

Strength Analysis of CFRP Composite Material Considering Inter-Laminar Fractures

Tadashi Naito and Yuta Urushiyama
Honda R&D Co., Ltd.

ABSTRACT

The strength characteristic of CFRP composite materials is often dependent on the internal micro-structural fracture mode. When performing a simulation on composite structures, it is necessary to take the fracture mode into account, especially in an automobile body structure with a complex three-dimensional shape, where inter-ply fractures tend to appear due to out-of-plane load inputs. In this paper, an energy-based inter-ply fracture model with fracture toughness criteria, and an intra-ply fracture model proposed by Ladeveze et al. were explained. FEM analyses were performed on three-dimensional test specimens applying both fracture models and the simulated results were compared with experimental ones. Reproducibility of the fracture mode was confirmed and the importance of combining both models was discussed.

CITATION: Naito, T. and Urushiyama, Y., "Strength Analysis of CFRP Composite Material Considering Inter-Laminar Fractures," *SAE Int. J. Mater. Manf.* 8(3):2015, doi:10.4271/2015-01-0694.

INTRODUCTION

Carbon Fiber Reinforced Plastic (CFRP) composite materials have higher specific strength and stiffness compared to steel, so they are expected to contribute greatly to the weight reduction of automobile structures. Unlike metals, CFRP tends to show micro-fractures of resin inside the structure, and often its strength is determined by its fracture mode. In automobile CFRP body design, a strength design process that premises the three-dimensional complexity of the structure must be established. A series of coupon and component tests are necessary to understand the strength characteristics of various geometrical configurations. Replacement of these tests with simulations is an effective means for significant reduction in design costs and time, as well as for further weight reduction of the structure.

There is a definite difference in strength between intra-ply fractures and inter-ply fractures. When applying CFRP to a complex three-dimensional structure such as an automobile body, load input in the out-of-plane direction is inevitable. Therefore, it is assumed that the strength is often determined by inter-ply fractures due to the stress applied in a combination of peel and shear directions between the plies. For accurate prediction of structural strength using a simulation, a model that can reproduce this failure mode must be applied.

Several fracture models have been proposed and discussed for inter-laminar fracture evaluation [1,2]. Of those, the energy-based CZM (Cohesive Zone Modeling) is known for its simplicity and easy implementation to FEM [3]. The stress applied between the plies will

definitely be affected by the stress distribution inside each ply, so their damage and stiffness degradation should also be considered. In this paper, strength simulations, combining the CZM inter-laminar fracture model and an intra-ply damage model proposed by Ladeveze et al. [4], were performed on three-dimensional test specimens. The simulated results were compared with experimental results to confirm the reproducibility of inter-laminar fractures, and the validity of the combined fracture model was discussed.

BUILDING-BLOCK DESIGN METHOD

The Building-Block Design Method is commonly known as one method for strength design of a structure. This method is thought to be effective for structural design and its validation for CFRP material with anisotropic stiffness and strength. [Figure 1](#) shows a conceptual diagram of this design method.

Design and validation by tests and CAE begin from the bottom of the "pyramid", or in other words, from the detailed parts of the structure, and the process successively moves upward to larger structures. The coupon is a level to fully clarify the material characteristics, which will become the foundation for all of the levels above. In the design factor level, there are many factors to consider, including planar parts, curved parts, corner geometry with different bending radii and angles, joints of the plies, including where and how they are joined, and many more. These geometrical factors are combined with several loading conditions, so many confirmations of strength must be made at this level or at the parts level. Performing tests for all these factors is unrealistic, as doing so consumes tremendous time and money, so the CAE needs to be applied for strength evaluations.

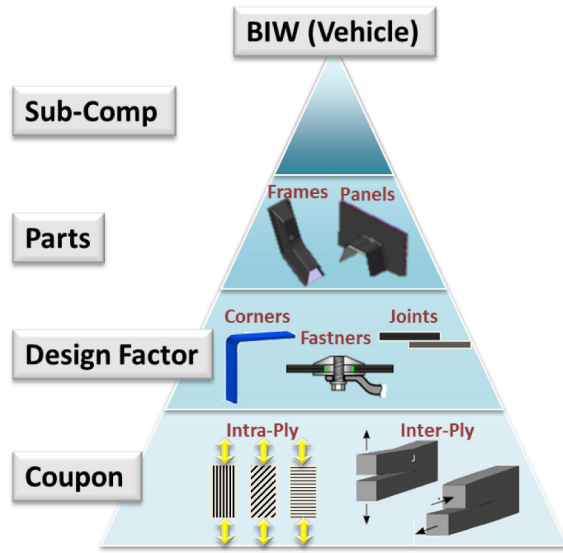


Figure 1. Concept of Building Block Design Method

CFRP MATERIAL MODEL

In this paper, both intra-ply and inter-ply fracture models were implemented in the FEM analysis. A damage model proposed by Ladeveze et al. was applied for the intra-ply model. For the inter-ply model, the CZM model was applied to evaluate delamination initiation by stress and delamination progression by energy.

Definition of Intra-Ply Model

In this section, the intra-ply damage model will be described. In the damage model proposed by Ladeveze et al., stiffness in the corresponding mode is reduced for the damage applied inside the ply. Two-dimensional strain energy E_d^{2D} is defined as in Eq. (1).

$$E_d^{2D} = \frac{\sigma_{11}^2}{2E_1^0(1-d_{11})} + \frac{\langle \sigma_{22} \rangle_+^2}{2E_2^0(1-d_{22})} + \frac{\langle \sigma_{22} \rangle_-^2}{2E_2^0} - \frac{\nu_{12}^0}{E_1^0} \sigma_{11} \sigma_{22} + \frac{\sigma_{12}^2}{2G_{12}^0(1-d_{12})} \quad (1)$$

E_i^0 and G_{ij}^0 are Young's modulus and shear modulus, respectively, σ is stress, ν is Poisson's ratio, and $\langle \rangle_+$ and $\langle \rangle_-$ represent tensile and compressive stress, respectively. Subscripts 1, 2, and 3 each represent the axis direction in the composite coordinate system, as shown in Fig. 2. d_{ij} are the damage variables that represent the stiffness reduction resulting from each fracture mode shown in Fig. 2, and are defined as the following equations.

$$\begin{aligned} E_1 &= E_1^0(1-d_{11}) \\ E_2 &= E_2^0(1-d_{22}) \\ G_{12} &= G_{12}^0(1-d_{12}) \end{aligned} \quad (2)$$

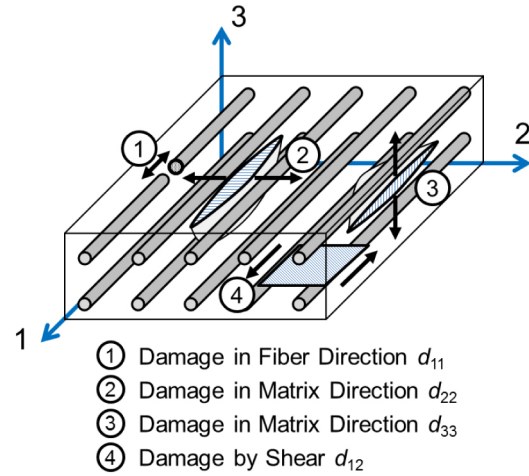


Figure 2. Schematic Drawing of Composite Coordinate System and Damage Modes

Here, thermodynamic force Y_{ij} is introduced as defined by Eq. (3).

$$Y_{ij} = - \frac{\partial E_d^{2D}}{\partial d_{ij}} \quad (3)$$

Therefore,

$$\begin{aligned} Y_{11} &= - \frac{\partial E_d^{2D}}{\partial d_{11}} = \frac{\sigma_{11}^2}{2E_1^0(1-d_{11})^2} \\ Y_{12} &= - \frac{\partial E_d^{2D}}{\partial d_{12}} = \frac{\sigma_{12}^2}{2G_{12}^0(1-d_{12})^2} \\ Y_{22} &= - \frac{\partial E_d^{2D}}{\partial d_{22}} = \frac{\langle \sigma_{22} \rangle_+^2}{2E_2^0(1-d_{22})^2} \end{aligned} \quad (4)$$

As can be seen from Eq. (4), damage variables d_{ij} can be defined as functions of thermodynamic forces Y_{ij} . These thermodynamic forces can be seen as energies impacting the different damages. When these energies increase, each related damage variable d_{ij} will also increase.

The damage d_{12} by shear and the damage d_{22} in the transverse direction with respect to the fibers are both caused by fractures of the resin. Therefore, their correlation needs to be taken into account. Applying a coefficient b_2 , an equivalent thermodynamic force Y that combines the effect of both shear and transverse direction is defined as follows.

$$Y = b_2 Y_{22} + Y_{12} \quad (5)$$

The damages in both directions are correlated by the following equation with a coefficient b_3 .

$$d_{22} = b_3 d_{12}$$

Figure 3 shows the relationship between d_{12} and d_{22} . Y^0 is the energy where damage is initiated, and Y^s is the critical energy value where damage reaches 1.

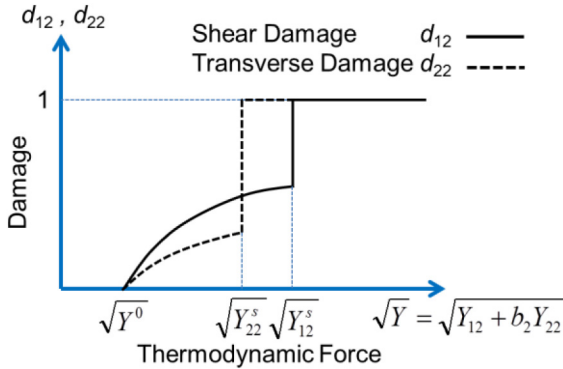


Figure 3. Comparison of Shear and Transverse Damage Characteristics

In addition, permanent deformation due to plastic strain in the resin, and non-linearity of the fiber modulus are also implemented in the model.

Definition of Inter-Ply Model

This section describes the inter-ply fracture model. Inter-ply damage will be applied in all three modes of fracture mechanics, 1, 2, and 3. Applying damages d_I , d_{II} and d_{III} caused by each fracture mode, strain energy in inter-ply elements is defined as follows.

$$E = \frac{1}{2} \left[k_I^0 \langle \varepsilon_{33} \rangle_-^2 + k_I^0 (1 - d_I) \langle \varepsilon_{33} \rangle_+^2 + k_{II}^0 (1 - d_{II}) \gamma_{31}^2 + k_{III}^0 (1 - d_{III}) \gamma_{32}^2 \right] \quad (7)$$

Where k_i^0 is the initial stiffness. The constituent stress-strain relationship can be described as follows.

$$\begin{Bmatrix} \sigma_{31} \\ \sigma_{32} \\ \sigma_{33} \end{Bmatrix} = \begin{bmatrix} k_{II}^0 (1 - d_{II}) & 0 & 0 \\ 0 & k_{III}^0 (1 - d_{III}) & 0 \\ 0 & 0 & k_I^0 (1 - d_I) \end{bmatrix} \begin{Bmatrix} \gamma_{31} \\ \gamma_{32} \\ \varepsilon_{33} \end{Bmatrix} \quad (8)$$

Similar to the intra-ply damage model, thermodynamic force Y_i ($i=I, II, III$) can be obtained by deriving the Eq. (7) with respect to each d_i ($i=I, II, III$). Letting fracture toughness be G_{Ic} , G_{IIc} , G_{IIIc} for each fracture mode, the equivalent thermodynamic force Y will be defined as,

$$Y = \sup_{\tau \leq t} G_K \left\{ \left(\frac{Y_I}{G_{Kc}} \right) + \left(\frac{Y_{II}}{G_{IIc}} \right) + \left(\frac{Y_{III}}{G_{IIIc}} \right) \right\} \quad (9)$$

This Y is expressed as a function of d_p , and the function corresponds to a shape of the cohesive law. In this paper, bi-linear function as shown in Fig. 4 was applied. The area surrounded by the two lines is equivalent to G_{Ic} .

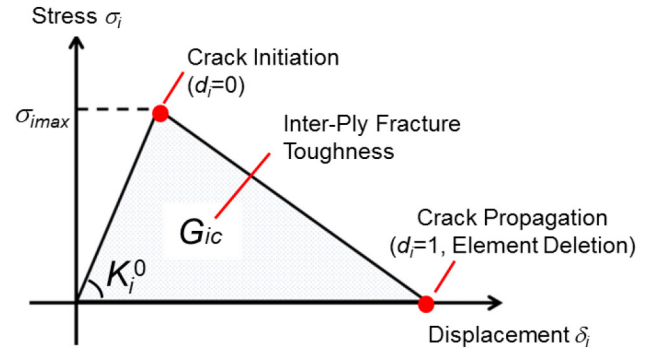


Figure 4. Bi-linear Function of Interface Damage

INFLUENCE OF INTRA-PLY DAMAGE MODEL TO INTER-PLY PROPERTY

With the intra- and inter-ply damage models explained in the previous sections, FEM analysis was performed. In this section, the influence of stiffness reduction caused by intra-ply damage on inter-ply damage behavior was confirmed.

FEM Model

Figure 5 shows the ENF (End Notched Flexure) test model used for the evaluation of inter-ply damage. It is a uni-directional laminate with a 140mm length, 25mm width, and 16-ply $[(+45/-45)_{2s}/(-45/+45)_{2s}]$ stacking sequence. The overall thickness is 3.63mm. The support span is 100mm, and bending load is applied at the center. The initial crack is applied at the center of the laminate for a 55mm length from the edge, and the rest of the area is modeled with CZM elements to reproduce damage propagation. The solid element mesh in the neighboring area of the crack and CZM elements are fractionated. Implicit solver SAMCEF was used for the analysis. With this FEM model, load-displacement characteristics and damage propagation behaviors near the crack front were compared between the result taking the intra-ply damage into account and the result not taking it into account. The inter-ply damage parameters were identified with consideration of intra-ply damage.

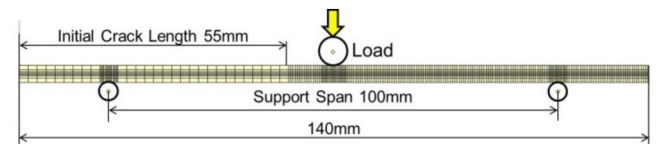


Figure 5. FEM Model of ENF Interface Test

Simulation Result

Figure 6 shows the load-displacement diagram of the ENF simulation results. The actual test result is also shown in the figure. When the intra-ply damage is taken into account, the stiffness reduction and the ultimate load accurately reproduce the test result. On the other hand, if the intra-ply damage is not implemented, the stiffness remains still and the ultimate load becomes higher with smaller displacement.