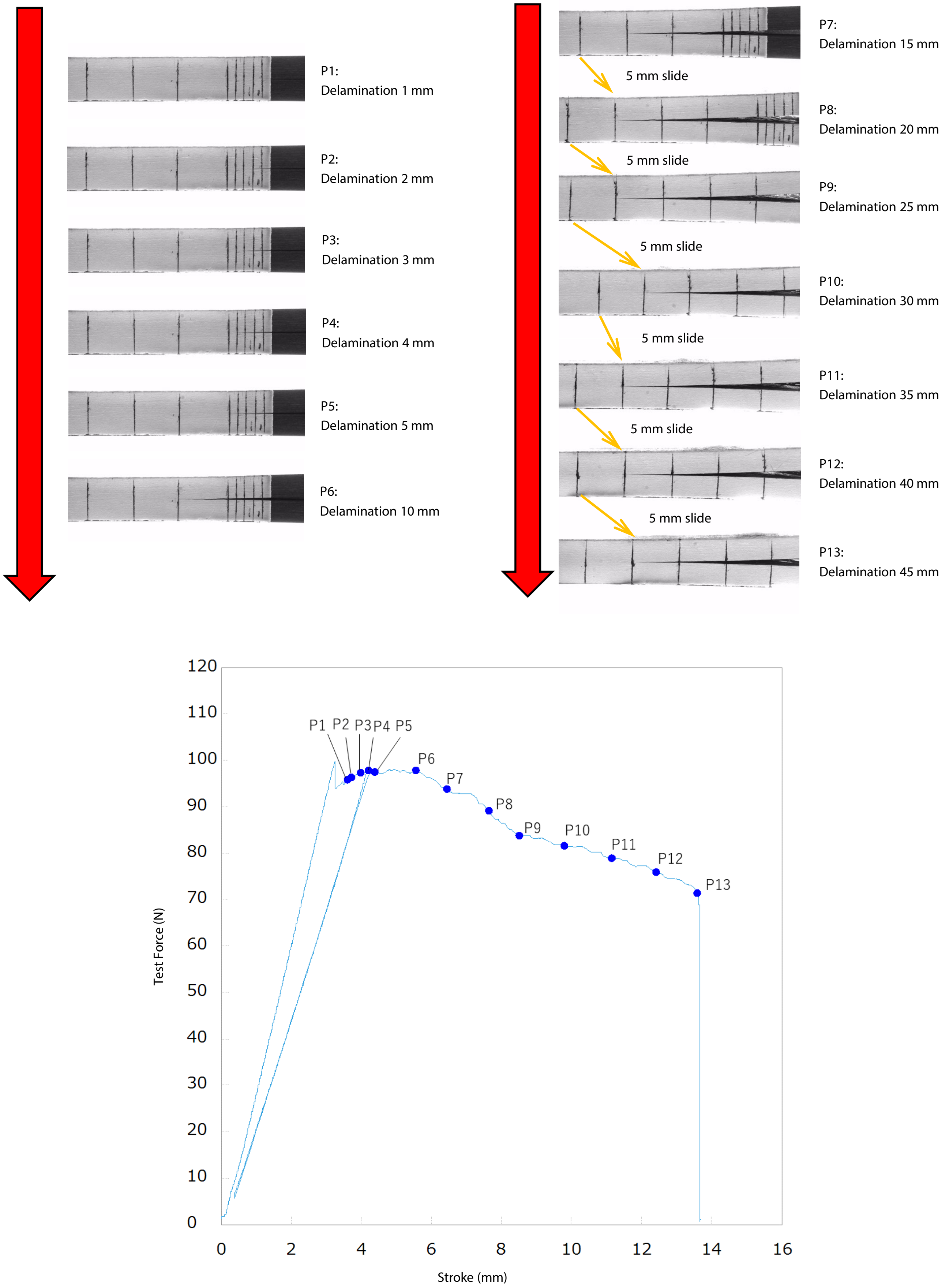

Fig. 7 Test Results (Lower Graph) and Linked TRViewX Images (Upper Photographs)

■ Conclusion

Tests were performed in accordance with ASTM D5528 to obtain the Mode I interlaminar fracture toughness G_{Ic}. ASTM D5528 describes how to obtain the change in Mode I interlaminar fracture toughness G_{Ic} for delamination up to 50 mm in length. In this case the tests were performed using a crack gauge and the TRViewX so that the calculations could be performed afterward. In addition, by using the slide rail, delamination up to 50 mm in length were easily observed with the TRViewX.

Supplementary Section (Method of Calculating G_{Ic})

• **No correction**

$$G_{Ic} = \frac{3P\delta}{2ba} \quad \cdots \text{Eq. (1)}$$

P: Test force
δ: Displacement of the loading point
b: Width of the test specimen
a: delamination length

• **MBT *(Modified Beam Theory)***

This is a reduction method in which a correction value Δ is added to the value *a* in the equation for no correction.

$$G_{Ic} = \frac{3P\delta}{2b\,(a+|\Delta|)} \quad \cdots \text{Eq. (2)}$$

where Δ is the value of the intercept on the horizontal axis of the graph of $C^{1/3}$ - *a* as shown in Fig. 8.
C is the value of compliance, and its value is *δ/P*.

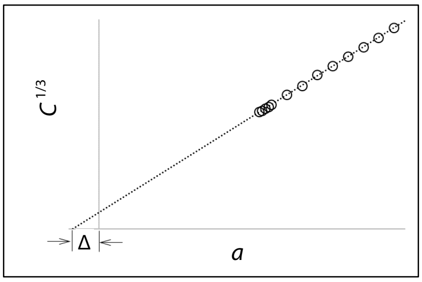

Fig. 8 Method of Obtaining Δ

• **CC *(Compliance Calibration)***

This is a method of reduction using *n* instead of 3 in the equation for no correction.

$$G_{Ic} = \frac{nP\delta}{2ba} \quad \cdots \text{Eq. (3)}$$

where *n* is the value of the slope of the log *C* - log *a* graph shown in Fig. 9.

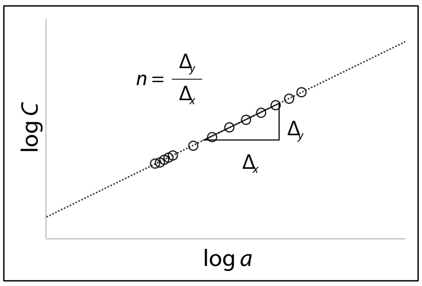

Fig. 9 Method of Obtaining *n*

• **MCC *(Modified Compliance Calibration)***

This is a method or reduction by correction using A_1.

$$G_{Ic} = \frac{3P^2C^{2/3}}{2A_1bh} \quad \cdots \text{Eq. (4)}$$

h : Test specimen thickness
a/h: Value of delamination length normalized by the test specimen thickness

where A_1 is the value of the slope of *a/h* – $C^{1/3}$ shown in Fig. 10.

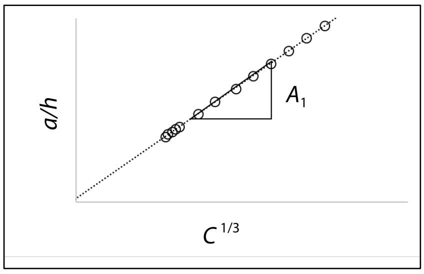

Fig. 10 Method of Obtaining A_1

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