MODE II FRACTURE BEHAVIOR AND TOUGHENING MECHANISM OF ZANCHOR REINFORCED COMPOSITES

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Abstract

The crack propagation behavior of CFRP laminates reinforced with Zanchor, which is a novel out-of-plane reinforcement technique developed by Mitsubishi Heavy Industries and Shikibo, under the mode II loading was experimentally investigated to clear the toughening mechanism with Zanchor reinforcement. Experimental result demonstrated that the Zanchor process was remarkably effective for the improvement of mode II interlaminar fracture toughness of composite materials, where the fracture toughness proportionally increased with the Zanchor density. Moreover, broken traces of the fiber bundles oriented to the through-thickness direction were observed, whereas fiber bridgings could not be observed under mode II loading. Therefore, it was suggested that the key factor of the increase in mode II fracture toughness would be the breaking energy of the fiber bundles.

1 Introduction

Laminated composites with high specific stiffness and strength have been extensively used in many structural applications, spacecraft, aircraft, automobile, railway vehicle and so on, because of their advantageous characteristics compared with conventional engineering materials. However, the strength in the through-thickness direction is significantly smaller than that in the fiber direction. The delamination has been, therefore, considered as one of the most serious defect in composite structures.

In order to overcome the defect, various techniques have been developed to improve the interlaminar strength of composite laminates, where the development of toughened matrix resins using thermoplastic resin etc. and out-of-plane reinforcement techniques using stitching [1] etc. was the matters of primary concern. However, since these techniques still have some problems on the productivity, manufacturing cost and so on, the development of techniques to improve the interlaminar strength efficiently and inexpensively has been expected. The Zanchor technique has been recently developed by Mitsubishi Heavy Industries and Shikibo [2] in order to meet such kinds of industrial needs. In the Zanchor process, in-plane fibers are entangled using special needles in the through-thickness direction as shown in Fig. 1. The interlaminar strength can be improved by using this technique without serious reduction of in-plane strength [3]or significant increase of manufacturing cost compared with the three-dimensional fabrics or stitching. Though another novel technique, so-called Z-pin [4], has been also developed for similar purpose to Zanchor, the performance of Z-pin has not been fully characterized yet [5-9].

Iwahori et al. [10] reported that the CAI (Compressive strength After Impact) performance of composite materials could be remarkably improved by Zanchor process. However, there are very few reports on the investigation of the Zanchor reinforced composites [11], which is more primitive

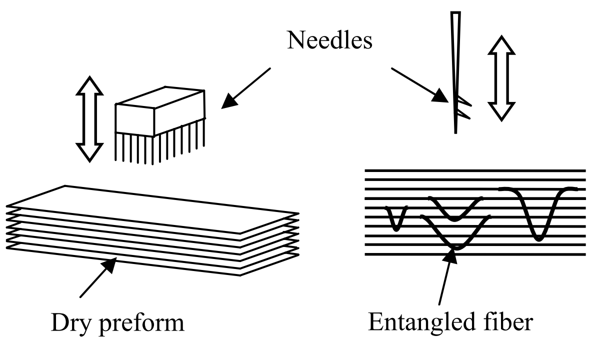


Fig. 1. Schematic of Zanchor technology

and well-defined parameter describing the damage tolerance of composite materials. In addition, the mechanisms of Zanchor reinforcement have not been sufficiently clarified yet. In the previous works, the authors have investigated the mode I and mode II fracture behavior of Zanchor reinforced CFRP laminates on the basis of fracture mechanics [12-18]. Especially, it is important to clarify the fracture characteristics under mode II loading, because it is closely related to the CAI performance, which is one of the most important properties for the selection of materials for aircraft.

In this study, the behavior of crack propagation of Zanchor reinforced CFRP laminates under mode II loading was experimentally investigated to clear the toughening mechanism with Zanchor reinforcement. Moreover, the results obtained in this study were compared with the results under mode I loading [19].

2 Materials and Experimental Procedure

2.1 Specimen Preparation

Carbon-fiber/epoxy (Mitsubishi Rayon Co., MR60H/#172) composite panels of $[0/90/90/0]_s$ in stacking sequence (Fig. 2) were fabricated with a carbon fiber dry fabric through the RFI (Resin Film Infusion) process. Zanchor process was applied to the dry fabric preforms prior to the RFI process. The nominal thickness of the panels was 2.4 mm. A 50 μm thick polyimide film was inserted at a part of midplane along the edge to introduce an artificial debonding. Three kinds of composite panels, Z1, Z2, Z4, of different Zanchor density, *Z*, were fabricated in order to study the effect of Zanchor density. Composite panels without Zanchor reinforcement, Z0, were also prepared for comparison. Z2 and Z4 were twice and four times the Zanchor density of Z1, respectively.

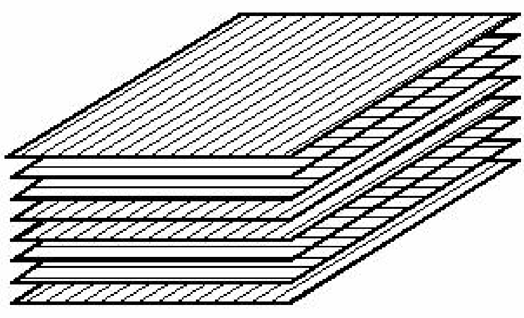


Fig. 2. Stacking sequence of the composite

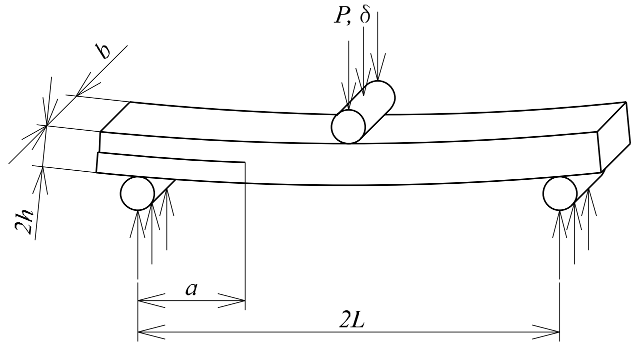


Fig. 3. Schematic of ENF specimen

2.2 Experimental Procedure

Mode II fracture toughness tests were carried out using the three-point end notched flexure (3ENF) specimen as shown in Fig. 3 [20]. The bending span, 2*L*, width, *b*, and initial crack length, a_0, of the specimen were 80 mm, 10 mm and 20 mm, respectively. Unidirectional CFRP plates of 0.6 mm thick were bonded on both sides of specimens for preventing flexural failure.

The ENF tests were conducted under a displacement controlled condition with the displacement rate of 1 mm/min. At least three specimens were employed for each condition of Zanchor density.

Mode II fracture toughness, G_{IIC}, was calculated using the following equations [20].

$$G_{IIC} = \frac{9a_1^{\,2} P_C^{\,2} C_1}{2b(2L^3 + 3a_1^{\,3})} \quad (1)$$

$$a_1 = \left[\frac{C_1}{C_0} a_0^{\,3} + \frac{2}{3}\left(\frac{C_1}{C_0} - 1 \right) L^3 \right]^{\frac{1}{3}} \quad (2)$$

where P_C is the critical load at the onset of crack growth, a_0 and C_0 are the initial crack length and load point compliance of the specimen. a_1 and C_1 are the crack length and load point compliance at $P=P_C$.

2.3 Microscopic Fracture Morphology

In order to investigate the fracture morphology of specimens after mode II fracture toughness test, the cross-sectional observation with an optical microscope and the fracture surface observation with a scanning electron microscope were conducted. In the cross-sectional observation, the distance from the end of crack after test, ξ, was defined as parameter to study the failure process of the specimens.

3 Results and Discussion

3.1 Load-Displacement Response

Figure 4 shows the typical relationship between the load, P, and the displacement, δ, on the ENF fracture toughness test of the composite Z1. The broken line represents the gradient in the initial linear region. The open circle and the solid circle represent the nonlinear point, P_{nl}, and the maximum point, P_{max}, respectively. As shown in the figure, the crack grew stably in fairly wide range from P_{nl} to P_{max}, though the ENF test is theoretically an unstable fracture toughness test under displacement controlled condition.

Figure 5 shows the typical relationship between the mode II fracture toughness, G_{IIC}, and the crack extension, Δa, i.e. crack resistance curve (R-curve), during the initial stage of crack extension. The open circle and the solid circle represent the nonlinear point, P_{nl}, and the maximum point, P_{max}, in Fig. 4, respectively. As shown in the figure, the stable fracture region was $0<\Delta a<2$ mm, where the mode II fracture toughness, G_{IIC}, increased rapidly with crack extension. It almost agreed with unsteady area of Zanchor density derived from the manufacturing procedure of the specimen.

3.2 Mode II Fracture Toughness

Figure 6 shows the typical relationship between the mode II fracture toughness, G_{IIC}, and the crack extension, Δa. ●, □, △ and ◇ represent the results of the composites Z0, Z1, Z2 and Z4, respectively. As shown in the figure, the fracture toughness, G_{IIC}, increased largely with increasing the Zanchor density, Z. In the case of the composite without Zanchor reinforcement, Z0, the fracture toughness, G_{IIC}, was almost constant regardless of the crack extension, Δa. On the other hand, in the case of the Zanchor reinforced composites Z1, Z2 and Z4, the fracture toughness, G_{IIC}, increased rapidly in the initial stable fracture region. Especially, on the composites Z1 and Z2, the fracture toughness, G_{IIC}, was almost constant regardless of the crack extension, Δa after the initial stable fracture region. On the composite Z4, the fracture toughness, G_{IIC}, tended to increase gradually until Δa=40 mm, and become constant after that.

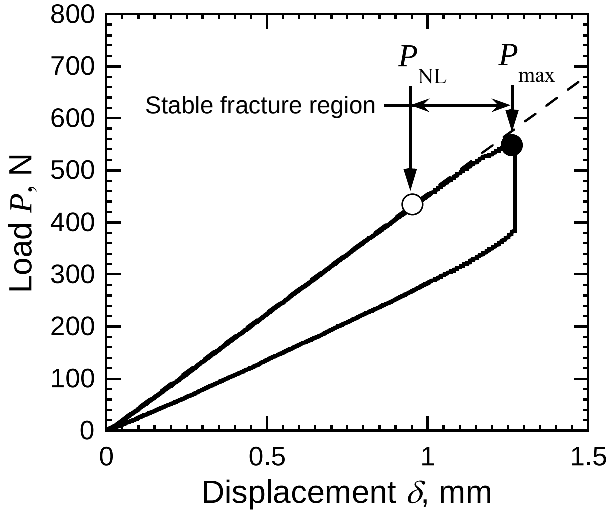


Fig. 4. Typical load-displacement relation at the first loading step (material; Z1).

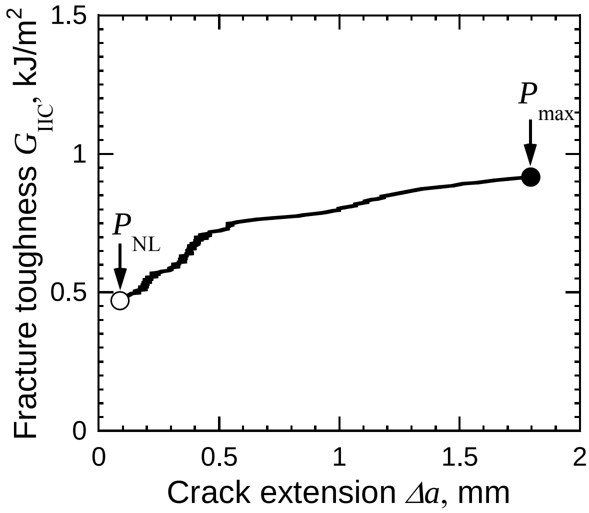


Fig. 5. Crack resistance curve (R-curve) of Zanchor reinforced composite during the initial stage of crack extension (material; Z1).

In order to investigate more quantitatively the effect of Zanchor density on mode II fracture toughness, the relationship between the mode II fracture toughness, G_{IIC}, and the Zanchor density, Z, parameterizing with the crack extension, Δa, is shown in Fig. 7. ○, ●, △ and ▲ represent the fracture toughness, G_{IIC}, at Δa=0, 10, 20, 40 mm, respectively. As shown in the figure, the fracture toughness, G_{IIC}, at Δa=0 mm was about 0.5 kJ/m^2 regardless of the Zanchor density, Z. On the other hand, the fracture toughness, G_{IIC}, after the initiation

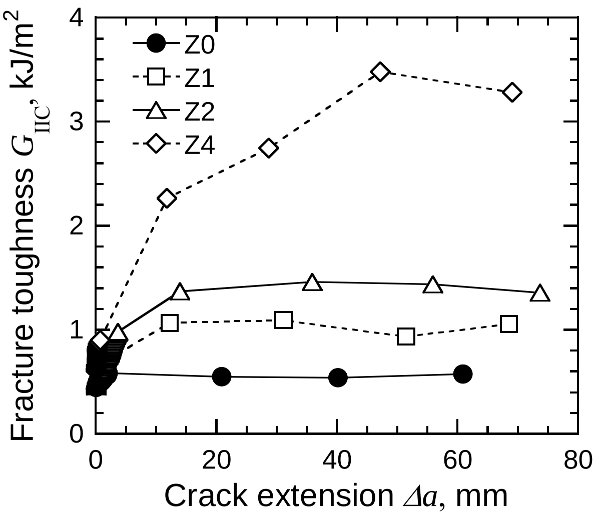


Fig. 6. Crack resistance curves (R-curve) of Zanchor reinforced composites.

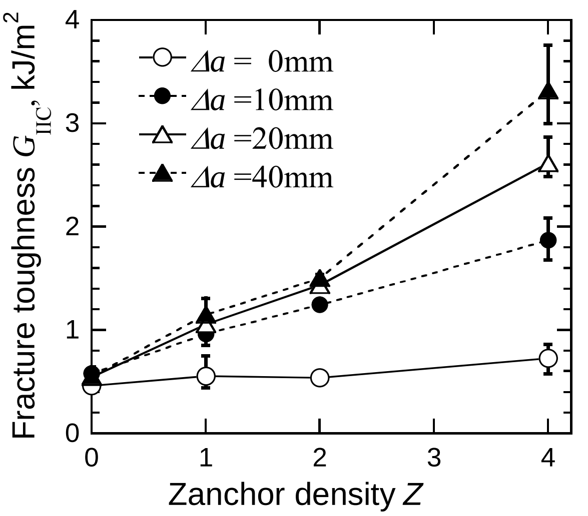


Fig. 7. Effect of Zanchor density on the mode II fracture toughness

of crack propagation, $\Delta a>0$ mm, increased proportionally with increasing the Zanchor density, Z. On the composite Z4, it slightly deviated from such proportional relationship owing to the delamination at 0/90 interface as described in the next section.

The above results suggested that the mode II fracture toughness, G_{IIC}, of composite materials could be improved effectively by the Zanchor process, where the mode II fracture toughness, G_{IIC}, increased almost linearly with the Zanchor density, Z. In addition, the fracture toughness, G_{IIC}, was almost constant regardless of the Zanchor density, Z, except for the very early stage of crack extension, $\Delta a<2$ mm, where the Zanchor density was unsteady.

3.3 Mode II Fracture Morphology

In order to understand the mode II fracture mechanism of Zanchor reinforced CFRP laminates in more detail, cross-section of specimen after mode II fracture toughness test was observed. Figures 8 (a)-(d) show cross-sectional images for the composites Z0, Z1, Z2 and Z4 at ξ=10 mm, respectively. The cutting plane is perpendicular to the longitudinal direction of specimens and the crack growth direction is inward to the page as shown by the symbol. As shown in figures, the fracture surface was relatively smooth for composite Z0, and the roughness of the fracture surface increased with increasing the Zanchor density, Z. Especially, on Z4 specimen, the crack path partially reached the 0/90 interface, which would affect the deviating tendency of the composite Z4 as show in Fig. 7. Moreover, though a large number of fiber bridgings were observed in mode I specimens [19], no fiber bridgings were observed in mode II specimens regardless of Zanchor density. Similar tendency was also observed at other locations ξ=5, 20, 30 mm.

Figure 9 shows photographs of mode II fracture surface with the scanning electron microscope. The crack growth direction is from left to right on the page as shown by the symbol. In

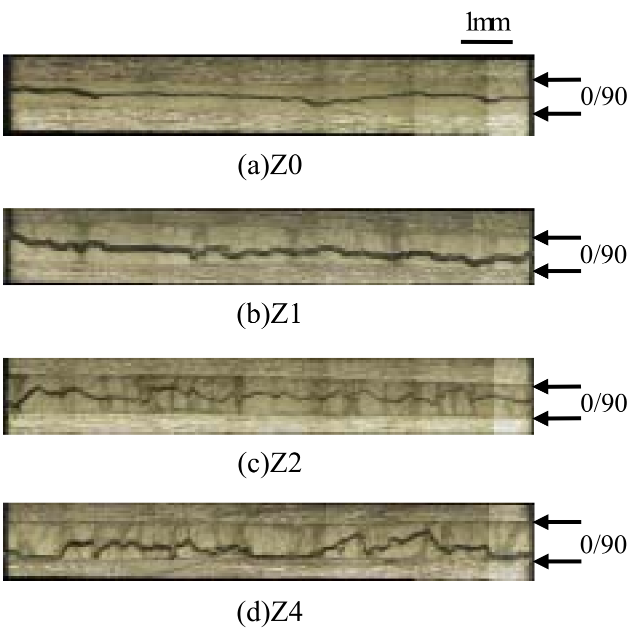
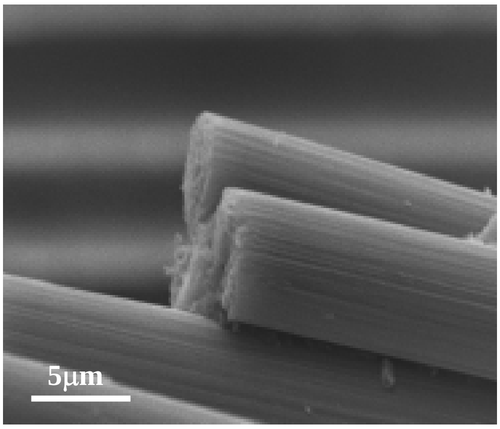
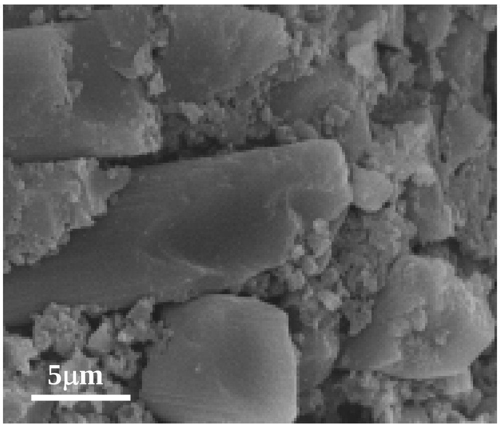


Fig. 8. Effect of Zanchor density on microscopic fracture morphology (distance from the end of crack; ξ=10 mm, crack growth direction; ⓧ).



(a) Tensile type



(b) Compressive type

Fig. 9. Scanning electron micrographs of mode II fracture surface (crack growth direction;→).

fracture surfaces of the composites Z1, Z2 and Z4, there were many broken traces of the fiber bundles oriented to the through-thickness direction by Zanchor process. They could be roughly classified into the tensile type (Fig. 9(a)) and the compressive type (Fig. 9(b)). For the tensile type, fibers were vertically broken to the direction of fiber orientation. On the other hand, for the compressive type, fibers were obliquely broken to the direction of fiber orientation, and fragments of the epoxy matrix remained around the broken bundles.

In the mode I fracture toughness test, the fracture toughness, G_{IC}, increased largely with increasing the crack extension, Δa, in considerably wide region of Δa<15 mm, and then increased gradually in the region of $\Delta a \geq 15$ mm [19]. To the contrary, in the mode II fracture toughness test, the fracture toughness, G_{IIC}, increased rapidly in the initial stable fracture region of Δa<2 mm, and became almost constant after then. These results suggest that the key factor of the improvement of fracture toughness under the mode II loading will be the breaking energy of fiber bundles induced by the Zanchor process, whereas that under the mode I loading will be the energy consumption related to fiber bridgings.

The above results suggested that the Zanchor process induced a large number of fiber bundles oriented to the through-thickness direction, resulting in the improvement of the mode II fracture toughness, G_{IIC}, of composite laminates. In other words, the mechanisms of Zanchor reinforcement against mode II fracture, which was mainly the contribution of breaking energy of fiber bundles, would be fundamentally different from those against mode I fracture, which was mainly the contribution of energy consumption related to fiber bridgings.

4 Conclusions

In this study, the behavior of crack propagation of Zanchor reinforced CFRP laminates under mode II loading was experimentally investigated to clear the toughening mechanism with Zanchor reinforcement. Moreover, the results obtained in this study were compared with the results under mode I loading. The major results are summarized as follows;

- The mode II fracture toughness of composite materials could be improved effectively by the Zanchor process, where the mode II fracture toughness increased almost linearly with the Zanchor density.
- The fracture toughness was almost constant regardless of the Zanchor density except for the very early stage of crack extension, Δa<2 mm, where the Zanchor density was unsteady.
- The Zanchor process induced a large number of fiber bundles oriented to the through-thickness direction, resulting in the improvement of the mode II fracture toughness of composite laminates.
- The mechanisms of Zanchor reinforcement against mode II fracture, which was mainly the contribution of breaking energy of fiber bundles, would be fundamentally different from those against mode I fracture, which was mainly the contribution of energy consumption related to fiber bridgings.

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References

[1] Nishimura A. and Aotani H. "New fabric structures for composite". *Proceedings of Composites '86*, Tokyo, pp 29-36, 1986.

[2] Abe T., Hayashi K., Sato T., Yamane S. and Hirokawa T. "A-VaRTM process and Z-anchor technology for primary aircraft structures". *Proceedings of 24th International SAMPE Europe Conference*, Paris, pp 87-94, 2003.

[3] Kato T., Iwahori Y., Ishibashi M., Fukuoka T. and Ishikawa T. "Evaluation of mechanical properties and failure process of Zanchor CFRP laminate". *Proceedings of 29th Composite material Symposium*, Okinawa, pp. 229-230, 2004, (in Japanese).

[4] Freitas G., Magee C., Dardzinski P. and Fusco T. "Fiber insertion process for improved damage tolerance in aircraft laminates". *Journal of Advanced Materials*, Vol. 25, No. 4, pp. 36-43, 1994.

[5] Rugg K.L., Cox B.N. and Massabo R. "Mixed mode delamination of polymer laminates reinforced through the thickness by z-fibres". *Composites Part A*, Vol. 33, pp. 177-190, 2002.

[6] YanW., Liu H.Y. and Mai Y.W. "Numerical study on the mode I delamination toughness of z-pinned laminates". *Composites Science and Technology*, Vol. 63, pp. 1481-1493, 2003.

[7] YanW., Liu H.Y. and Mai Y.W. "Mode II delamination toughness of z-pinned laminates". *Composites Science and Technology*, Vol. 64, pp. 1937-1945, 2004.

[8] Dai S.C., YanW., Liu H.Y. and Mai Y.W. "Experimental study on z-pin bridging law by pullout test". *Composites Science and Technology*, Vol. 64, pp. 2451-2457, 2004.

[9] Partridge I.K. and Cartié D.D.R. "Delamination resistant laminates by Z-Fiber® pinning: Part I manufacture and fracture performance". *Composites Part A*, Vol. 36, pp. 55-64, 2005.

[10] Iwahori Y., Yamada K., Ishibashi M., Fukuoka T., Ishikawa T. and Ben G. "Compression after impact properties of Z-anchor CFRP laminates". *Proceedings of 33rd JSMS Composites*, Kyoto, pp. 213-215, 2004, (in Japanese).

[11] Itabashi T., Iwahori Y., Ishikawa T., Ishibashi M., Takeda F. and Watanabe N. "Experimentally evaluation of interlaminar mechanical properties of CFRP laminates enhanced by Zanchor". *Proceedings of 30th Composite material Symposium*, Ehime, pp. 267-268, 2005, (in Japanese).

[12] Hojo M., Nakashima K., Tanaka M., Adachi T., Kusaka T., Fukuoka T. and Ishibashi M. "Mode I interlaminar fracture mechanism of Zanchor-CFRP". *Proceedings of 29th Composite material Symposium*, Okinawa, pp. 233-234, 2004, (in Japanese).

[13] Tsuda K., Kusaka T., Hashiba M., Hojo M., Fukuoka T. and Ishibashi M. "Evaluation of mode I fracture toughness of CFRP reinforced with Zanchor". *Proceedings of 34rd JSMS Composites*, Kyoto, pp. 53-55, 2005, (in Japanese).

[14] Nakashima K., Hojo M., Tanaka M., Adachi T., Kusaka T., Fukuoka T. and Ishibashi M. "Mode II interlaminar fracture toughness of Zanchor CFRP laminates". *Proceedings of 34th JSMS Composites*, Kyoto, pp. 289-291, 2005, (in Japanese).

[15] Nakashima K., Hojo M., Tanaka M., Adachi T., Kusaka T., Fukuoka T. and Ishibashi M. "Comparison between static and fatigue delamination of Zanchor-CFRP". *Proceedings of the 2005 Annual Meeting of the JSME/MMD*, Fukuoka, pp. 457-458, 2005, (in Japanese).

[16] Nishiura K., Kusaka T., Watanabe K., Hojo M., Fukuoka T. and Ishibashi M. "Rate dependence of fracture behavior of Zanchor reinforced CFRP". *Proceeding of the 50th Japan Congress on Materials Research*, Kyoto, pp. 232-233, 2006, (in Japanese).

[17] Kusaka T., Hojo M., Fukuoka T. and Ishibashi M. "Effect of strain rate on the interlaminar fracture toughness of Zanchor reinforced composites". *Journal de Physique IV, Proceedings DYMAT 2006*, Vol. 134, pp. 1105-1111, 2006.

[18] Kusaka T., Hojo M., Fukuoka T. and Ishibashi M. "Effect of strain rate on the interlaminar fracture toughness of Zanchor reinforced composites", *Proceedings of JSME/ASME International Conference on Materials and Processing 2005 - The 13th JSME Materials and Processing Conference (M&P 2005) -*, Seattle, IMP-12-1-5, 2005.

[19] Kusaka T., Yamaguchi Y., Watanabe K., Hojo M., Fukuoka T. and Ishibashi M. "Mode I fracture behavior and toughening mechanism of Zanchor reinforced composites", *Proceedings of ICCM-16*, Kyoto, 2006 (in press).

[20] "Testing methods for interlaminar fracture toughness of carbon fibre reinforced plastics". JIS K 7086-1993, (1993).