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Comparison of testing methods for fibre-reinforced polymers (FRP) in resistance to in-plane sliding mode of delamination (Mode II)

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A new testing mehtod, named Beam Test, was recently proposed to quantify delamination resistance of fibre-reinforced polymers (FRP) when subjected to out-of-plane loading [1]. This short communication presents results from a follow-up study that compares the new testing method with end-notched-flexure (ENF) test [2] that has been popular in the research community for the measurement of the resistance to in-plane sliding mode of delamination (commonly known as Mode II delamination).

Specimens used in the current study had glass fibre fabric of 9 oz/yd^2 as the reinforcement, provided by ZCL Composites, Edmonton. The glass fibre fabric consists of uni-directional fibre bundles of around 1.5 mm wide in the weft (transverse) direction, separated by a gap of around 1 mm using stitching threads. Two types of resins were used as the matrix, isophthalic polyester (from Triple M Fibreglass Mfg. Ltd., Edmonton) and polyurethane (from Resin Systems Inc., Edmonton). The polyester was deemed a much more brittle resin than the polyurethane. Therefore, use of the two resins provided a comparison of FRP's delamination resistance with different matrix properties.

Table I summarises materials information for FRPs used in this study. All specimens had nominal length and width of 210 and 20 mm, respectively. Lay-up of the ENF specimens followed the recommendation given in ref. [3], that is, unidirectional with fibre along the specimen length direction. All ENF specimens consisted of 20 layers of fibre fabric, resulting in a nominal thickness of around 6 mm. An aluminium foil of 13 μm thick and 70 mm long was placed at one end of the specimen between 10th and 11th layers, to act as the starting defect for delamination during the testing.

Two types of Beam specimens were used, with the main difference in thickness: one around 6 mm and the other 11 mm. The former used 21 layers of fibre fabric and the latter 35 layers. All layers, except the middle one (11th and 18th, respectively), had fibre oriented in the specimen length direction (0°), while the middle layer had fibre in the transverse direction (90°). Thickness of 6 mm was chosen to be consistent with that of the ENF specimens, and that of 11 mm was because delamination could not be generated in the 6-mm-thick polyurethane-based FRP specimens.

Set-up for the two tests is shown in Fig. 1. Both tests used 3-point bending as the loading mode. Span length for the ENF test was 100 mm of which 25 mm was the length of the starting defect. However, span length for the Beam test varied from 50 to 80 mm, due to uncertainty in the optimum span length, especially for the polyurethane-based FRP, to generate sufficiently large delamination area without inducing fibre fracture during the test. Results from a previous study [1] have shown that variation of span length in this range does not affect the delamination resistance measured from the Beam test as long as no additional damage mode was involved in the deformation process.

Typical load-displacement curves for the ENF specimens are summarized in Fig. 2. The curve for the polyester-based FRP, Fig. 2a, showed a sudden drop of the load when delamination occurred, after an approximately linear increase of the load with the displacement. The curve for the polyurethane-based FRP, on the other hand, showed a significant yielding before the load drop, as shown in Fig. 2b. The unloading part is similar in the two curves.

The delamination resistance measured from the ENF test, in terms of critical strain energy release rate ($G_{c,ENF}$) was calculated using the following two equations, based on the Corrected

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TABLE I Information of FRP used in this study

Matrix	Fibre lay-up		Thickness (mm)	Fibre volume fraction (V_f%)	Number of specimens
Polyester	ENF	$(0_{10}/F/0_{10})$	6.3	38	7
	Beam-thin	$(0_{10}/90/0_{10})$	6.3	40	6
	Beam-thick	$(0_{17}/90/0_{17})$	10.8	38	7
Polyurethane	ENF	$(0_{10}/F/0_{10})$	6.5	37	7
	Beam-thick	$(0_{17}/90/0_{17})$	11.4	37	7

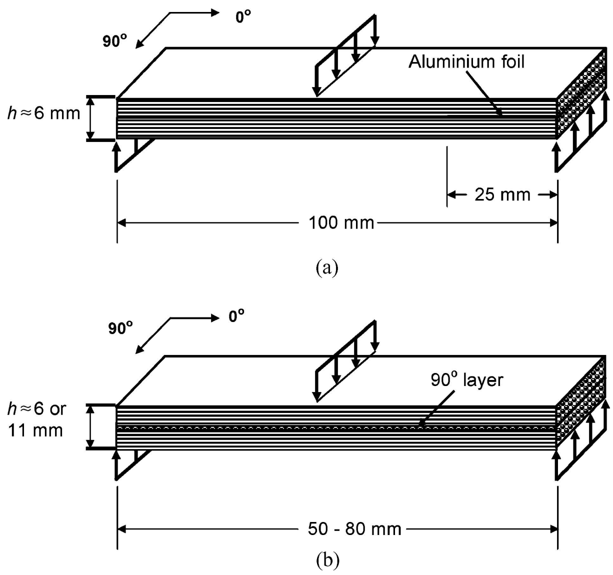

Figure 1 Test set-up and fibre lay-up used in this study: (a) ENF test for $(0_{10}/F/0_{10})$ where "F" represents aluminium foil, and (b) Beam test for $(0_{10}/90/0_{10})$ or $(0_{17}/90/0_{17})$.

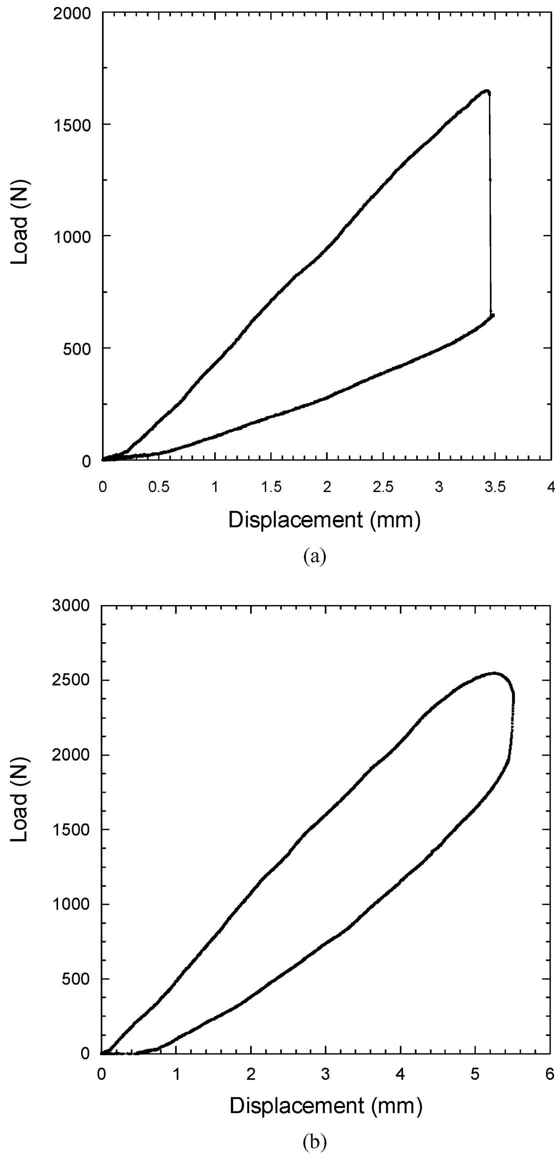

Figure 2 Typical load-displacement curves from the ENF test: (a) polyester-based FRP, and (b) polyurethane-based FRP.

Beam Theory [3].

$$G_{C,ENF} = \frac{9a^2P^2}{16B^2E_f h^3} \quad (1)$$

$$E_f = \frac{L^3}{4BCh^3} \quad (2)$$

where "a" is the crack length (25 mm), P the force for delamination, B the specimen width, L half the span length (50 mm), h half the specimen thickness, and C compliance of the specimen, with $1/C$ equal to the initial slope of the load-displacement curve. It should be noted that three P values were obtained from each load-displacement curve for the calculation of $G_{c,ENF}$, as suggested in the protocol [3]: (i) the first non-linear point of the loading part of the curve (NL), (ii) the point at 5% off-set of the initial slope (5%), and (iii) the point at the maximum force (Max). Values of $G_{c,ENF}$ are summarized in the middle column of Table II. The values suggest that in general, the polyurethane-based FRP has higher delamination resistance than the polyester-based counterpart.

TABLE II Critical strain energy release rate (G_c) in J/m^2, measured from ENF or Beam tests. Number in the parentheses is the standard deviation of the test results. E_f in the column of ENF is the average flexure modulus of the ENF specimens

Matrix of FRP	ENF	Beam
Polyester	$G_{c,NL}$: 2680 (320)	Thin: 3270 (450)
	$G_{c,5\%}$: 2940 (360)	
	$G_{c,Max}$: 3020 (340)	Thick: 3040 (340)
	E_f = 25.0 GPa (0.9)	
Polyurethane	$G_{c,NL}$: 3460 (440)	Thick: 7910 (2120)
	$G_{c,5\%}$: 6050 (1080)	
	$G_{c,Max}$: 6340 (1130)	
	E_f = 23.3 GPa (0.7)	

Typical load-displacement curves from the Beam tests are summarized in Fig. 3. Two curves are shown for polyester-based FRP, Figs 3a and 3b. The former was from a 6-mm-thick specimen and the latter

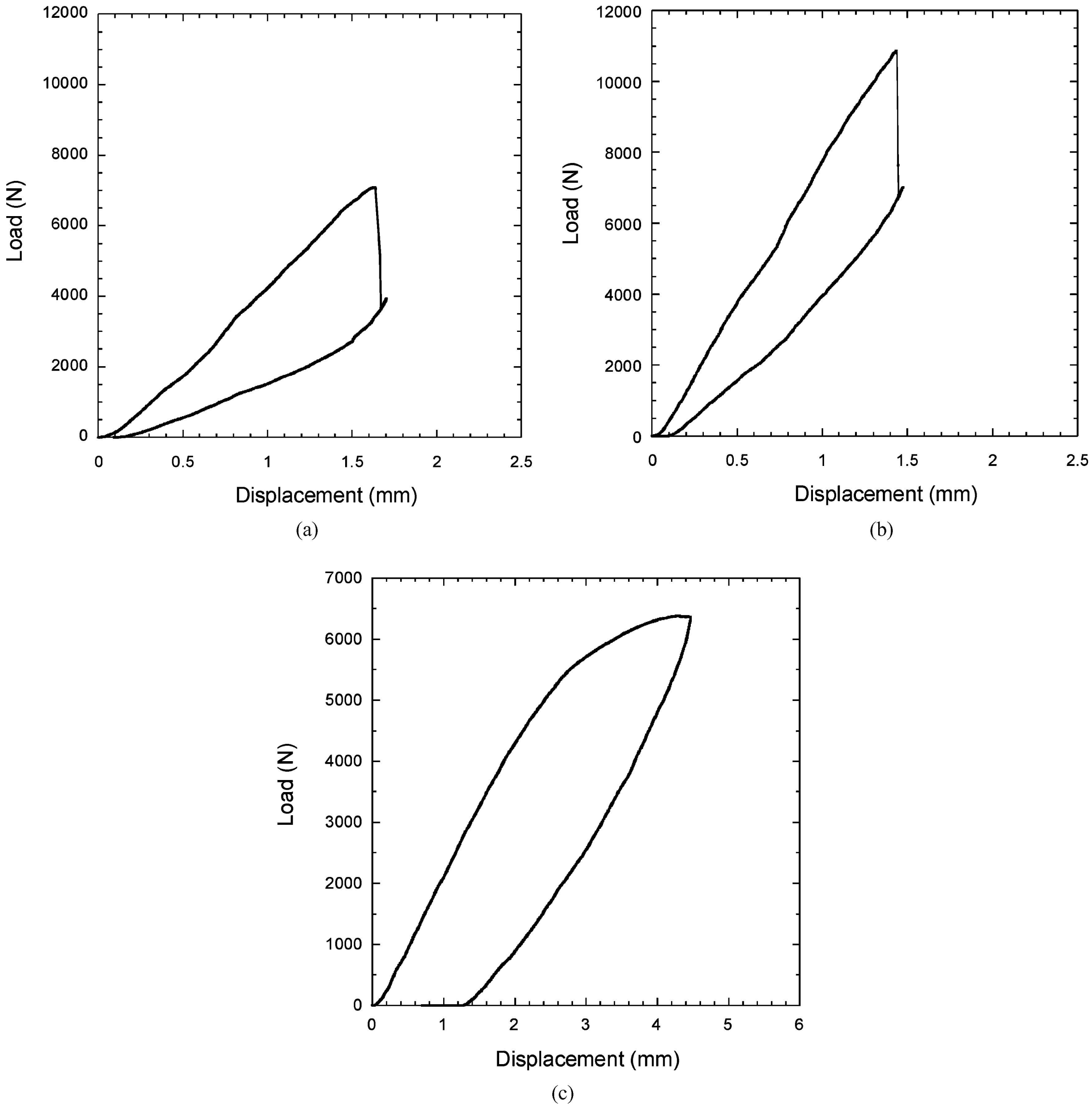

Figure 3 Typical load-displacement curves from the Beam test: (a) polyester-based FRP with $h \approx 6$ mm, (b) polyester-based FRP with $h \approx 11$ mm, and (c) polyurethaner-based FRP with $h \approx 11$ mm.

11-mm-thick. Both curves show a significant drop of the load after an approximately linear increase of the load. For the polyurethane-based FRP, however, significant yielding was observed when delamination occurred, as shown in Fig. 3c, instead of load drop. This suggests that delamination growth in the polyurethane-based Beam specimens was stable and its development was progressive with the increase of the load. The specimen for Fig. 3c was unloaded before any fibre fracture, but after sufficient development of delamination so that the delamination size was large enough to be measured using a ruler. For all polyurethane-based Beam specimens that were tested in this study, the maximum load was in the range of 5500 and 6500 N. It should be noted that for the 6-mm-thick polyurethane-based FRP, the Beam specimens failed via fibre fracture in tension before any delamination occurred.

The critical strain energy release rates for the Beam specimens, $G_{c,\mathrm{Beam}}$, were calculated based on energy loss per unit area of delamination, that is, by dividing the total energy loss (area enclosed by the load-displacement curves in Fig. 3) by the measured total delamination area [1]. The results are summarized in the right column of Table II. The two values for the polyester-based FRP are very close to each other, in view of the range of standard deviation and the 2% difference in their fibre volume fraction (Table I). This suggests that the change of the specimen thickness did not have much effect on the measured G_c values. Table II also suggests that $G_{c,\mathrm{Beam}}$ is very close to $G_{c,\mathrm{ENF}}$ obtained at the point of the maximum load ($G_{c,\mathrm{Max}}$ in Table II). Overall, G_c values in Table II indicate that the polyurethane-based FRP is more than 2 times stronger than the polyester-based counterpart in the resistance to Mode II delamination.

The study concludes that the Beam test provides consistent results in delamination resistance with that from the ENF test, even though the former has delamination growth between layers of orthogonal fibre orientation and the latter parallel. Fibre orientation did not seem to have any significant effect on the delamination resistance. The study also showed that the polyurethane-based FRP is stronger than the polyester-based FRP in the delamination resistance. This is evident from the measured G_c values from both tests and stability of crack growth in the Beam test.

Consistency of the results between the two tests indicates that the Beam test can be an alternative for ENF test, especially when comparison of delamination resistance is desired between plies of different orientation. Further study is being conducted to explore the potential of the Beam test in the measurement of the delamination resistance in different interlaminar regions of FRP, by varying the 90°-layer position in the thickness direction. Other studies are also planned, with the objective of identifying potential benefits of the Beam test for understanding delamination behaviour of FRP.

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