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Experimental investigation of interlaminar mechanical properties on carbon fiber stitched CFRP laminates

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Abstract—Experimental investigations of interlaminar mechanical properties for carbon fiber reinforced plastic (CFRP) laminates were carried out using aramid fiber (Kevlar®-29 1000d) and carbon fiber (TR40-1K 612d, Mitsubishi Rayon) stitching. Various carbon fiber (CF) stitch densities were used to prepare a number of CF stitched CFRP laminates for double cantilever beam (DCB) tests. An insert tongue-type loading fixture, developed by the Japan Aerospace Exploration Agency (formerly the National Aerospace Laboratory of Japan), was also employed in the DCB test. Interlaminar tension tests were carried out under an out-of-plane directional loading using a single CF stitch thread in the CFRP laminates. The DCB test results clarified that the relationship between the volume fractions of the CF stitch thread (V_{ft}) and mode I critical energy release rate (G_{Ic}) showed a mostly linear function with a higher gradient than that of the Kevlar® stitched CFRP laminates. The CF stitched CFRP tension test results indicated that the consumption energy per unit area (E_i) was larger than that of Kevlar® stitched CFRP laminates.

Keywords: Stitched CFRP laminates; interlaminar crack energy release rate; DCB test.

1. INTRODUCTION

Composite materials, especially carbon fiber (CF) epoxy 2-D laminates, are highly suited for in-plane high loading structures in lightweight designs. However, their interlaminar strength is not strong enough to withstand a through-the-thickness directional load. Through-the-thickness characteristic improvements in carbon

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fiber reinforced plastic (CFRP) laminates for aircraft structures are currently being investigated in Japan, US and other countries, by employing a combination of stitching and low cost consolidation techniques such as resin transfer molding (RTM) and resin film infusion (RFI). The authors' group previously carried out an evaluation of Kevlar® and CF stitched CFRP laminates consolidated by RTM processes, involving a number of tests for static strength, compression after impact (CAI), fatigue, and fracture toughness tests of G_{Ic} and G_{IIc} [1–4]. Watanabe *et al.* [5, 6] reported numerical simulation results of G_{I} for 3-D woven CFRP and stitched CFRP laminates. These reports showed that the numerical simulation results are in good agreement with the experimental double cantilever beam (DCB) test results, when the Z-fiber slack and pull-out effects are taken into account in the finite element method (FEM) modeling. Moreover, the author's group also found that the relationship between stitch density and G_{Ic} increments are almost linear, as confirmed by FEM analysis and DCB test results [7]. Similar efforts to improve interlaminar strength include those by Mai's group [8, 9] and Robinson *et al.* [10]. Both groups are currently developing Z-pin technology (Z-fiber®), in which CFRP bundles (pins) are driven into the prepreg using either an ultrasonic vibration device or cure pressure, to improve the interlaminar strength of CFRP laminates. As mentioned above, although researches on improving interlaminar strength in CFRP laminates are particularly active, there has been very little work conducted on improving the interlaminar strength of RTM-fabricated CFRP laminates using CF stitching. Fortunately, as part of the Research and Development Program Key Technology for Innovative Structures, which is supported and managed by New Energy and Industrial Technology Development Organization (NEDO) and Japan Aircraft Development Corporation (JADC), improvements to the CF-stitched preform manufacturing process and the development of RTM infusion technology have been advanced. Using these technologies, the G_{I} values of CF stitched CFRP laminates of various stitch densities have been investigated by DCB tests. Moreover, interlaminar tension tests of a single CF stitched CFRP laminates were also carried out under out-of-plane directional load. In these tests, for several representative test specimens, fracture state of through-the-thickness thread was analyzed using micro-focus X-ray computed tomography (Micro CT) [11, 12] at several displacement levels. The DCB test results and Micro CT observations of the CF stitched CFRP laminates and a comparison of the CF and Kevlar® single stitch tension test data are discussed below.

2. EXPERIMENTAL

2.1. DCB tests

2.1.1. Specimen conditions and test method. DCB tests were carried out on various stitch densities for CF stitched CFRP laminates to obtain the mode I critical interlaminar crack energy release rate (G_{Ic}). The CF stitch thread was

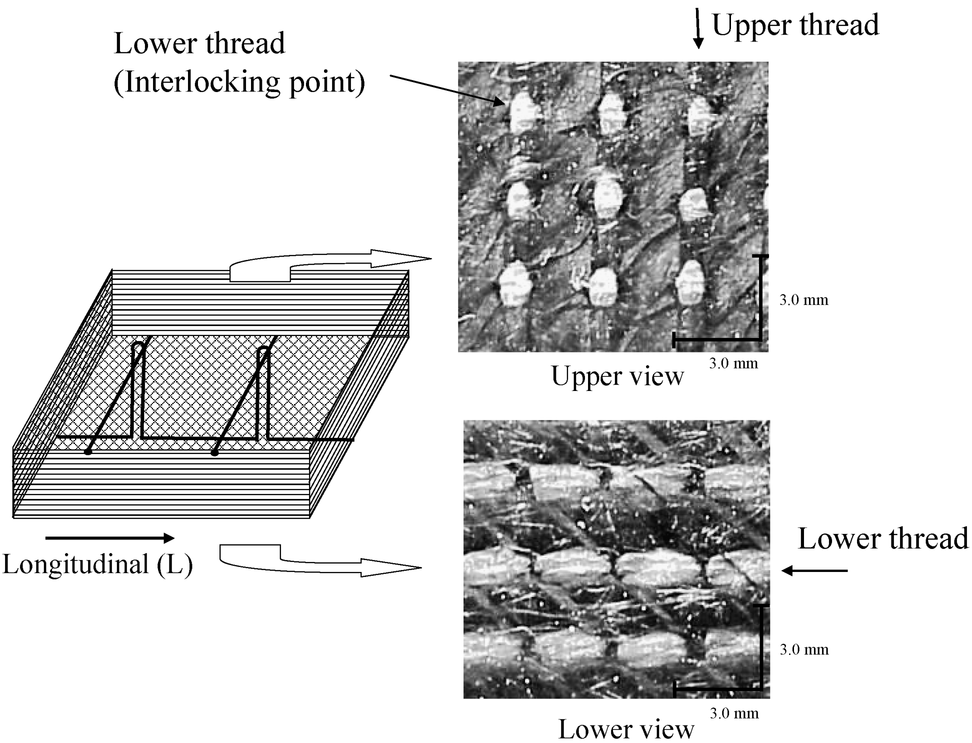


Figure 1. Stitch thread pattern of the CF stitched CFRP laminates.

TR40-1K (Mitsubishi Rayon), in-plane fiber was T700-12K (Toray Industries), and resin system was TR-A31 (Toray Industries) based on an RTM with a curing temperature of 180˚C. The CFRP laminates were an in-plane fiber orientation of $[+45/0/-45/90]_{S3}$ as quasi-isotropic laminates. A stacked and stitched dry preform was inserted into a metallic closed mold and was heated. The resin was transferred to the closed mold and cured at 180°C for 2 h. The CF stitched CFRP laminates were manufactured by Fuji Heavy Industries Ltd. using the technology developed by the Research on Composite Material Evaluation Technology using Advanced Cure Molding Method, as part of the Research and Development Program Key Technology for Innovative Structures. Figure 1 shows a schematic illustration of the stitch pattern used in the CF stitched CFRP laminates. These laminates have a unique stitch structure, in which the stitched thread intersects near the surface and the direction of upper and lower threads cross perpendicularly on the upper and lower surfaces. This stitched laminate structure is similar to a modified lock stitch and 3-D woven fabric preforms. A sectional cut view of the CF stitched CFRP laminates is shown in Fig. 2. The large radius of stitch thread loops at the interlock region is observed that are formed due to the CF stitch threads having higher rigidity than other threads (e.g. Kevlar®). Moreover, some resin rich portions are observed around the stitch threads. Five stitch parameters, unstitched, stitched pitch and

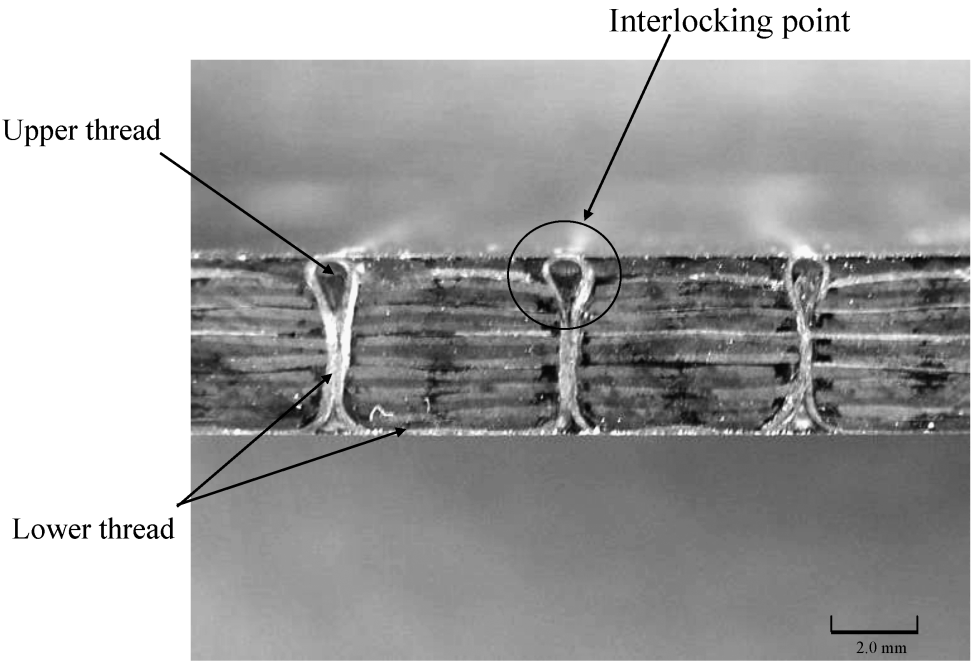


Figure 2. Sectional cut view of the CFRP laminates on the stitch line.

Table 1.
Test matrix of DCB tests

Stitch space and pitch (design)	*SD* (mm^{-2})	V_{ft} (%)	Number of test specimen
0	–	–	3
6 × 12	0.0141	0.107	1
6 × 6	0.0256–0.0304	0.193–0.230	4
3 × 6	0.0509–0.0537	0.385–0.406	3
3 × 3	0.105	0.794	1

space were 6 mm by 12 mm, 6 mm by 6 mm, 3 mm by 6 mm, and 3 mm by 3 mm, were prepared for DCB test specimens. The actual stitch densities were measured after the DCB tests, and used in data analysis. The stitch densities (*SD*) and stitch thread volume fraction (V_{ft}) for each DCB specimen are listed as a test matrix of DCB tests in Table 1. Unidirectional (UD) CFRP laminates (tabs) were secondarily bonded to both surfaces of the DCB test specimens prior to testing. An insert tongue-type loading fixture developed by the Japan Aerospace Exploration Agency was employed [13]. The dimensions of the DCB test specimen are shown in Fig. 3, and an image of the overall DCB test set is given in Fig. 4. Load, crack opening displacement (COD), and propagated delamination length (crack propagation) were measured during the DCB tests using an Instron 5500R screw-

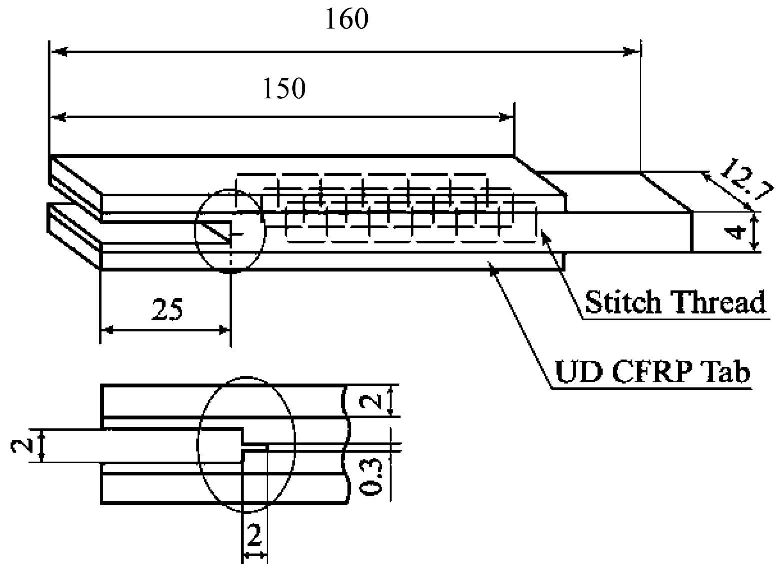


Figure 3. Dimension of the DCB test specimen.

driven testing machine, operating at a speed of 0.25 mm/min. Here, the CODs were assumed an approximation values that traveled displacement of the cross-head from the unload position. The propagated delamination lengths along both edges of the specimen were measured and averaged to afford a representative delamination length. G_{Ic} were calculated using these values by area method.

2.1.2. DCB test results. Typical examples of the DCB test results for the CF stitched and unstitched CFRP laminates, using a stitch density of 0.0303 mm^{-2}, are shown in Fig. 5. It is clear that higher load-COD curves and shorter propagated delamination lengths are found on the CF stitched CFRP laminates than that of the unstitched CFRP laminates at the same COD value. The load-COD curve of CF stitched CFRP laminates shows a typical 'saw blade' shape in accordance with that observed for the Kevlar® stitched CFRP laminate results [7]. A summary of the DCB test results, including the averaged G_{Ic} values for the CF stitched CFRP laminates, are shown in Table 2. A plot of G_{Ic}–V_{ft} is shown in Fig. 6. In this graph, the relationship between G_{Ic} and V_{ft} of the CF stitched CFRP laminates increases almost linearly, which is similarly observed for the Kevlar® stitched CFRP laminates [7]. It is supposed that the relationship between G_{Ic} and V_{ft} of the CF stitched CFRP laminates maintains linearity, even when different stitch thread materials are employed.

2.2. Single-stitched CFRP interlaminar tension test

2.2.1. Specimen and test method. First, a 12.5 mm by 12.5 mm square specimen was cut from a mother plate of CF stitched CFRP laminates so that the single-

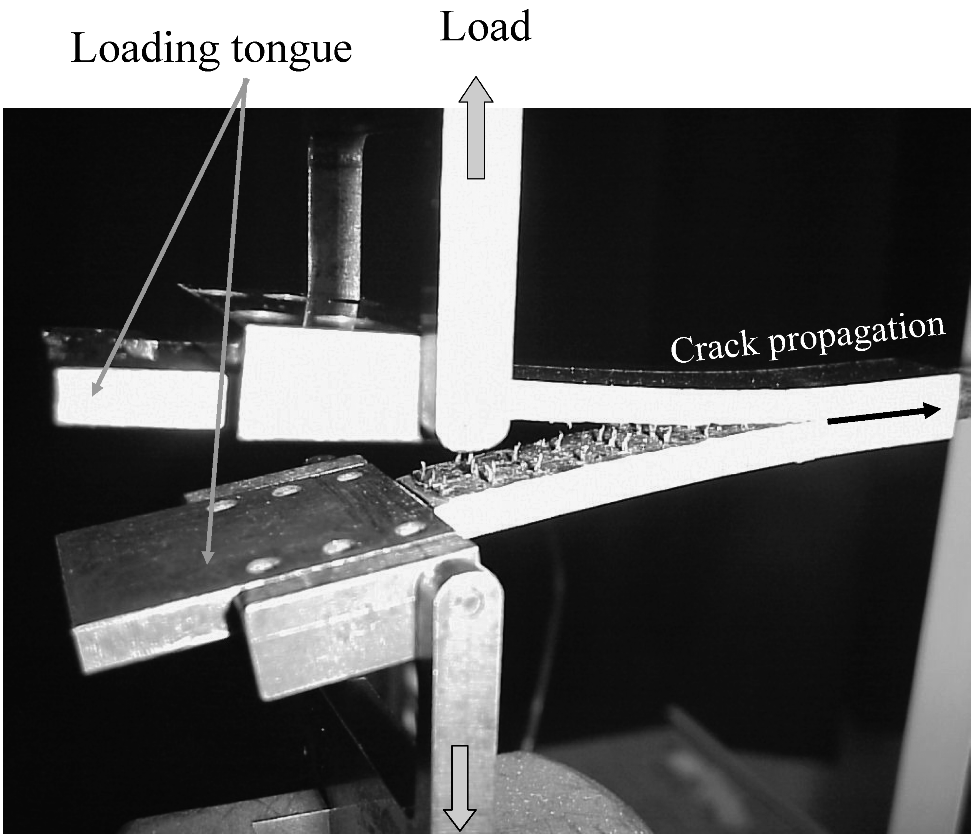


Figure 4. A picture of DCB test set.

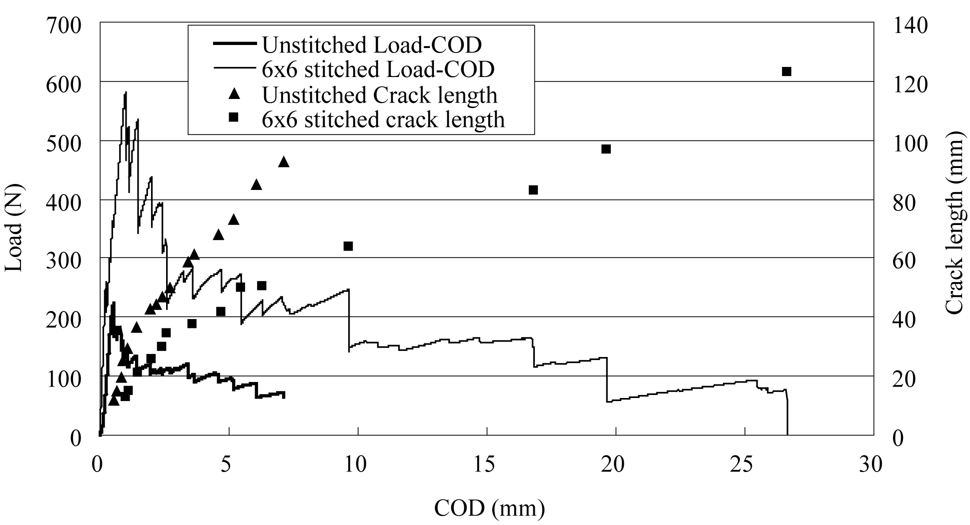


Figure 5. Load-COD curves and crack lengths.

Table 2.
Summary of DCB test results

Stitch space and pitch (design)	Stitch density (SD) (mm^{-2})	V_{ft} (%)	G_{Ic} (N/mm)
0	0	0	0.507
	0	0	0.457
	0	0	0.531
6 × 12	0.0141	0.107	1.974
6 × 6	0.0256	0.193	2.285
	0.0257	0.194	2.102
	0.0303	0.229	3.002
	0.0304	0.230	2.879
3 × 6	0.0509	0.385	5.380
	0.0524	0.396	5.200
	0.0537	0.406	4.770
3×3	0.1051	0.794	8.711

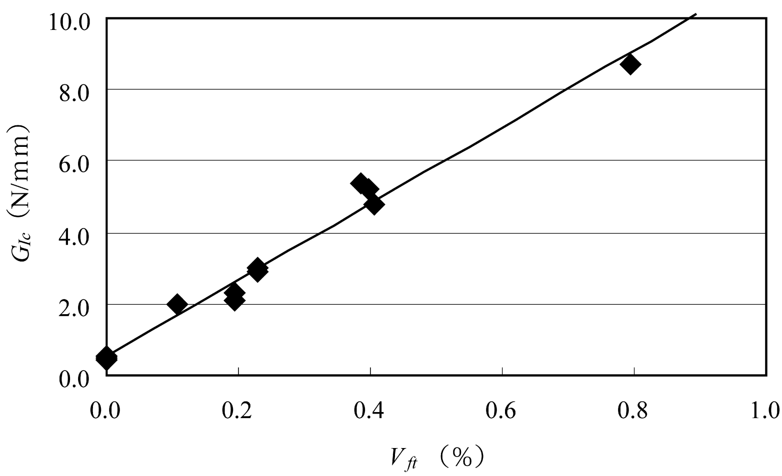


Figure 6. G_I–V_{ft} plots for CF stitched CFRP laminates (linear regression curve).

stitched interlock portion was contained near the central part of the specimen. Next, 0.3 mm width slits were cut from the edges horizontally of the CFRP laminates using a diamond blade cutter to leave a 5 mm by 5 mm central portion. The dimensions of the test specimen are shown in Fig. 7. As shown in the two cross-sections (A–A) and (B–B), the specimen had a single CF stitched interlock point near the central part of the CFRP laminates. The test specimen was bonded via both the upper and lower surfaces to T-type aluminum angles of 3 mm thickness using epoxy adhesive to grip it more easily within the crossheads. An unstitched test specimen was also prepared for comparison with stitched specimen. Stitched specimens were prepared for observation of internal stitch thread fracture

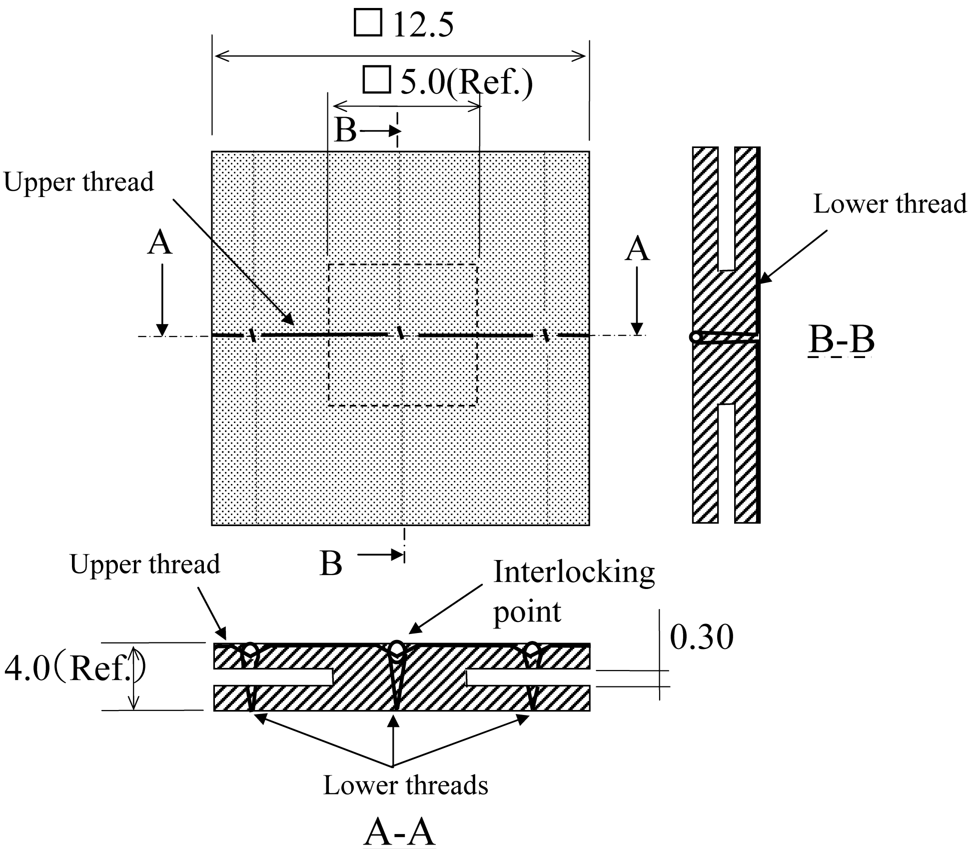


Figure 7. Dimensions of the interlaminar tension test specimen.

transition in the CFRP laminates, as described later. Micro CT observations were performed with a screw-driven type (Instron 5500R) test machine (crosshead speed of 0.1 mm/min) as the same as DCB test. Displacement and tension load were measured. An image of the single-stitched CFRP tension test set is shown in Fig. 8. Micro CT observations were performed to observe the internal state of the CFRP laminates about the interlaminar fracture of CFRP laminates and the stitch thread fracture under the tension test. The single CF stitched CFRP tension test was halted at a specific displacement after the second load drop, and an epoxy resin was fed into the test specimen slits in order to hold of the specimen's displacement. The aluminum angles were then removed, and the Micro CT observations were conducted.

2.2.2. Single-stitched CFRP interlaminar tension test results. Typical load–displacement curves for the CFRP laminates containing a single CF stitch thread are shown in Fig. 9. At the start of each test run, both load–displacement curves were observed to increase linearly. A rapid load drop (the first load drop) occurred at

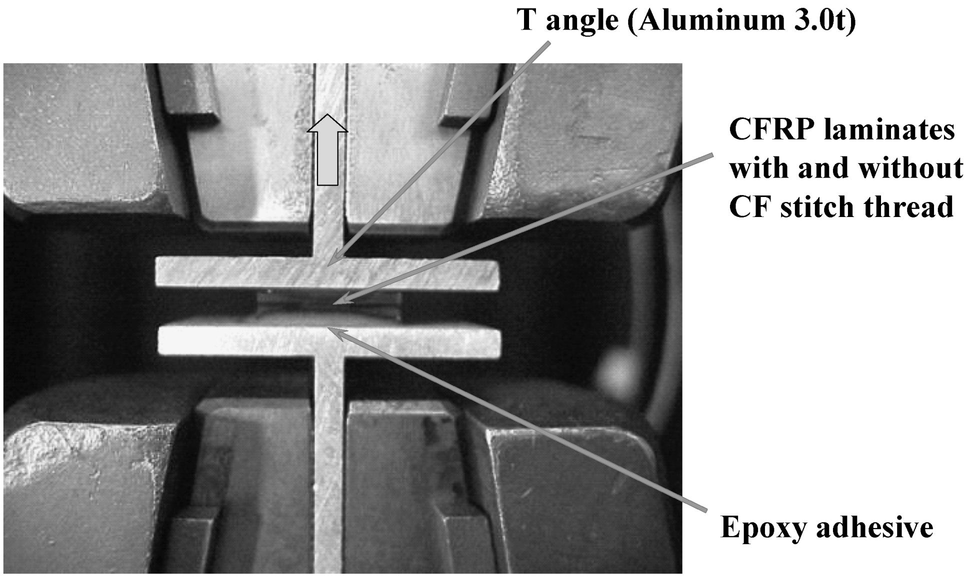
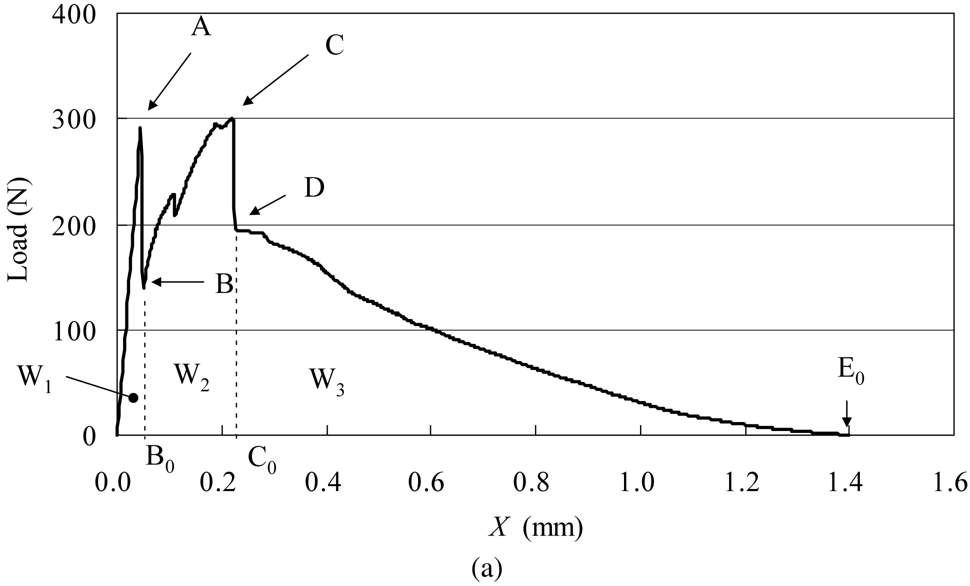


Figure 8. Test setup of the stitched CFRP laminates for interlaminar tension test.

a displacement of 0.05 mm, forming a load peak at that point (0–A–B). At the load drop (B), the load still remained greater than 100 N. After the first load drop, two shapes of the load–displacement curves were obtained. In the first instance, load decreased immediately to 200 N (C to D) with a displacement somewhere between 0.15 mm and 0.35 mm (Fig. 9(a)), the load–displacement curve was formed sharp shape after the load reached a peak (C). The shape of this load–displacement curve is denoted as Type I. The second instance shows a gradual load decrease of 100 N–150 N after passing peak (C) as shown Fig. 9(b), such that the load–displacement curve (B–C–D) adopts a typical 'bell-like' shape, denoted as Type II. The load peak values of types I and II were almost equivalent near 300 N. After the second load drop (D point), for transitions of types I and II both load–displacement curves showed the same trend. Indeed, the decreasing slope was almost constant up to the point where the stitched thread was finally pulled out from the CFRP laminates (i.e. load equals 0).

The consumption energy corresponding to the area (0–A–B–B_0) in each load–displacement curve is shown in Fig. 9 as W_1 (integration with load multiply displacement). Similarly, the area corresponding to the point between the first load drop and the second load drop (B_0–B–C–D–C_0) is denoted as W_2, and the area between the second load drop and the point where the stitch thread is completely pulled out from the CFRP laminate (C_0–D–E_0) is denoted as W_3. The total consumption energy (gross) between the start of the test and the end point of the test where the stitch thread was pulled out completely is denoted as W_t, where

$$W_t = W_1 + W_2 + W_3. \tag{1}$$



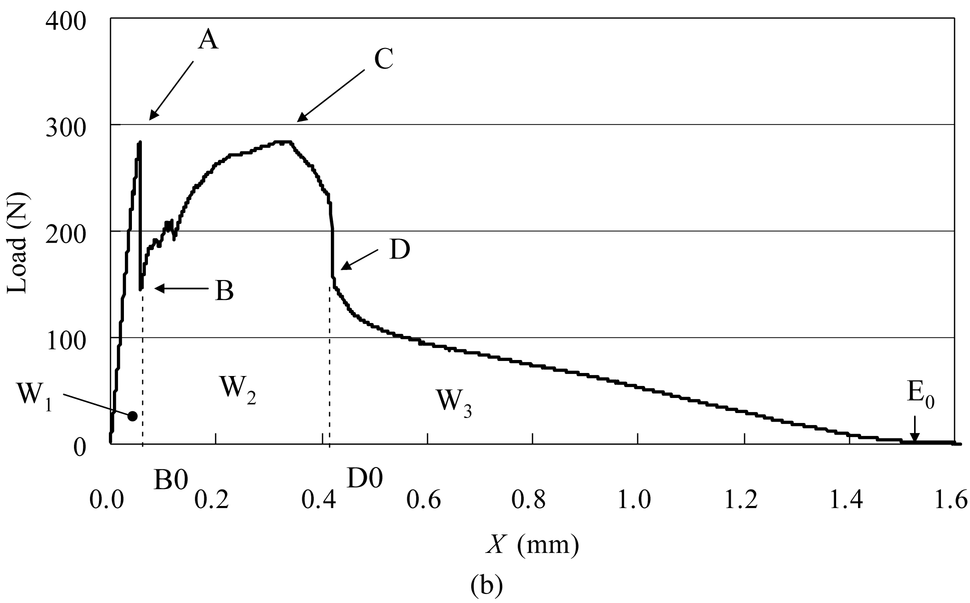


Figure 9. Load–displacement curve for stitched CFRP laminates. (a) Type I. (b) Type II.

Each displacement and load value for peaks A, C and D are indicated in Table 3, along with the average consumption energies of W_1–W_3, and W_t. The consumption energies of the Kevlar® stitched CFRP laminates are listed together with their corresponding literature values [7]. On the other hand, a typical load–displacement curve for an unstitched specimen is shown in Fig. 10. Here, although the load increases almost linearly with increasing displacement, the displacement level

Table 3.
Summary of CF stitched CFRP interlaminar tension test results

			CF stitch		Kevlar®-29
			Type I	Type II	1000d stitch
Area (thread section)		mm^2	0.0756		0.1542
First peak (A)	X_a	mm	0.049	0.054	0.068
	P_a	N	266.4	271.1	442.9
Second peak (C)	X_c	mm	0.209	0.210	0.352
	P_c	N	294.3	259.5	301.0
Second load drop (D)	X_d	mm	0.200	0.419	0.352
	P_d	N	217.5	121.1	104.2
Consumption energy	W_1	N mm	6.89	9.81	15.9
	W_2	N mm	40.7	76.8	62.4
	W_3	N mm	90.1	50.7	59.2
	W_t	N mm	132.7	137.2	137.6

All data were averaged.

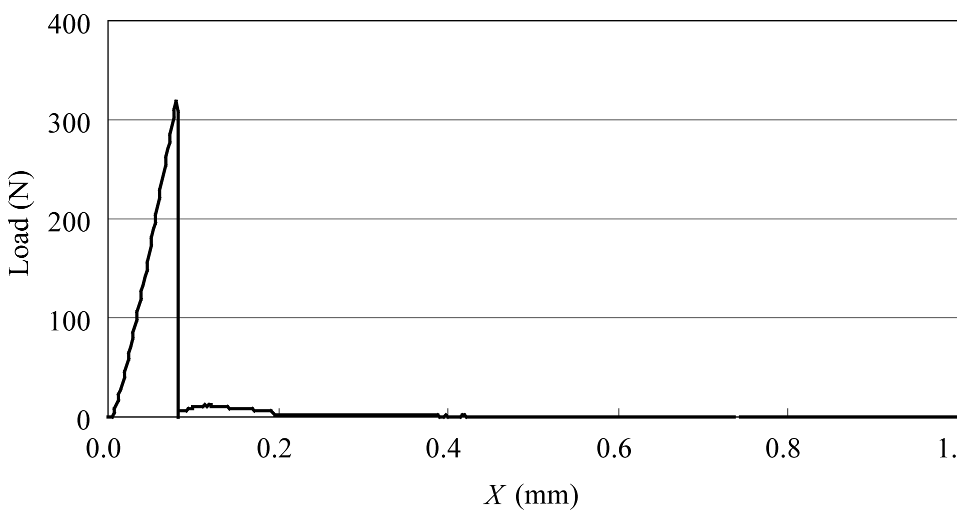
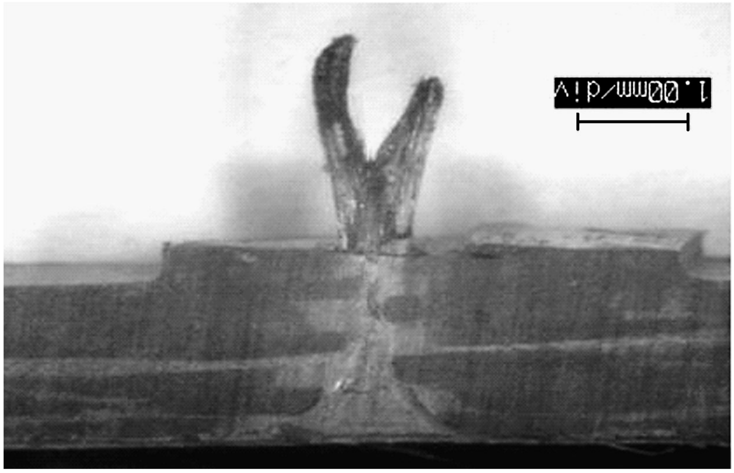
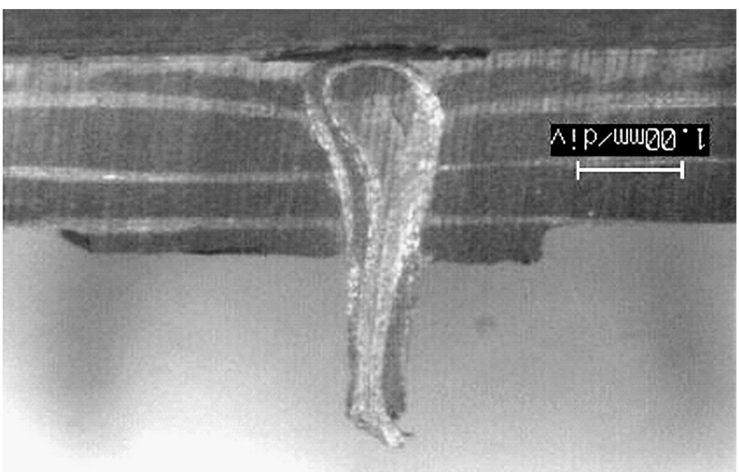


Figure 10. Load–displacement curve for unstitched CFRP laminates.

(0.03–0.08 mm) shows a rapid load drop, which is accompanied by an audible sound. After the load drop, the residual load was very low (under 20 N) and the upper and lower parts of the specimen showed complete separation even before the displacement of 0.3–0.4 mm. The fracture aspect of the CF stitched CFRP laminates was observed with an optical fiber type microscope (Keyence VH-6300/VH-Z35) after the tension test, as shown in Fig. 11. It was observed that the interlock loop end of the CF thread had fractured and had been pulled out completely from the CFRP laminates as shown in Fig. 11(a). In a related manner, the point near where the stitch thread enters the CFRP laminate (thread root) had also fractured and been



(a)



(b)

Figure 11. Pictures of pulled out threads. (a) Pulled out thread was broken at the end of thread loop; (b) Pulled out thread was broken at the root of the lower stitch thread.

pulled out from the CFRP laminates as shown in Fig.11(b). Thus, two fracture modes of CF stitch thread are observed single-stitched CFRP interlaminar tension test under tensile loading.

3. DISCUSSION

3.1. DCB test results of CF stitched CFRP laminates

The relationship between G_{Ic} and V_{ft} of the CF stitched CFRP laminates is plotted in Fig. 12. The corresponding literature results for DCB test of Kevlar® 1000d thread

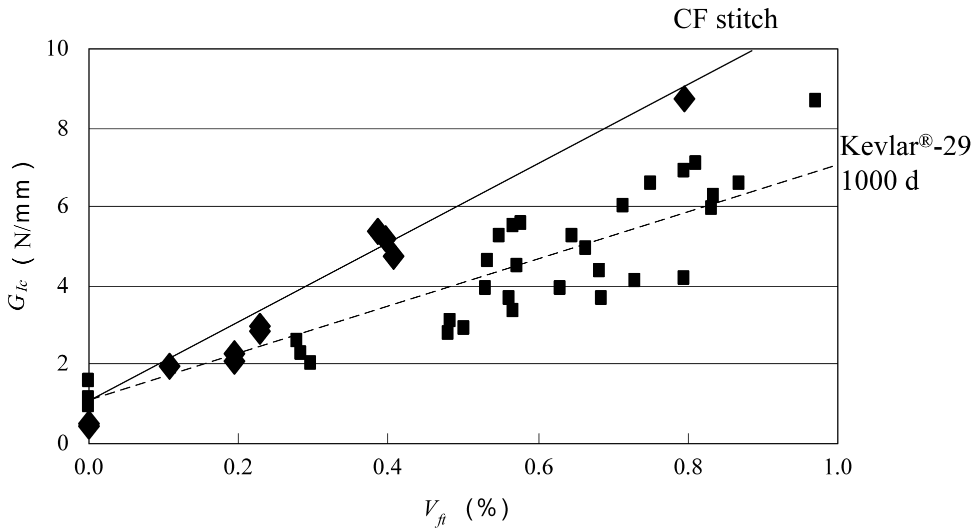
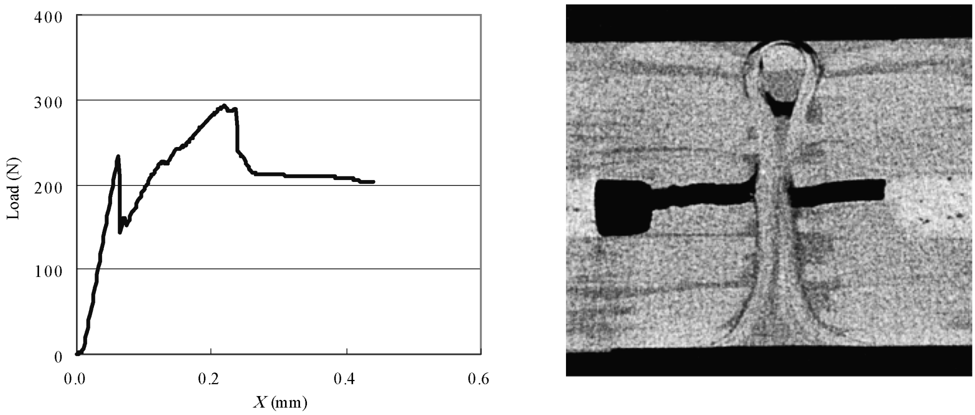


Figure 12. G_{Ic}–V_{ft} plots for CF stitch and Kevlar® stitched CFRP laminates.

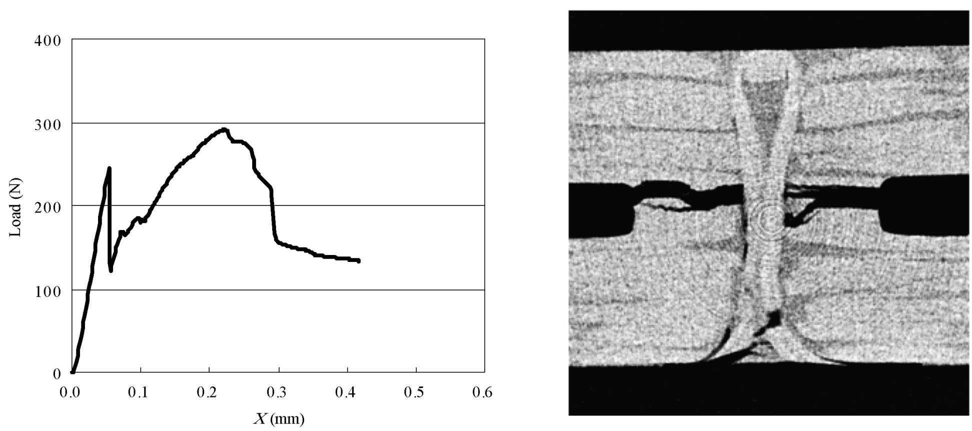
[7] are also plotted for comparison with the present data. It is clear that the increase in the gradient of G_{Ic}–V_{ft} for the CF stitched CFRP laminates is higher than that in the case of the Kevlar® stitched DCB test result. It is therefore possible to increase the mode I critical energy release rate with lower volume content by using CF stitch threads rather than Kevlar® stitch threads.

3.2. Single-stitched CF interlaminar tension tests

As described in Section 2.2.2 and illustrated in Fig. 11, it is clear that two distinct fracture positions of the CF stitch thread in the CFRP laminates occurred. The first is at the stitch thread interlock loop end, and the second is at the stitch thread root position. Therefore, all the tension test specimens were cut with a diamond blade at the position of the stitch thread. The fracture modes and the shapes of load–displacement curves were verified. As a result, in the shape of load–displacement curve of type I (Fig. 9(a)), it was confirmed that the thread fracture occurred at the loop end of the stitch thread at interlock position, as shown in Fig. 11(a). In the case of type II (Fig. 9(b)), the thread fracture occurred at the stitch thread root position, as shown in Fig. 11(b). Furthermore, the Micro CT observations carried out after the load drop of the second load peak (about 0.4 mm displacement). The Micro CT images and the corresponding type I and type II load–displacement curves are shown in Fig. 13. From these results, it was clear that the type I load–displacement curve corresponded to the interlock loop end fracture, while type II corresponded to the thread root fracture. Thus, the CF stitch thread used in the CF-stitched CFRP laminates was fractured in two positions, either at the stitched interlock end or the thread root position, under out-of-plane tension loading. It was also confirmed that the difference in the shape of the load–displacement curves was dependent on the



(a) Type I



(b) Type II

Figure 13. Load–displacement curves for type I, II and micro CT images of the stitch thread in the CFRP laminates.

thread fracture position. The consumption energies of the type I and type II shapes of load–displacement curves are given in Table 3. From here, it was found that the W_t values are almost equivalent, despite the difference in the shape of the load–displacement curves, type I and type II.

3.3. Relationship between the DCB test and stitched CFRP interlaminar tension test

Images of a pair of separated CF stitched CFRP laminates used in the DCB tests are shown in Fig. 14. It can be observed that the interlock end fractures and thread root fractures appear mingled in the same test specimen. Figure 14 shows the surviving stitch threads that fractured at the interlock loop end and at the stitch thread root on the separated DCB specimen, as the similar fracture modes shown in Fig. 11. Thus, the two fracture modes were observed not only in the single CF stitched CFRP

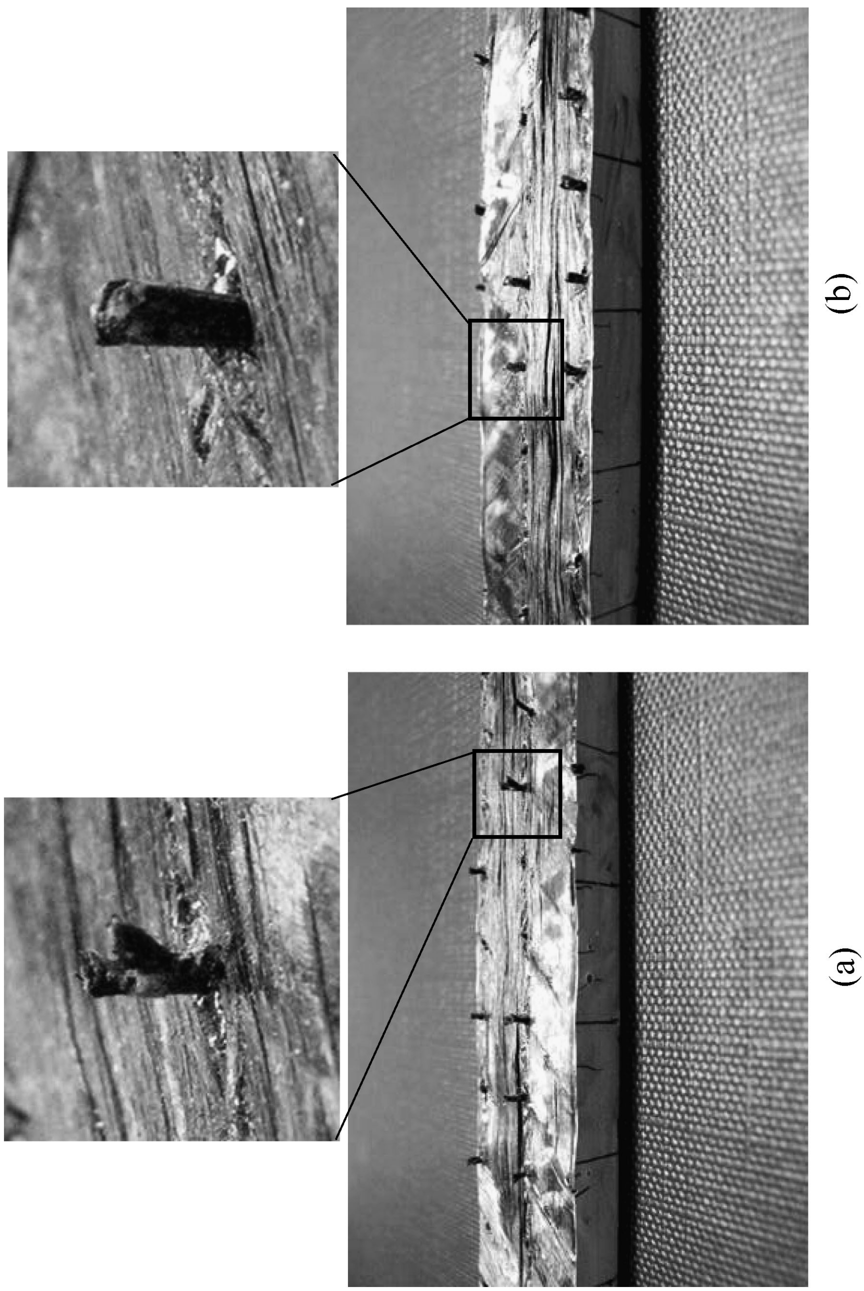


Figure 14. Pictures of separated DCB test specimen after DCB test. (a) Survived threads were broken at the end of the thread loop. (b) Survived threads were broken at the root of the lower stitch thread.

interlaminar tension test results, but also in the DCB test results. It is supposed that a similar phenomenon occurs inside of both DCB specimens and CF stitched CFRP interlaminar tension test specimens.

3.4. Comparison of consumption energies for CF and Kevlar® stitched CFRP laminates

A comparison of the consumption energies associated with the CF and Kevlar® stitched CFRP laminates obtained from the stitched CFRP interlaminar tension tests is discussed below. It was known that all the surviving Kevlar® stitch thread fractures in the tension test specimens occur at the interlock loop end, while these are completely removed from the CFRP laminates [11]. However, two fracture modes were observed in the surviving CF stitched CFRP laminates. Typical examples of both type I and II load–displacement curves from the CF-stitched CFRP tension test results are compared with the Kevlar® data in Fig. 15. It appears that displacements of the first (delamination) and second load peaks of the CF thread have smaller than the Kevlar® thread. After the second load drop, load–displacement curves of both types were almost equivalent gradient in decrease rate with increasing displacement. Moreover, the total consumption energies (W_t) of the CF and Kevlar® threads were almost equivalent as indicated Table 3. The consumption energy associated with the stitch thread in the CFRP laminates (W_i) is determined by equation (2).

$$W_i = W_t - W_1. \tag{2}$$

The cross-sectional areas of the CF and Kevlar® stitch threads are defined as A_t. Here, it is assumed that the specific consumption energy (E_i) is determined

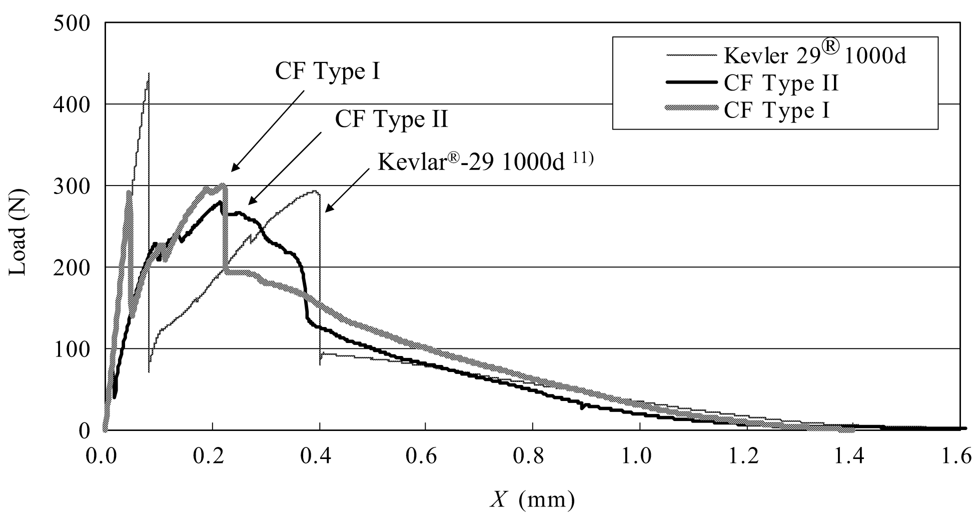


Figure 15. Comparison of load–displacement curves for CF and Kevlar® thread.

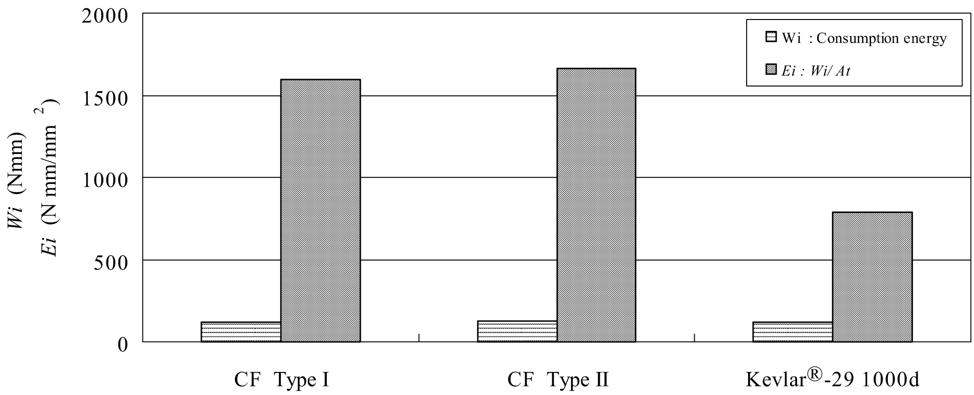


Figure 16. Comparison of W_i and E_i.

according to equation (3).

$$E_i = W_i / A_t. \tag{3}$$

The specific consumption energies (E_i) with respect to W_i are compared for each thread are shown in Fig. 16. Here, the cross-sectional area (A_t) of CF and Kevlar® threads is 0.0756 mm^2 and 0.1542 mm^2, respectively. It is revealed that the total consumption energies for CF and Kevlar® CFRP (W_i) are almost equivalent. However, the energy consumed per unit area (E_i), i.e. the specific consumption energy, is typically higher for the CF stitched CFRP laminates than the Kevlar® stitched CFRP laminates. That is, the CF-stitched CFRP laminates have a high-energy consumption capability even in a low volume fraction of stitch threads. From Section 3.1 and the above discussion, it is clear that the CF stitched CFRP laminates are more advantageous than the Kevlar® stitched CFRP laminates in improving the relation between G_{Ic} and V_{ft}. However, careful evaluation is required to confirm the integrity of the CF stitching within the CFRP laminates, since the interlaminar properties cannot always be improved effectively. The position of the interlocking point, the thread thickness, damage to the thread by stitch processing, the production quality of CFRP laminates, etc., must all be taken into account. It is also necessary to conduct further research into the effects of the mode II crack energy release rate for the stitched CFRP laminates. Moreover, a detailed research of the fracture mechanism involved in the stitched CFRP laminates is necessary.

4. CONCLUSIONS

DCB tests were carried out on CF stitched CFRP laminates with various stitch densities, and the mode I critical crack energy release rate (G_{Ic}) was obtained. Moreover, CF stitched CFRP interlaminar tension tests were conducted and the pull out behaviors of the CF stitch thread from the CFRP laminates were observed and analyzed. The following conclusions were drawn from the above results and discussions.

(1) It was confirmed that the mode I interlaminar critical energy release rate (G_{Ic}) tends to increase with increasing volume fractions of CF stitched CFRP laminates.

(2) The CF stitched CFRP laminates have the possibility to improve G_{Ic} more effectively than Kevlar® stitching, even with small volume fractions of the CF stitch thread.

(3) There are two shapes of load–displacement curves observed on the single-stitched tension test results. The corresponding fracture modes, the interlock loop end fracture was type I and thread root fracture was type II, respectively. However, there was no great difference in their consumption energies.

(4) The total consumption energies of CF and Kevlar® stitched CFRP (W_{i}) laminates from interlaminar tension tests were equivalent. However, it is clear that the specific consumption energy (E_i) associated with the CF stitching is more effectively compared with the Kevlar® stitching.

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