Mode I and Mode II Delamination of Flax/Epoxy Composite Laminate

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Abstract. In recent decades, natural fibres are getting their attention as reinforcement in composite materials. This is because natural fibres are environmental friendly. However, delamination is commonly recognised as one of the earliest failures in composite laminates. The objective of the present work is to investigate mode I and mode II delamination behaviour of flax fabrics reinforced epoxy composite. The delamination characterisation was carried out using double cantilever beam (DCB) and three point end notched flexure (ENF) tests. The fracture toughness were calculated using experimental calibration method (ECM). Results showed that the average fracture toughness was 485 N/m and 962 N/m, respectively. Finally, through scanning electron micrographs, it was observed that the ply/ply debonding and fibre/matrix debonding were the major fracture mechanisms in DCB specimen. As for ENF specimen, shear fracture dominated the energy dissipation process.

1 Introduction

In recent decades, natural fibres are getting more attention as reinforcements for polymer composites due to their advantages of being low weight, low cost and environmentally friendly (renewable, recyclable and biodegradable) [1]. However, similar to other types of reinforcements, delamination is frequently known as an early failure in composite laminates. Delamination refers to the separation of two adjacent layers of the composite laminates. This would greatly reduce the load carrying capability of the entire composites. Therefore, when using natural fibres as reinforcement, it is of paramount importance to characterise the delamination behaviour in the composites.

In the studies of delamination behaviour of composite laminates, extensive works have been done on pure mode I, II and mixed-mode I+II loadings. Some recent publications on synthetic fibre composites include the research reported in [2–8]. In general, it was observed that the interlaminar fracture toughness increased with the mode II ratio. The highest fracture toughness was obtained under pure mode II loading. This implied that shear mode provided more resistance in delamination and hence more energy was dissipated to initiate the crack propagation. Not only, that the fracture toughness and the variation of the fracture toughness with respect to the mode ratio was dependent on the material, fabrication method, fibre orientation and exposed environment [4–8]. Interlaminar fracture characterisation of polymer reinforced by flax fabrics has been carried out by some researchers [9–12]. For example, the mode I and mode II delamination among different final fibre preform architectures were compared [9]. It was observed that plain weave fabric exhibited the lowest mode I initiation value, G_{IC} (457 N/m) but the highest mode II fracture toughness, G_{IIC} (1872 N/m) compared to other types of architectures. It has been demonstrated that G_{IC} could be improved by incorporating carbon nanotube buckypaper interleaf [10] and through-the-thickness stitching of the flax yarn [11]. Stitching has also shown to have improve G_{IIC} for flax/basalt hybrid composite [12]. In addition, both unstitched and stitched flax/basalt hybrid composites have shown to have higher G_{IIC} as compared to the flax fibre composite itself [12]. Furthermore, upon immersion in the distilled water, G_{IIC} was generally found to have augmented. It was postulated to be due to the increment in the matrix ductility [12]. Based on the literature, it was observed that the delamination characterisation of flax composites was still rather limited. Hence, there is a need for further works to develop better understanding on the delamination behaviour of flax fibre composite.

The objective of this study is to characterise the mode I and mode II interlaminar fracture behaviour of flax fabrics reinforced epoxy composite. The specimens were tested using double cantilever beam (DCB) and three point end notched flexure (ENF) test at initial crack lengths, a_o of 50 mm and 30 mm, respectively. For each test, additional tests at four different initial crack lengths were performed to obtain the compliance plots. The fracture toughness were calculated using experimental calibration method (ECM). Finally, scanning electron micrographs (SEM) of the delaminated surfaces were captured to analyse the failure mechanisms during crack propagation.

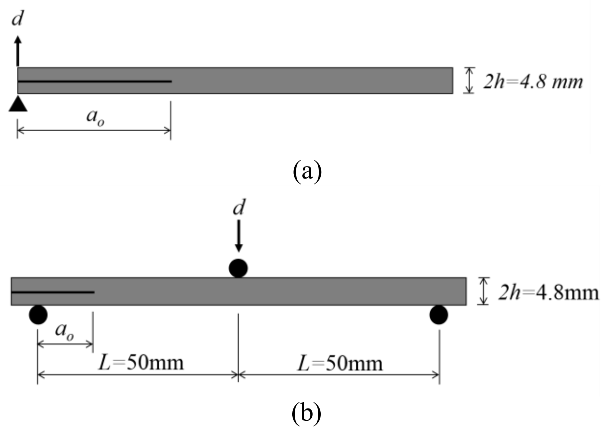
2 Materials and Methods

2.1 Materials

The materials used in this study were 200 g/m^2 twill weave 2/2 flax fabric and 1006 epoxy resin. Firstly, the flax fabrics were cut into 420×420 mm^2 size for 10 plies. Secondly, the epoxy resin was mixed with the hardener at the ratio of 10:6 and stirred gently. Next, the mixture was rolled on the flax fabrics layer by layer. At the mid-plane of the composite, a Teflon film of 15 µm thickness was placed to initiate the pre-crack. The laminate was then cured using vacuum bagging method. Upon completion of the curing process, the composite plate with average thickness of 4.8 mm were cut into specimens at 20 mm width and 200 mm length.

2.2 Interlaminar fracture tests

Double cantilever beam (DCB) and three point end notched flexure (ENF) tests were carried out using a universal testing machine with a 5 kN load cell. Figure 1 shows the test setup of the DCB and ENF tests. For DCB test, the initial crack length, a_o was 50 mm. As for ENF test, specimens were tested at initial crack length, a_o of 30 mm until crack propagation. Three replicates were performed for each test to obtain the average fracture toughness. Besides, for DCB test, additional four specimens at a_o of 30, 35, 40 and 45 mm each were tested. As for ENF test, the additional specimens were loaded at a_o = 20, 25, 35 and 40 mm. The purpose was to obtain the compliance plots for fracture toughness determination using experimental compliance method (ECM). All tests were conducted at crosshead speed of 2 mm/min at ambient conditions.



a_o = initial crack length
d = imposed displacement
h = half thickness of the specimen
L = half span length

Figure 1. Setup configurations for (a) DCB and (b) ENF tests.

2.3 Fracture surface morphology

To examine the microscopic fracture morphology, the delaminated surfaces of the specimens were first gold coated by 134 Bio-Rad Polaron Division E5100 and images were captured after that using Hitachi S-3400N variable pressure scanning electron microscope (SEM).

3 Results and discussion

3.1 Force-displacement curves

Figure 2 illustrates the experimental force-displacement curves of the flax/epoxy composite under mode I and mode II loadings. Good repeatability was observed for both tests. In addition, it could be seen that all curves increased in a high non-linear manner before the peak load (critical load) was attained. Beyond that, crack was initiated and slight load drop was observed. After that, crack was propagated and the force-displacement curves remained almost plateau.

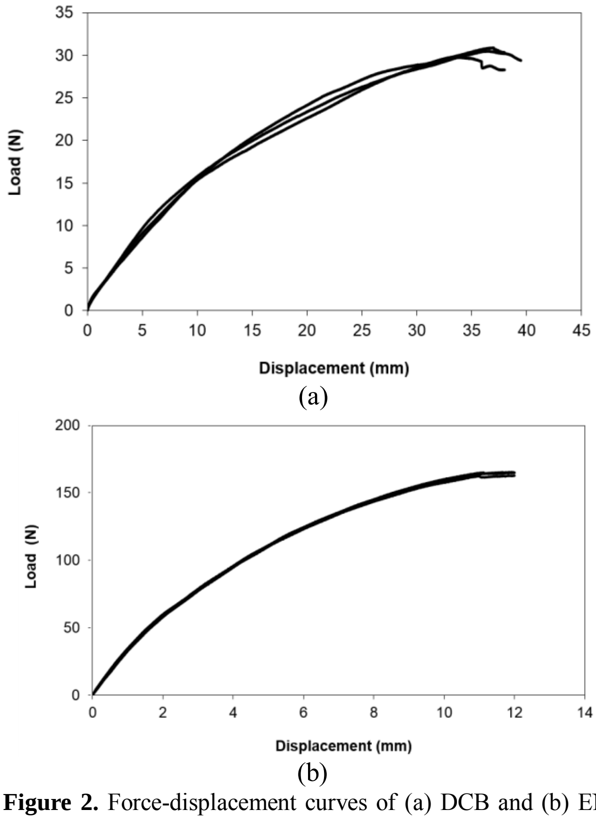


Figure 2. Force-displacement curves of (a) DCB and (b) ENF tests.

3.2 Calculation of interlaminar fracture toughness

The interlaminar fracture toughness, G_C was calculated using experimental calibration method (ECM), which is expressed by:

$$G_C = \frac{P_C^2}{2B} \cdot 3C_2 a_o^2 \qquad (1)$$

In Equation (1), P_C is the peak load from the force-displacement curve, B is the average width of the specimen, C_2 is the coefficient obtained from the following compliance equation:

$$C = C_2 a_o^3 + C_1 \qquad (2)$$

As could be observed from Equation (2), C_1 and C_2 were the coefficients fitted from C versus a_o^3 plot. Figure 3 shows the compliance plots of the flax/epoxy composite at various a_o. From the plot, it could be seen that for DCB test, $C_1 = 1.73\times10^{-1}$ and $C_2 = 3.05\times10^{-6}$. As for ENF test, $C_1 = 1.58\times10^{-2}$ and $C_2 = 5.66\times10^{-7}$. In addition, both plots showed good fit, with $R^2 = 0.98$.

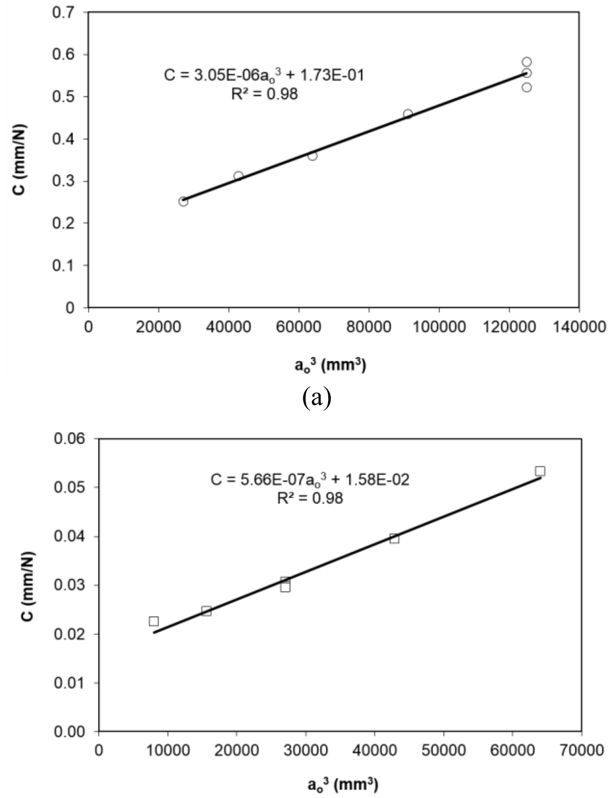


Figure 3. Compliance plots of flax/epoxy composite for (a) DCB and (b) ENF tests.

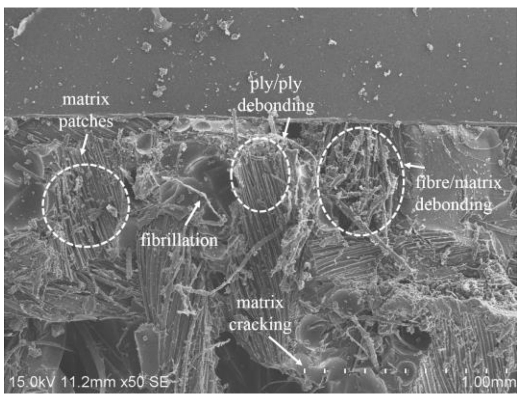
Table 1 displays the parameters involved in the calculation of G_C. The average mode I and mode II fracture toughness, $G_{C,avg}$ was calculated as 485 N/m and 962 N/m for DCB and ENF tests, respectively. The average G_{IC} was similar to those reported in [9–10] for plain weave flax/epoxy composite, which was in the range of 400–500 N/m. For average G_{IIC}, it was lower compared to the one reported by Bensadoun *et al.* (1872 N/m) [9], however, it was higher than the one tested by Almansour *et al.* (266 N/m) [12]. The possibilities could be due to the different source of flax fabrics, epoxy resin and fabrication method. In addition, the coefficient of variation (C.V) was less than 5 %, which indicated excellent repetition of the results.

Table 1. Calculation of interlaminar fracture toughness of flax/epoxy composite laminates.

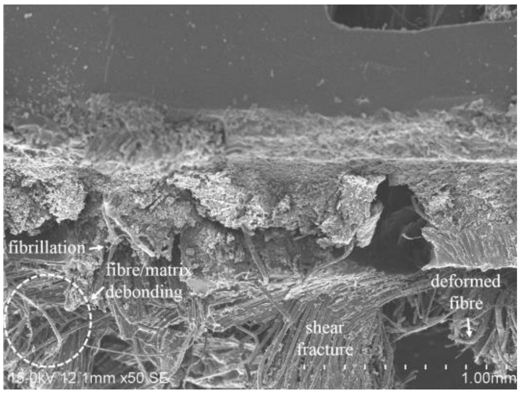
B (mm)	P_C (N)	G_C (N/m)	$G_{C,avg}$ (N/m)	C.V (%)
Mode I DCB				
21.93	29.8	464	485	4
21.76	30.5	489		
21.74	30.9	502		
Mode II ENF				
21.25	164.9	977	962	2
21.45	162.6	941		
21.61	165.5	968		

3.3 Morphology study

Figure 4 shows the scanning electron micrographs of the delaminated surfaces of the DCB and ENF specimens. Figure 4(a) shows that significant ply/ply debonding was observed. In addition, fibre/matrix debonding was also noticed. Not only that, there were matrix cracking and small amount of fibrillation on the surface. Some matrix patches were also seen to be attached on the delaminated surface. This could be the reason of having a slight higher G_{IC} compared to the one reported by Chen *et al.* [10]. In their studies, it was reported that the scanning electron micrograph showed clean debonded surface with significant fibre pull-out and bridging [10]. Besides, the mode II fracture surface of flax/epoxy composite (Figure 4(b)) showed shear fracture due to the sliding between the plies was the major fracture mechanism that contributed to energy dissipation process. Furthermore, deformed fibres were noticed, which was an indication of poor interfacial adhesion. According to Almansour *et al.* [12], shear kink bands in flax fibres caused stress concentration in the matrix and fibres. In addition, fibre/matrix debonding and slight amount of fibrillation were observed.



(a)



(b)

Figure 4. Scanning electron micrograph of the delaminated surface of flax/epoxy composite under (a) mode I and (b) mode II loadings.

4 Concluding remarks

This study examined the mode I and mode II delamination behaviour of flax fabrics reinforced epoxy composite. Mode I and mode II interlaminar fracture tests were conducted using double cantilever beam (DCB) and three point end notched flexure (ENF) specimens, respectively. The interlaminar fracture toughness were calculated using experimental calibration method (ECM). Significant non-linear behaviour was observed from the force-displacement graphs of both tests. In addition, results showed that the average mode I and mode II fracture toughness were 485 N/m and 962 N/m, respectively. Excellent repetition was found, with maximum coefficient of variation of 4%. Finally, scanning electron micrographs revealed that ply/ply debonding and fibre/matrix debonding were the major fracture mechanisms in the DCB specimen. As for the ENF specimen, shear fracture dominated the fracture process. Deformed fibres were also noticed. This suggested poor fibre/matrix bonding between flax fibre and epoxy resin. Future works could be carried out by improving the interfacial adhesion through fibre surface treatment.

Acknowledgements

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