MIXED MODES INTERLAMINAR FRACTURE TOUGHNESS OF CFRP LAMINATES TOUGHENED WITH CNF INTERLAYER

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1 Introduction

Over the past few decades, a number of experimental and analytical techniques have been proposed to evaluate the fracture toughness for mode I[1], mode II[2], mixed mode[3] with several combinations of carbon fiber and matrix resin. Previous attempts to improve the interlaminar fracture toughness of CFRP laminates has shown various useful results. Namely, a certain level of toughening technique has already been achieved by inserting an interleaf (interlayer) between the CFRP Prepregs. 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[4]. In recent years, carbon nanotubes and carbon nanofibers have received a great deal of attention in the aeronautical, biological, electrical andmechanical sciences, and engineering fields.

Due to the electrical conductivitysuperiority of the CNF, MWCNT or vapor grown carbon fiber `VGCF' has established a strong presence in the storage battery field as the conductive filler. In addition, carbon nanotubes 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 traditional carbon fiber based on polyacrylonitrile (PAN).

In the present study, interlaminar fracture toughness for mixed mode (modes I and II) were investigated for carbon fiber (CF)/epoxy laminates toughened by a carbon nanofiber/epoxy interlayer. Vapor grown carbon fiberVGCF, VGCF-S and MWNT-7 were chosen as the reinforcement for the interlayer between the prepregs in the CFRP laminates[5].

To illustrate the effect of the interlayer on the fracture toughness of the laminates, several types of carbon fiber reinforced plastics/carbon nanofiber (CFRP/CNF) hybrid laminates were fabricated. Each laminate was composed of unidirectional carbon/epoxy prepregs with carbon nanofiber varying the interlayer thickness. Mixed modes interlaminar fracture toughness was evaluated by mixed mode bending (MMB) test.

The mixed modes interlaminar fracture toughness was evaluated by numerical analysis based on a boundary element method. As a result, it was confirmed that the interlaminar fracture toughness for hybrid CFRP laminate with a interlayer is higher than that of base CFRP laminates.

Especially, the fracture toughness of the hybrid laminate with a CNF interlayer is 2 to 3 times greater than base CFRP laminates in the area where the shearing transformation becomes predominant. It was found that the recommended range of CNF interlayer thickness is between 100 to 150 μm.

2 CFRP Specimens

Unidirectional Carbon/Epoxy prepreg (P3051S-22, TORAY) has been used for the unidirectional CFRP laminates in the present study. Unidirectional CFRP specimens are composed of 20 prepreg layers. An artificial crack was inserted in the middle plain of CFRP using polyimide film (30μm thickness)

Table 1 Dimension of CFRP specimen.

Thickness	4.5mm
Length	115mm
Width	20mm
Crack length	25mm

Table 1 Young's modulus of CNF interlayer.

VGCF	5.52GPa
VGCF-S	4.47GPa
MWMT-7	4.55GPa

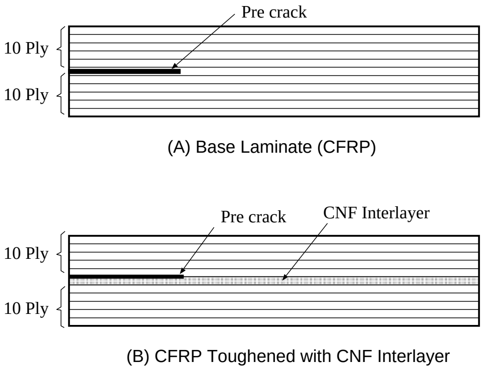

Fig.1 CFRP Specimen with pre crack.

as shown in Fig.1(A). The CFRP spacimens were made by autoclave in our laboratory. The dimensions of the CFRP laminates are specified in Table.1.

On the other hand, in the present study, the unidirectional CFRP laminates toughened with carbon nanofiber interlayer were employed, too.

In this specimens, carbon nanofiber interlayer was inserted between 10^{th} and 11^{th} prepreg layer of the laminates as shown in Fig.1(B). The pre crack with polyimide film was inserted between 0^{o}prepreg layer and CNF interlayer.

VGCF, VGCF-S (Showa Denko K. K.) and MWNT-7 (MITSUI & CO., LTD.) were used for the reinforcement of the CFRP laminates.

Powder of CNF was inserted between prepregs of the CFRP specimens with an area density of 10, 20 and 30g/m^2 using a sifter. An interlayer from 50μm to 150μm mean thickness was naturally formed by the fusion of CNF and epoxy resin leaking into the interlayer during the production of the specimens.

The youngs moduli of the CNF interlayer in Table 2 was evaluated by Vickers Hardness (VH) using a Micro Vickers testing machine (DUH--201, Shimadzu Co.).

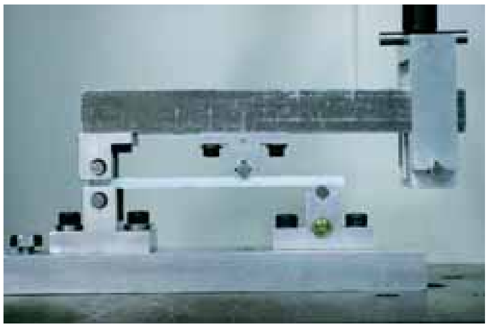

Fig.2 MMB Test for CFRP laminates.

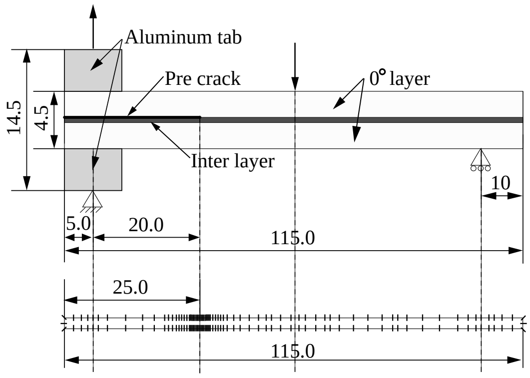

Fig.2 Analytical model for BEM analyses.

3 Fracture Toughness Tests of CFRP

In the present study, mixed mode bending (MMB) test was employed to evaluate interlaminar fracture toughness of CFRP laminates. Using MMB tests, the mixed mode rate (opening mode and shearing mode) can be controlled with wide range. In the present study the MMB equipment as shown in Fig.2 has been used.

The vertical load was applied on the cantilever of the equipment by the universal material testing machine (SHIMADZU AGE-100kNE). In case that the opening mode and shearing mode were predominant, the DCB and ENF tests were executed additionally.

4 Boundary Element Analysis

In the present study, the boundary element method has been applied for 2-dimensional analyses of CFRP laminates. In boundary element method, the following integral equation, which is the relational equation between the displacement u(Q) and traction t(Q) on the boundary, is employed.

$$\frac{1}{2}u_i(\mathrm{P}) + \int_\Gamma T_{ij}(\mathrm{P},\mathrm{Q})u_j(\mathrm{Q})d\Gamma = \int_\Gamma U_{ij}(\mathrm{P},\mathrm{Q})t_j(\mathrm{Q})d\Gamma \quad (\mathrm{P} \in \Gamma) \tag{1}$$

where U_{ij}(P,Q) is a green function (fundamental solution) for the 2-dimensional anisotropic solid body. T_{ij}(P,Q) is a traction component on Q derived from U_{ij}(P,Q). Discretizing the boundary integral equation (1) using boundary element, and applying the boundary conditions, we obtain the numerical solutions of displacements and tractions on the boundary.

The analytical model for BEM analysis is shown in Fig.2. The total domain was divided into 5 domains (2 domain for CFRP laminates, 1 domain for CNF interlayer and 2 domain for aluminum tab). Non-conforming quadratic boundary element was used for the discretization of the boundary.

The number of element were 472 for the base CFRP laminates and 694 for CFRP toughened with CNF interlayer.

5 Evaluation of Fracture Toughness of CFRP

In order to evaluate the interlaminar fracture toughness of CFRP laminates toughened by CNF interlayer, the definition of the interlaminar fracture toughness of CFRP laminate has been introduced.

The delamination between the prepreg layer and CNF interlayer should be treated as a crack between dissimilar anisotropic materials. Therefore, the stress field near the crack tip becomes mixed mode state derived by complex stress intensity factor K_1 and K_2 .

If the normal direction of the anisotropy is parallel to the axis x_i, the tensile stress components at the vicinity of the crack can be expressed as

$$\sigma_y + i\sqrt{\frac{H_{11}}{H_{22}}}, \quad \tau_{xy} = \frac{K_1 + i\sqrt{\frac{H_{11}}{H_{22}}}K_2}{\sqrt{2\pi r}}\left(\frac{r}{l}\right)^{i\varepsilon} \tag{2}$$

A energy release rate G can be derived as

$$G = \frac{H_{22}K_1^2 + H_{11}K_2^2}{4\cosh^2(\varepsilon\pi)} \tag{3}$$

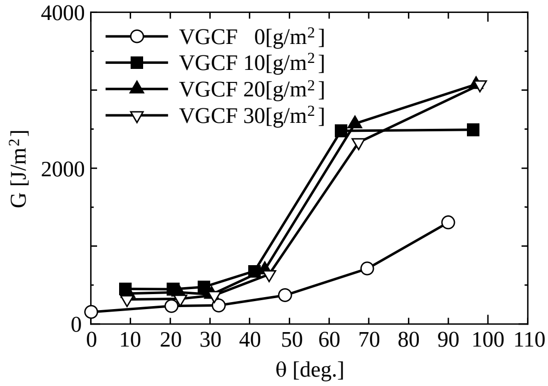

Fig.4 Relation between mode angle θ and interlaminar fracture toughness G_c (VGCF)

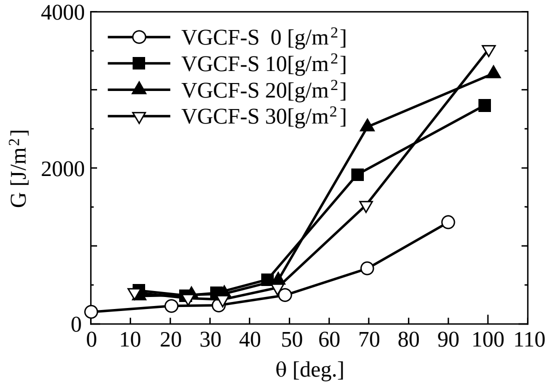

Fig.5 Relation between mode angle θ and interlaminar fracture toughness G_c (VGCF-S)

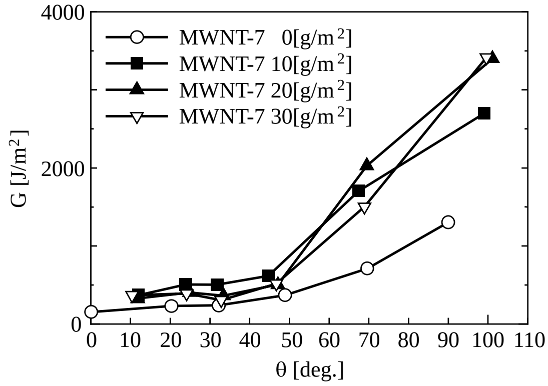

Fig.6 Relation between mode angle θ and interlaminar fracture toughness G_c (MWNT-7)

where H_{11}, H_{22} and ε can be calculated by elastic moduli of the anisotropic materials of the laminate, r denotes the distance from the crack tip, l is crack length, **i** is a imaginary unit, respectively.

Rewriting the Eq.(3), the energy release rage G can be written by

$$G = \frac{H_{22} K_i^2}{4 \cosh^2(\varepsilon \pi)} \tag{4}$$

where $K_i = \sqrt{K_1^2 + S^2 K_2^2}$, $S = \sqrt{H_{11} / H_{22}}$. Parameter K_i can be determined by extrapolation by the following equation.

$$K_i = \lim_{r \to 0} \sqrt{2\pi r(\sigma_y^2 + S^2 \tau_{xy}^2)} \tag{5}$$

mode ratio K_2/K_1 for opening and shearing mode can be extrapolated as

$$\frac{K_2}{K_1} = \lim_{r \to 0} \frac{1}{S} \frac{S \dfrac{\tau_{xy}}{\sigma_y} - \tan Q}{1 + S \dfrac{\tau_{xy}}{\sigma_y} \tan Q}, \quad Q = \varepsilon(r/l) \tag{6}$$

In the following discussion, the definition of ``mode angle" has been employed to discuss the effect of mixed-mode ratio.

$$\theta = \tan^{-1} \frac{K_2}{K_1} \tag{7}$$

5 Experimental Results

Relations between mode angle and intarlaminar fracture toughness Gc for the base CFRP laminates and CFRPs toughened with CNF interlayer are shown in Figs 3, 4 and 5. From these figures, we can confirmed that the interlayer fracture toughness improves as the mode ratio becomes larger in the area where the shear mode becomes predominant. In the area where the shear mode becomes predominant, the interlayer fracture toughness improves as the mode ratio becomes larger.

As shown in these figures, in the area where the shear mode becomes predominant, the interlayer fracture toughness improves as the mode ratio K_2/K_1 becomes larger. From these results, it is thought that the nano carbon interlayer is useful when the shear mode deformation becomes predominant in the crack extension.

In the past research[5], it was found that the adaptive quantity of CNF interlayer was 20g/m^2 in the Mode II interlaminar fracture toughness testing. It was found that the recommended quantity of CNF is also about 20g/m^2 in the mixed mode state using for VGCF, VGCF-S and MWNT-7 interlayers.

6 Conclusion

In the present study, to illustrate the effect of the CNF interlayer on the fracture toughness of the CFRP laminates, several types of CFRP laminates toughened by CNF interlayer were fabricated and the fracture toughness was evaluated by mixed mode bending (MMB) tests under several values of mode ratio K_2/K_1. Each CFRP specimen was composed of unidirectional carbon/epoxy prepreg with carbon nanofiber interlayer varying the thickness. It was confirmed that the interlaminar fracture toughness of CFRP/CNF laminate in mixed mode state becomes higher than that of base CFRP laminates. Especially, the fracture toughness of the CFRP/CNF laminate is 2 to 3 times greater than base CFRP laminates in the area where the shear deformation becomes predominant.

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