MODE I FRACTURE BEHAVIOR AND TOUGHENING MECHANISM OF ZANCHOR REINFORCED COMPOSITES

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Abstract

The mode I interlaminar fracture behavior of the composite laminates reinforced with the Zanchor process, which is a novel through-the-thickness reinforcement technique developed by Mitsubishi Heavy Industries and Shikibo, was studied on the basis of the experimental results of DCB tests. The effects of the Zanchor reinforcement on the macroscopic fracture toughness and microscopic fracture morphology were mainly focused on. Experimental results demonstrated that the mode I interlaminar fracture toughness was improved effectively by the Zanchor reinforcement, where the fracture toughness, G_{IC}*, increased almost linearly with the Zanchor density, Z. In addition, the fracture toughness,* G_{IC}*, increased drastically during the early stage of crack extension in the Zanchor reinforced composites, where the interlaminar crack propagated stably accompanied by a large amount of fiber bridgings. The above results suggested that the increase in mode I fracture toughness was the consequence of the fiber bridgings induced by the Zanchor process.*

1 Introduction

Advanced composite materials, such as CFRP (Carbon Fiber Reinforced Plastics), have been widely used in various industrial applications owing to their superior properties in stiffness, strength, lightness, chemical resistance, and so forth. Recently, increasing scientific attention has been engaged to the extensive use of the advanced composite materials for the primary structures of next generation passenger air vehicles. The progress in mechanical properties has immensely contributed to the expansion of application of composite materials as well as the progress in the manufacturing and quality-control techniques [1]. Especially, the improvement of interlaminar strength, which has been considered as a weak point of laminated composite materials, is highly important, as can be understood from the example of interlayer toughened composite, T800H/3900-2, applied to the primary structures of Boeing 777.

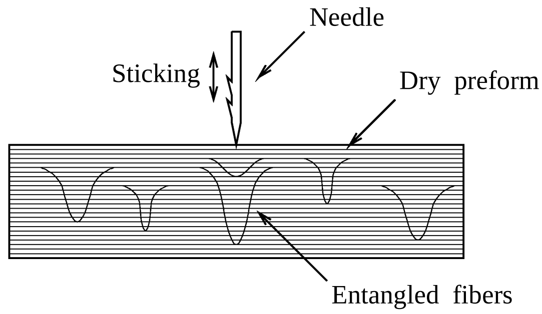

Fig. 1. Schematic drawing of Zanchor process.

In order to improve the interlaminar strength of composite laminates, applications of toughened resins and modification of fiber/matrix interface have been mainly examined heretofore. On the other hand, applications of through-the-thickness reinforcements, such as stitching or tree-dimensional fabrics, have been actively examined in recent years. However, there are some drawbacks in in-plane properties or manufacturing cost in such kinds of through-the-thickness reinforcements in spite of their very high effectiveness against interlaminar strength. Z-pinning, which is a kind of through-the-thickness reinforcement using fine pins of composites, was developed to

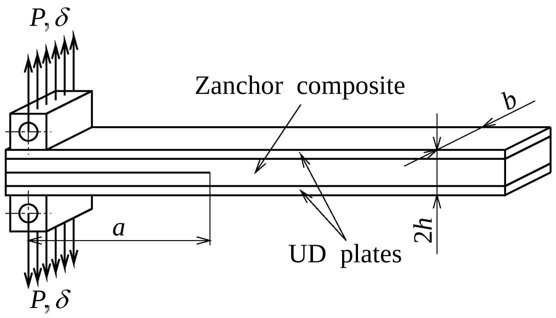

Fig. 2. Schematic drawing of DCB specimen.

overcome the drawbacks of conventional through-the-thickness reinforcements. However, the performance of the Z-pinning has not been fully characterized yet [2–5].

Zanchor, which is a novel through-the-thickness reinforcement developed by Mitsubishi Heavy Industries and Shikibo, can effectively and inexpensively improve the interlaminar strength of composite laminates [6]. In the Zanchor process, in-plane yarns are entangled each other by sticking with special needles as shown in Fig. 1. Iwahori et al. [7] showed that the CAI performance of composite laminates could be largely improved by the Zanchor process without significant reduction of in-plane properties [7]. However, the mechanism of Zanchor reinforcement has not been clarified yet. The authors have, therefore, investigated the interlaminar fracture behavior of Zanchor reinforced composites on the basis of the linear fracture mechanics [8–13].

In this work, the mode I interlaminar fracture behavior of Zanchor reinforced composite laminates was experimentally characterized to study the mechanism of Zanchor reinforcement.

2 Experimental Procedures

2.1 Materials and Specimens

CF/epoxy composite panels (MR60H/#172, Mitsubishi Rayon) of $[0°/90°/90°/0°]_s$ in stacking sequence and 2.4 mm in nominal thickness were fabricated with a CF dry fabric through the RFI (Resin Film Infusion) process. Zanchor process, which is not a stitching process but a kind of sticking process using special needles, was applied to dry preforms prior to the RFI process. Kapton films of 50 μm in thickness were inserted at the midplane of the panels to introduce an artificial interlaminar debonding. Three types of composite panels with different Zanchor density, Z1, Z2, Z4, were prepared to study the toughening mechanism of Zanchor, where the Zanchor density, Z, was defined as a nondimensional parameter proportional to the number of Zanchor per unit area. A composite panel without Zanchor, Z0, was also prepared for comparison.

2.2 Experimental Procedures

DCB (Double Cantilever Beams) specimens [14] of 10 mm in width, 170 mm in length and 40 mm in initial crack length were employed to study the mode I interlaminar fracture behavior of the Zanchor reinforced composites, as shown in Fig. 2. Unidirectional CFRP plates of 2 mm in thickness were bonded to both faces of the specimens for preventing the bending failure. Aluminum blocks of 10×10 mm^2 in sectional area were also bonded to the specimen for applying the mode I loading. DCB tests were carried out on a screw-driven testing machine at a displacement rate, $\dot{\delta} = 1$ mm/min, under a displacement controlled condition

2.3 Data Reduction Scheme

The mode I fracture toughness of the Zanchor reinforced composites investigated by using the energy release rate, G_I, given by the following equation [14];

$$G_\mathrm{I} = \frac{3}{2(2h)} \left(\frac{P}{b}\right)^2 \frac{\sqrt[3]{(bC)^2}}{\alpha} \qquad (1)$$

where b, $2h$ and C $(= \delta/P)$ are the width, thickness and compliance of the specimen, respectively. P is the load applied to the specimen. δ is the displacement of loading point. α and β, which depend on the material properties, are the coefficient given by the following equation.

$$\frac{a}{2h} = \alpha \sqrt[3]{bC} + \beta \qquad (2)$$

2.4 Microscopic Observation

Microscopic observation using a optical microscope was carried out to investigate the fracture morphology of the materials. The specimens were cut at the planes perpendicular to the longitudinal direction to study the micro- and macroscopic failure process of the Zanchor reinforced composites under mode I loading. The cutting planes were 5, 10, 20 and 30 mm from the final crack tip after the DCB tests. Microscopic observation using

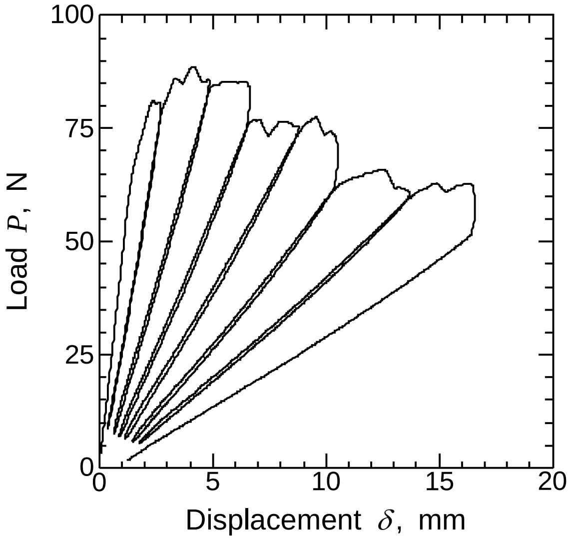

Fig. 3. Load-displacement responses of the Zanchor reinforced composite, Z1, in DCB tests.

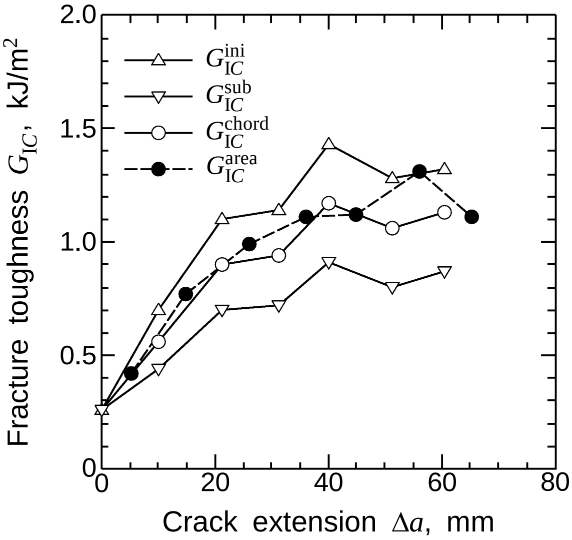

Fig. 5. Comparison of fracture toughness of the Zanchor reinforced composite, Z1, in DCB tests.

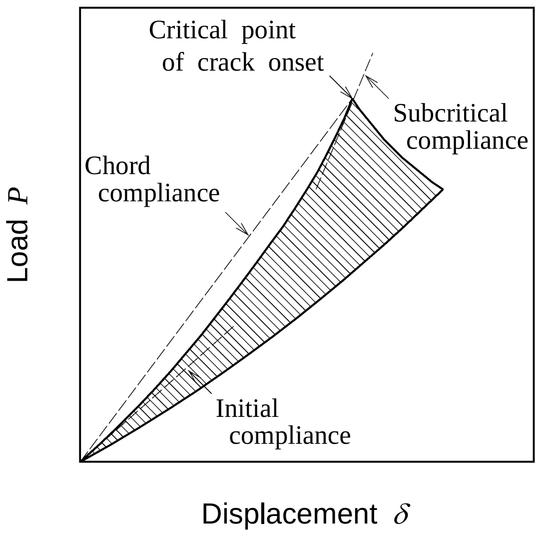

Fig. 4. Definition of loading point compliance in DCB tests.

a scanning electron microscope was also carried out to investigate the fracture morphology of the materials in detail.

3 Results and Discussion

3.1 Load-Displacement Response

Figure 3 shows the typical load-displacement curves obtained by the DCB tests, where the loading and unloading were alternately repeated until the crack extension, Δa, reached about 70 mm. The abscissa represents the displacement of the loading point, δ. The ordinate represents the load applied to the specimen, P. As shown in the figure, the load-displacement curves were nonlinear except for the first loading process; the gradient of the curves slightly increased with loading resulting in a concaved shape below the critical points of crack onset for each loading process. The nonlinearity was suggested to be the consequence of fiber bridgings induced with crack extension.

The above nonlinearity, which affects the estimation of the compliance, C, is not considered in the derivation process of Eq. 1; considerable error can be included in the energy release rate, G_I, calculated by the equation. Three types of compliance, C_{ini}, C_{sub}, C_{chord}, were, therefore, defined to study the estimation error in the energy release rate, G_I. C_{ini} was the initial compliance determined from the gradient during the early stage of loading. C_{sub} was the subcritical compliance determined from the gradient just below the critical point of crack onset. C_{chord} was the chord compliance defined as the ratio, δ/P, of the state of interest, as shown in Fig. 4.

Figure 5 shows the crack resistance curves of the Zanchor reinforced composite, Z1. The abscissa represents the crack extension, Δa. The ordinate represents the fracture toughness, G_{IC}. Open regular triangles are the results, G_{IC}^{ini}, calculated from the initial compliance, C_{ini}. Open

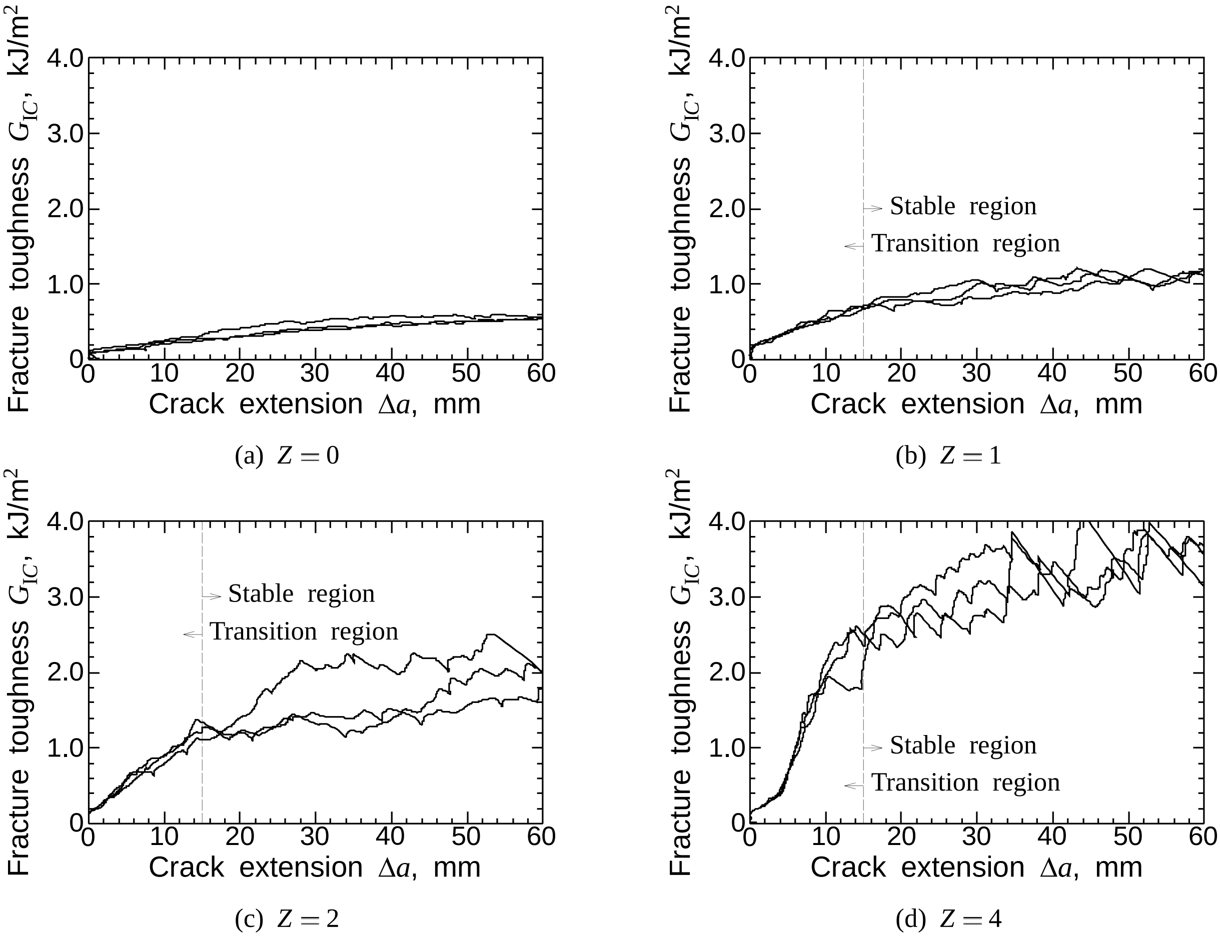

Fig. 6. Crack resistance curve of the composites under mode I loading.

inverted triangles are the results, G_{IC}^{sub}, calculated from the subcritical compliance, C_{sub}. Open circles are the results, G_{IC}^{chord}, calculated from the chord compliance, C_{chord}. Solid circles are the results, G_{IC}^{area}, calculated on the basis of the area method, which can rigorously give the average fracture toughness, G_{IC}, even if the nonlinearity of load-displacement curves is not negligible. As shown in the figure, the values of G_{IC}^{chord} well agreed with the rigorous values of G_{IC}^{area}, while the values of G_{IC}^{ini} and G_{IC}^{sub} gave the over- and underestimation of G_{IC}^{area}, respectively.

The above results suggested that the mode I fracture toughness, G_{IC}, could be calculated from the chord compliance, C_{chord}, with reasonable accuracy, though the nonlinear feature of load-displacement response was clearly observed in DCB tests.

3.2 Mode I Fracture Toughness

Figure 6 shows the crack resistance curves obtained by the DCB tests. The abscissa represents the crack extension, Δa. The ordinate represents the fracture toughness, G_{IC}. (a), (b), (c) and (d) are the results of the composites, Z0, Z1, Z2 and Z4, respectively. As shown in the figure, the fracture toughness, G_{IC}, largely increased with crack extension in the Zanchor reinforced composites, Z1, Z2, Z4; the fracture toughness, G_{IC}, drastically increased during the early stage of crack extension, $\Delta a < 15$ mm, where the fracture toughness, G_{IC}, for $\Delta a = 15$ mm reached more than ten times as large as that for $\Delta a = 0$ mm in the composite, Z4. On the other hand, the fracture toughness, G_{IC}, gradually increased with crack extension for $\Delta a > 15$ mm. The saw-toothed region observed in the results of the composite, Z4, was caused by the debonding occurred at the 0°/90° interface, where the 0° layer behaved as a kind of large-scale bridging.

Figure 7 shows the summary of the results shown in Fig. 6 parametrized with the crack extension, Δa. The abscissa represents the Zanchor density, Z. The ordinate represents the fracture

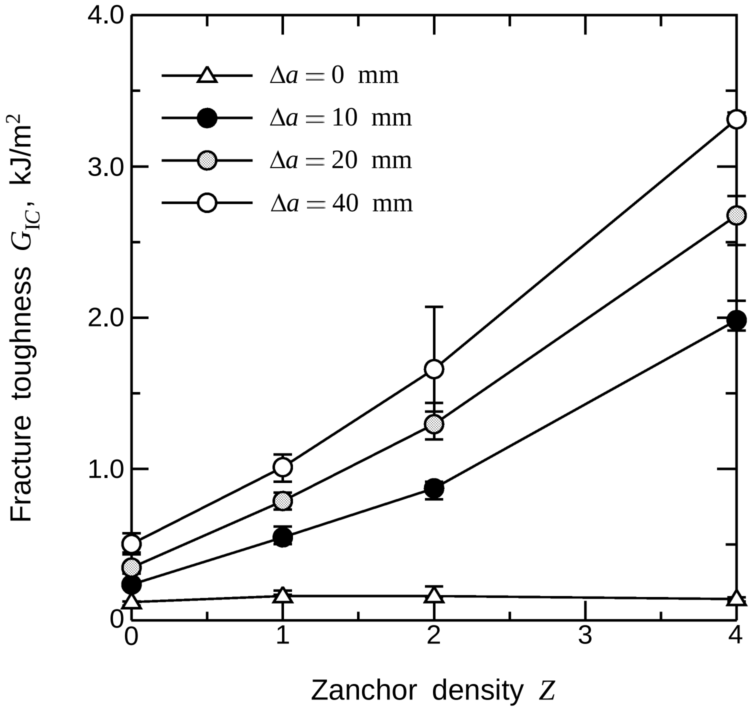

Fig. 7. Effect of Zanchor density on mode I fracture toughness of the Zanchor reinforced composites.

toughness, G_{IC}. The open triangle, solid circles, shaded circles and open circles are the results for $\Delta a = 0$, 10, 20, 40 mm, respectively. As shown in the figure, the fracture toughness, G_{IC}, increased almost linearly with the Zanchor density, Z, regardless of crack extension, Δa. The fracture toughness, G_{IC}, of the Zanchor reinforced composite, Z4, reached more than six times as large as that of the composite without Zanchor, Z0, for $\Delta a = 40$ mm. Itabashi et al. suggested that the increase in the fracture toughness, G_{IC}, would be slowed down when the Zanchor density, Z, reach a certain value [15]. The discrepancy between their and our results may be due to the difference of the base materials; the effect of Zanchor will not be saturated even for the composite, Z4.

The above results suggested that the mode I fracture toughness, G_{IC}, of composite materials could be improved effectively by the Zanchor process, where the mode I fracture toughness, G_{IC}, increased almost linearly with the Zanchor density, Z. In addition, there existed a transition region of mode I fracture toughness, G_{IC}, during the early stage of crack extension, $\Delta a < 15$ mm, where the mode I fracture toughness, G_{IC}, increased drastically with crack extension.

3.3 Mode I Fracture Morphology

Figure 8 shows the side view of the specimen, where the crack extension, Δa, is about 40 mm. As shown in the figure, a large amount of fiber bridgings were observed in the Zanchor reinforced composites, Z1, Z2 and Z4, where the amount of fiber bridgings increased with Zanchor density. In the composite, Z4, the 0° layer behaved as a kind of large-scale bridging for $\Delta a > 40$ mm. Figure 9 shows the scanning electron micrograph of the fracture surface, where the observation point is about 20 mm from the crack tip. As shown in the figure, a large number of conical protrusions induced by the Zanchor process were observed in the composites, Z1, Z2 and Z4.

Figure 10 shows the transverse section of the specimens, where the cutting plane is about 10 mm in distance from the final crack tip. (a), (b), (c) and (d) are the micrographs of the composites, Z0, Z1, Z2 and Z4, respectively. As shown in the figure, relatively smooth profile was observed in the composite without Zanchor reinforcement, Z0. On the other hand, relatively rough profiles were observed in the Zanchor reinforced composites, Z1, Z2 and Z4, where the roughness of the profile obviously increased with Zanchor density.

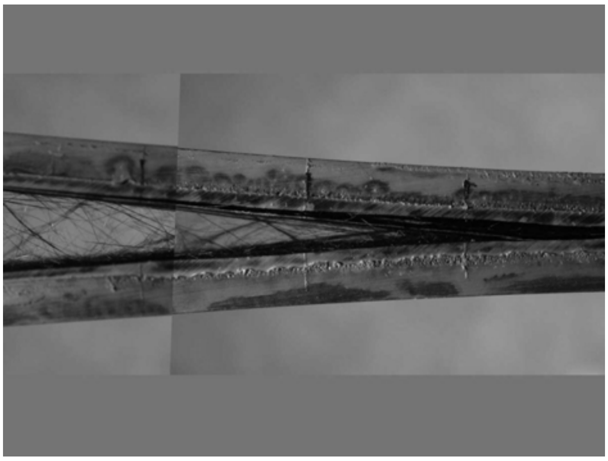

Fig. 8. Macroscopic fracture morphology of the Zanchor reinforced composites, Z1, under mode I loading (crack growth direction ⇒).

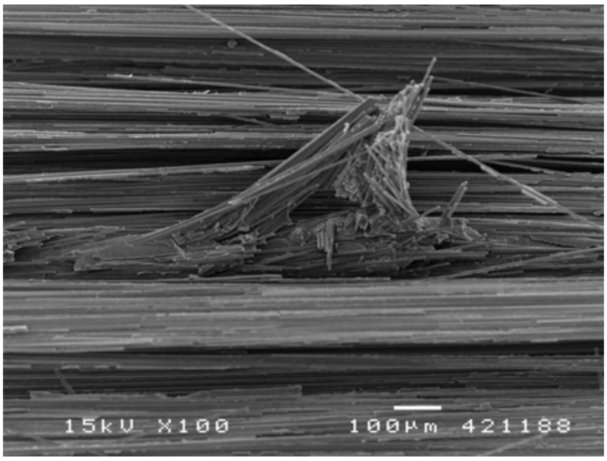

Fig. 9. Microscopic fracture morphology of the Zanchor reinforced composites, Z2, under mode I loading (crack growth direction ⇒).

In addition, the number and thickness of fiber bridgings also showed an increasing trend with Zanchor density.

The above results suggested that the Zanchor process could induce a large amount of fiber bridgings during the mode I crack propagation process, resulting in the improvement of the mode I fracture toughness, G_{IC}, of composite laminates. In addition the roughness of the fracture surface was significantly affected by the Zanchor process. However, the quantitative analysis of the effects of fiber bridgings and surface roughness on mode I fracture behavior is still in progress.

4 Conclusions

The mode I interlaminar fracture behavior of Zanchor reinforced composite laminates was experimentally characterized to study the mechanism of Zanchor reinforcement. The major results are summarized as follows;

- The mode I fracture toughness, G_{IC}, of composite materials could be improved effectively by the Zanchor process, where the mode I fracture toughness, G_{IC}, increased almost linearly with the Zanchor density, Z.

- There existed a transition region of mode I fracture toughness, G_{IC}, during the early stage of crack extension, $\Delta a < 15$ mm, where the mode I fracture toughness, G_{IC}, increased drastically with crack extension.

- The Zanchor process could induce a large amount of fiber bridgings during the mode I crack propagation process, resulting in the improvement of the mode I fracture toughness, G_{IC}, of composite laminates.

- The mode I fracture toughness, G_{IC}, could be calculated from the chord compliance, C_{chord}, with reasonable accuracy, though the nonlinear feature of load-displacement response was clearly observed in DCB tests.

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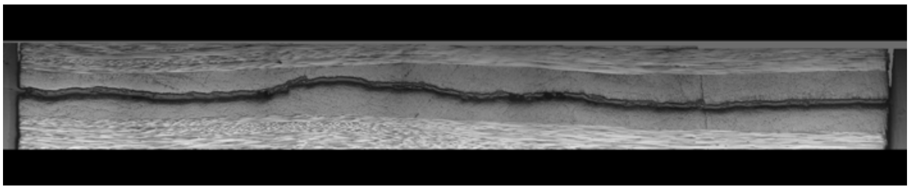
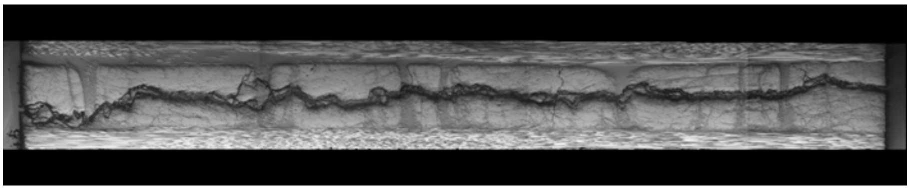
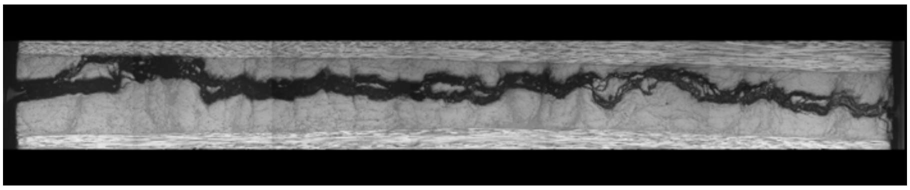


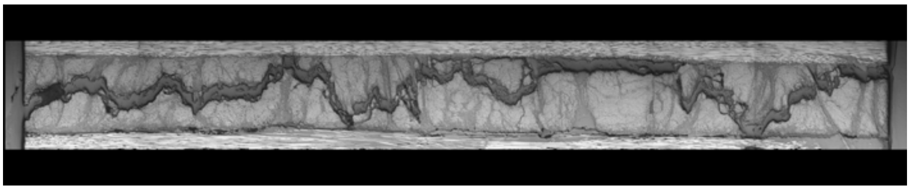
(a) $Z = 0$



(b) $Z = 1$



(c) $Z = 2$



(d) $Z = 4$

Fig. 10. Effect of Zanchor density on mode I fracture morphology of the Zanchor reinforced composites (cutting position $\xi = 10$ mm, crack growth direction $\otimes$).

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