# CHARACTERISTIC OF MODE I CRACK PROPAGATION OF CFRP LAMINATES TOUGHENED WITH CNF INTERLAYER

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**Abstract**
In the present study, characteristic of mode I crack propagation of CFRP laminates toughened with CNF interlayer has been investigated. CFRP laminated beam composed of carbon fiber woven fabric and epoxy resin has been fabricated by VaRTM process, where carbon nanofiber interlayer has been inserted between woven fabric laminates. Mode I fracture toughness tests have been applied to evaluate the relation between mode I fracture toughness and crack length (R-curve). The effect of CNF interlayer on the mode I fracture toughness of CFRP laminate has been investigated in detail by the experimental results and observation of fracture surface of the specimens, and the results obtained with woven fabric specimen were compared with those obtained with unidirectional CFRP laminate. Additionally, mode II fracture toughness of CFRP laminate has been investigated using end notch flexure (ENF) test.

## 1. Introduction
Over the past few decades, fiber reinforced plastics (FRP) have been developed as the foremost material for products in fields such as mechanical, electrical, architectural, and structural engineering. Carbon fiber reinforced plastic (CFRP) has especially attained a prominent position in use as structural materials for aeronautical and space engineering. Application in this industry requires further reduction in weight to satisfy the demand for higher fuel efficiency. In the Boeing 787 project, the overall weight was reported to have considerably decreased owing to the adoption of CFRP for the main wing and fuselage.
Considering delamination growth in view of fracture mechanics, interlaminar fracture toughness still plays an important role in damage propagation of CFRP. Therefore, a number of experimental and analytical techniques have been proposed to estimate the fracture toughness for mode I, mode II, mixed mode and dynamic deformations[1]–[3] with several combinations of carbon fiber and matrix resin.
Previous attempts to improve the interlaminar fracture toughness of CFRP laminates has shown a variety of useful results. Namely, a certain level of toughening technique has already been achieved by inserting an interleaf (interlayer) between the CFRP prepregs[4, 5]. T800H/3900-2, with a heterogeneous interlayer consisting of fine thermo plastic particles, has shown high compressive strength after impact (CAI). In contrast, ionomer interleaved CFRP laminates have

shown higher toughness under mode II deformations[6]. On the other hand, the author's group have been suggested the CNF interlayer for unidirectional CFRP laminates to obtain higher fracture toughness in mode I and mode II deformations[7, 8].
Since discovery of the carbon nano tube in the 1970s[9] and the publication in Nature clarifying the structure of the carbon nanofibers [10], carbon nano tubes and carbon nanofibers have received a great deal of attention in the aeronautical, biological, electrical and mechanical sciences, and engineering fields. Due to CNF's superiority in electrical conductivity, MWCNT or vapor grown carbon fiber 'VGCF' has established a strong presence in the storage battery field as the conductive filler.
Carbon nano tubes and fibers have been applied as the toughening filler of the structural material for resin or metal based composites. They are suitable for this application as they also have excellent mechanical properties such as elastic moduli, strength, fracture toughness, and flexibility compared with the traditional carbon fiber which are based on polyacrylonitrile (PAN).
In this study, we implemented an alternative way to increase the interlaminar fracture toughness of CFRP laminates by inserting carbon nanofibers between the CFRP laminates composed of woven fabric. Carbon nanofiber was employed as reinforcement for the interlayers for mode I and II fracture toughness tests. CNF, VGCF(SHOWA Denko K.K.) and MWNT-7(Hodogaya Chemical Co.,LTD.), were used for the reinforcement of the CFRP laminate. The carbon fiber of twill woven fabric was used as main composition materials in the present study.
Mode I and mode II interlaminar fracture toughness of the composite was evaluated by double cantilever beam (DCB) and end notched flexure (ENF) tests using CFRP beam specimens, respectively. The experimental results showed that the interlaminar fracture toughness of the CFRP/CNF hybrid laminates made by woven fabric are superior to base CFRP laminates.

## 2. CFRP specimens

CFRP specimens for mode I and mode II fracture toughness tests were made by vacuum assisted resin transfer molding (VaRTM) in the laboratory. Carbon fiber woven fabric CO6324B (TORAY) and separated type liquid epoxy resin "DENATOOL XNR 6809/XNH6809 " (Nagase chemtex, Corp.) are used for CFRP laminates. Vapor grown carbon fiber 'VGCF' and multi walled carbon fiber 'MWNT-7' (Hodogaya Chemical Co.,LTD.) were used as reinforcement for the interlayer.
The carbon nanofiber reinforcement was inserted between prepregs in the middle layer of the CFRP specimens to an area density between 5 – 40g/m$^2$. After making a slurry of the carbon nanofiber with liquid epoxy resin, the CNF slurry was applied on a woven fabric of carbon fiber. Area density and weight fraction of the CNF in the CNF/epoxy slurry for the interlayer is shown in Table 1.
After the above process, two parts of stacked woven fabric are put together. CNF/epoxy interlayer was naturally formed during fabrication process in VaRTM[7]. Note that, in the case of woven fabric CFRP laminates, it is difficult to measure correctly the thickness of CNF/epoxy interlayer. However, it seems that the interlayer of 50 to 300 $\mu$m thickness is formed if it

Table 1: Area density and weight fraction of the CNF in the CNF/epoxy slurry for the interlayer

| CNF area density [g/m$^2$] | 5 | 10 | 20 | 30 | 40 |
|---|---|---|---|---|---|
| Weight fraction [wt%] | 1.25 | 2.50 | 5.00 | 7.50 | 10.00 |

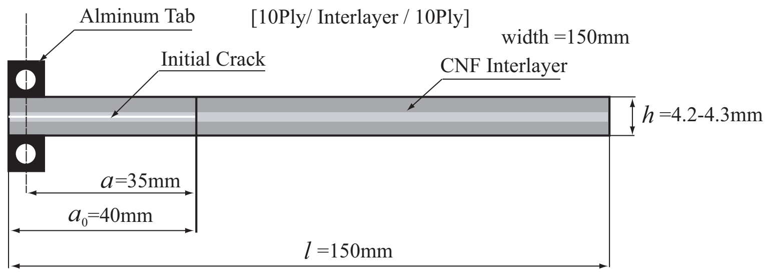


Figure 1: CFRP Specimen for DCB test.

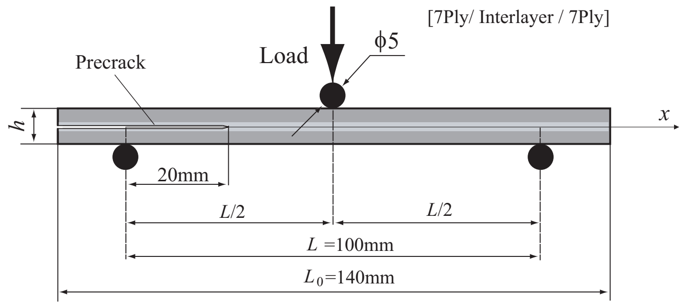


Figure 2: CFRP Specimen for ENF test.

guesses from the result of the past unidirectional CFRP laminate toughened with CNF/epoxy interlayer[7].
Dimensions of the DCB specimen is shown in the Fig. 1. DCB specimen is composed of 20ply woven fabric. The CNF/epoxy interlayer was inserted between 10th and 11th layer of the CFRP laminates. On the other hand, ENF specimen (see Fig. 2) is composed of 14ply woven fabric. The CNF/epoxy interlayer exists between 7th and 8th layer. The initial crack formed in the middle plane of the laminates was made by inserting polyimide film (Kapton, TORAY, 25$\mu$m thickness) in the stacking process of the CFRP laminates.

**2. Mode I and mode II fracture toughness tests**

As shown in Fig. 3, double cantilever beam (DCB) and end notch flexure (ENF) tests were carried out for mode I and II fracture toughness tests. Cross head rate was specified to 0.5mm/min. In DCB test, applied load, crack opening displacement and crack length were measured in the experiment. To measure the crack extension, the scale was stuck along the specimen and the amount of crack propagation was measured by viewing. In ENF test, only applied load was measured. Displacement on the load point was converted by crosshead rate and lapsed time. The energy release rate for mode I deformation of the DCB specimen is given by the following equation according to the compliance calibration method (JIS K 7086) [7, 11].

$$G_{\rm I} = \frac{3}{2h}\left(\frac{P}{b}\right)^2 \frac{(b\lambda)^{2/3}}{\alpha_1}, \tag{1}$$

where $\lambda$ is the compliance of the crack opening displacement (COD) and $h$ and $b$ are the height and width of the specimen, respectively. $P$ is the load applied on the end section of the ENF specimen. $\alpha_1$ is the coefficient derived by the linear approximation of following relation:

$$\frac{a}{h} = \alpha_1 (b\lambda)^{1/3} + \alpha_0 \,, \tag{2}$$

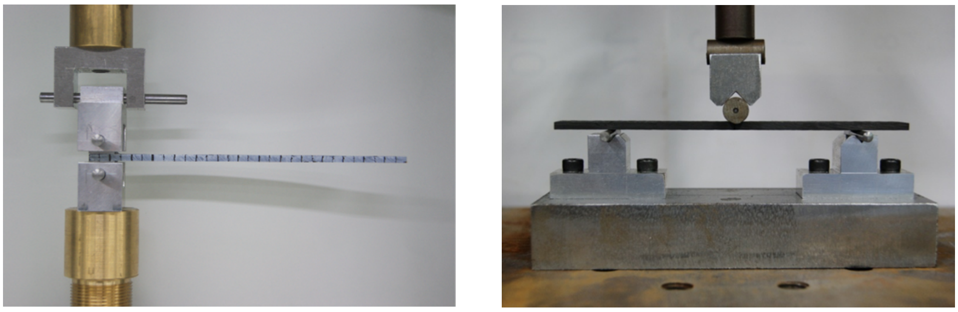

Figure 3: Equipment of DCB (left) and ENF (right) fracture toughness tests.

where $a$ is the crack length. Therefore, mode I fracture toughness of the CFRP specimen can be estimated from the measurement of the applied load, COD compliance, and crack length in the DCB test.
On the other hand, mode II fracture toughness can be estimated by the following equation using compliance method (JIS K 7086) [11].

$$G_{\mathrm{II}} = \frac{9a_1^2 P_c^2 C_1}{2B(2L^3 + 3a_1^3)a}, \tag{3}$$

$$a_1 = \left[\frac{C_1}{C_0}a_0^3 + \frac{2}{3}\left(\frac{C_1}{C_0} - 1\right) - L^3\right]^{1/3}, \tag{4}$$

where $a_0$, $P_c$, $C_0$, $C_1$ are initial crack length, critical load, initial elastic compliance of the specimen, the compliance on the critical load point. $a_1$ is the crack length on the critical load point. $L$ and $B$ is span length and width of the specimen.

## 3. Experimental results

From DCB fracture toughness tests, relationship between mode I fracture toughness and the increment of the crack length (R-curve) can be obtained as shown in Fig.4 for VGCF/CFRP laminates and Fig. 5 for MWNT-7/CFRP laminates, respectively, In the CFRP laminates toughened with VGCF interlayer (Fig. 4), mode I fracture toughness of nano-modified CFRP laminate indicates approximately two times of that of base laminate as for the extent of 20-70mm crack length.
In the CFRP laminates toughened with MWNT-7 interlayer, mode I fracture toughness increases as the crack length increases as shown in Fig. 5. Fracture toughness of the specimen with CNF interlayer reaches approximately 2 - 3 times of that of base laminate as for the extent of 40-70mm crack length. As shown in these results, MWNT-7/epoxy interlayer shows a very high effect to improvement in mode I interlaminar fracture toughness.
These results confirm that the mode I fracture toughness of the CFRP/VGCF specimens is dependent on the area density of the CNF interlayer. The experimental results indicate the optimal value of the CNF area density for the interlayer is 10g/m$^2$ for VGCF/epoxy interlayer and 30g/m$^2$ for MWNT-7/epoxy interlayer, respectively.
Figure 6 shows the relationship between mode II fracture toughness of the ENF specimens and the area density of CNF. Fracture toughness of base laminate CFRP specimens (area density of CNF = 0g/m$^2$) is also indicated in the figure. The optimum value of the CNF area density, which gives the highest value of mode II fracture toughness for nano-modified CFRP laminates was shown to exist in the extent of 10 – 20 g/m$^2$. The VGCF interlayer was confirmed to increase

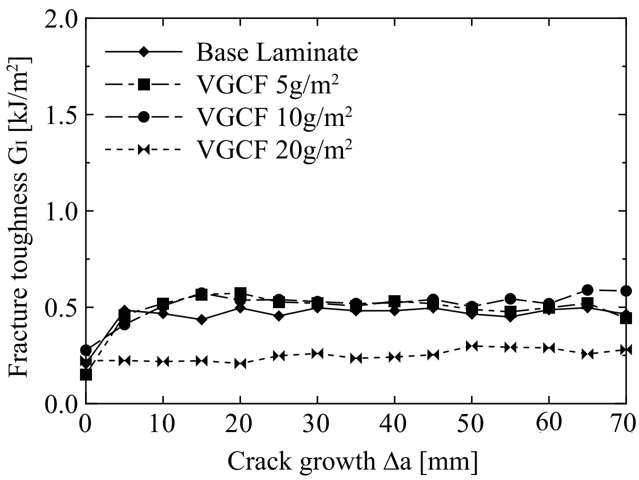


Figure 4: R-curve of mode I crack extension for VGCF/CFRP laminates.

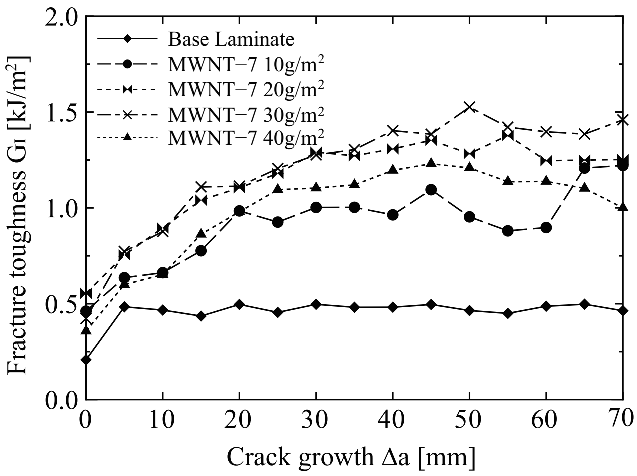


Figure 5: R-curve of mode I crack extension for MWNT-7/CFRP laminates.

the fracture toughness approximately 70% greater than the original base laminates. On the other hand, it is confirmed that CFRP laminates toughened with MWNT-7 interlayer gives two times fracture toughness of base laminate. Therefore, it is shown that MWNT-7/epoxy interlayer is valid to increase interlaminar fracture toughness also for the mode II not only for the mode I.

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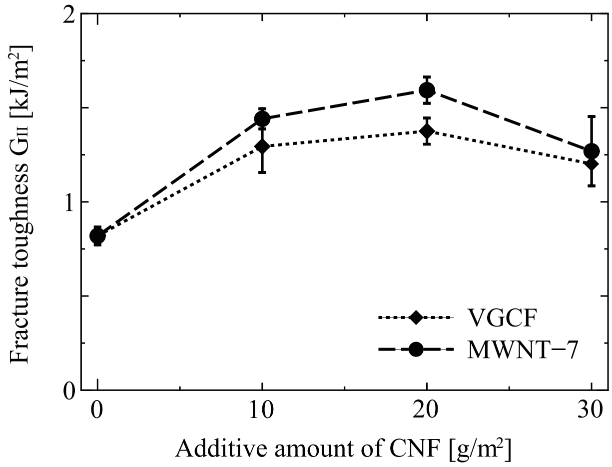


Figure 6: Mode II fracture toughness v.s. area density CNF interlayer of CFRP laminates toughened with CNF interlayer.


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