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Novel test method for accurate characterization of intralaminar fracture toughness in CFRP laminates

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ABSTRACT

A novel initial crack insertion method, "intralaminar film insertion method", was proposed to investigate the fracture toughness of unidirectional carbon fiber reinforced plastic (CFRP) laminates when the crack propagates inside the ply and not in the interlayer resin-rich area. Here, a release film was inserted inside a single lamina during the resin impregnation process of prepreg manufacturing. Mode I intralaminar fracture toughness tests were carried out for conventional CFRP laminates and interlayer toughened CFRP laminates. For comparison, two conventional methods were used to introduce initial cracks. One is the "interlaminar film method", where a release film is inserted between two prepreg plies during the lay-up process. The other is the "machined slit method", where a slit notch is machined in parallel to the layer of CFRP laminates. It was demonstrated that the proposed "intralaminar film method" can correctly evaluate the intralaminar fracture toughness of both conventional CFRP laminate and interlayer toughened CFRP laminate from the initial value to the propagation value. For this range, it was also found that the intralaminar fracture toughness of interlayer toughened CFRP laminate was the same as that of conventional CFRP laminate. Thus, the intralaminar fracture toughness was not influenced by interlayer toughening.

1. Introduction

Evaluation of the fracture toughness of CFRP (carbon fiber reinforced plastic) is essential to ensure reliability in structural applications [1–3]. The introduction of initial defects is a key factor for determining the initial values and following propagation values of the fracture toughness. For the CFRP laminates with tough matrices, it is common that the fracture toughness value increases with the crack extension for the initial stage of the crack propagation due to fiber bridging effect [4,5]. Therefore, many active discussions were held regarding the method to introduce initial defects and precracks [6–11].

The most typical method to introduce initial defect is the film insertion method, in which a thin release film is inserted between prepreg plies during the lay-up process, and this prepreg laminate is cured in an autoclave [12–14]. The result is a cured CFRP laminate fabricated with the release film inserted in interlayer region. In this study, this method is referred to as the "interlaminar film insertion method". Here, for the case of CFRP laminate, the thickness of the initial defect should be about 10 μm or less in order to obtain a conservative value of the fracture toughness [8]. This interlaminar film insertion method is used in the standards ASTM D5528, JIS K 7086, ISO 15024, and so on. Fig. 1(a) shows the schematic drawing of the interlaminar delamination which can be observed for these interlaminar fracture toughness tests.

However, it is important to note that the cracks in the CFRP laminate are often generated and propagated within the fiber-rich "intralayer region" of the prepreg, as shown in Fig. 1(b). For example, Lorriot indicated that the crack possibly initiated from the intralayer region in the case of the edge delamination of tensile tests for CFRP laminates [15]. If voids or other kind of defects in CFRP laminate were trapped between prepregs during the lay-up process, these defects can remain in the interlayer region. On the other hand, if volatile components were contained in the matrix resin of the prepreg, or if the prepreg was not completely impregnated with matrix resin, then the CFRP laminate can contain voids in the intralayer region [16,17]. Considering the possibility that these voids may become sites of crack initiation, the crack initiations are possibly located in both interlayer and intralayer regions. Thus, many researchers continue active efforts to study both interlayer and intralayer crack behavior, in order to enhance not only the interlaminar fracture toughness but also the intralaminar fracture toughness of CFRP laminates [18–20].

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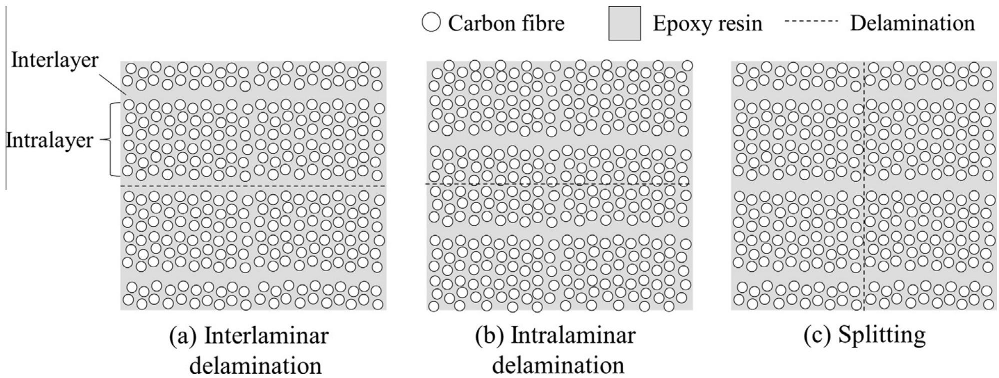

Fig. 1. Schematic drawings of delamination in cross-section of non-toughened CFRP laminate.

The crack propagation properties must depend on the location of the crack initiation, that is, in the fiber-rich intralayer region or in the resin-rich interlayer region. Thomas et al. showed that the local fiber density in the intralayer region was higher than that in the interlayer region [21]. Hou et al. indicated that intralaminar and interlaminar toughness can be different, as the resin-rich interlayer area is tougher than the fiber-matrix interfaces concentrated in the intralayer region, where high residual stresses can be accumulated [22]. In addition, the fibers in each layer are completely separated from the fibers of the adjacent layer. The degree of entangled fibers in the intralaminar region is much higher than that in the interlayer region. Then, the amount of bridging fibers in the intralayer region is higher than that in the interlayer region. Since the fracture toughness is sensitive to the local fiber arrangement near the crack tip, the fracture toughness values likely depend on the crack location. Hojo and Aoki observed the cross-section of the specimens after DCB (double cantilever beam) test for unidirectional CFRP laminates, and the propagation value of the fracture toughness became higher when the crack propagated in the intralayer region [23]. These residual stress effect and fiber bridging effect are probably attributed to the difference between the intralaminar fracture toughness and the interlaminar fracture toughness. However, the intralaminar crack propagation properties had been hardly discussed in detail, because there is no reliable and standardized characterization method for the intralaminar crack propagation [3,24]. Thus, it is important to develop a suitable method to characterize the intralaminar fracture toughness in order to characterize the difference between intralaminar and interlaminar fracture toughness.

There were several studies which made efforts to evaluate the intralaminar fracture toughness [5,24–32]. Here, for the case of Fig. 1(b), the crack plane is parallel to the lamination plane, and this case is true "intralaminar" delamination. For the case of Fig. 1(c), the crack plane is perpendicular to the lamination plane, and so the geometrical location of the crack in this case is almost identical to a transverse crack. This failure is often called splitting. In most of the studies, the mechanical slit notch was introduced in the CFRP laminate to evaluate the crack propagation behavior for the splitting [5,24–30]. Here, the micro-scale fiber network and orientation for the splitting must be different from those for the intralaminar delamination. In most of all cases, the propagation value of the fracture toughness for splitting was over 1000 J/m^2 [5,27–29], which was much higher than the representative fracture toughness for the interlaminar delamination [23,29]. At the same time, the larger number of bridging fibers were observed in the DCB test for the splitting than that for the interlaminar delamination [29]. As for the evaluation of true intralaminar delamination which is parallel to the lamination plane, Kageyama et al. carried out fracture toughness testing with a mechanical slit notch in the in-plane direction of CFRP laminate [32]. The main purpose of their research was to develop an interlaminar fracture toughness test method using CFRP laminate without use of initial film insert defects, and the potential application of this method to study the intralaminar fracture toughness was not discussed. Furthermore, when a pre-crack was introduced by a knife, the fracture toughness was increased by the fiber bridging effect.

As stated above, there is currently no proper method to evaluate the intralaminar fracture toughness of CFRP laminates. This is one of the reasons why prediction of failure and reliability are still difficult for loadings in the out-of-plane direction. In this study, a novel initial crack insertion method, "intralaminar film insertion method", was proposed to evaluate the intralaminar fracture toughness. In this method, the initial crack was introduced inside the intralaminar region of a CFRP laminate. Then, mode I intralaminar fracture toughness testing was carried out for conventional unidirectional CFRP laminates and interlayer toughened CFRP laminates. The latter material system was designed as the model material of standard interlayer toughened CFRP laminate with particles in the heterogeneous interlayer region, which had been widely used as primary structures of aircraft and already well evaluated [33–35]. Two conventional crack insertion methods, "interlaminar film insertion method" and "mechanical method", were also carried out for comparison. The validity of the new proposed method was discussed by comparing these results.

2. Materials and testing methods

2.1. Materials

Conventional unidirectional CFRP laminates and unidirectional interlayer toughened CFRP laminates were prepared. The former conventional CFRP laminate is also referred to as "non-toughened CFRP", and the latter interlayer toughened CFRP laminate as "toughened CFRP" in this paper.

2.1.1. Non-toughened CFRP

PAN-based intermediate modulus, high tensile strength carbon fiber (T800S, Toray industries Inc.) was used as the reinforcing fiber. For the matrix resin, diglycidyl ether of Bisphenol A epoxy (jER828, EEW 189 g/mol) was mixed with 4,4′-diamino diphenyl sulfone (4,4′-DDS, Seikecure-S, Wakayama Seika Kogyo Co., Ltd.) and polyethersulfone (PES5003P, Sumitomo Chem. Corp.) in ratios of 100:33:15 by weight. The formulation of the matrix resin was selected from the study by Kishi [36]. The prepregs were fabricated by using a drum winding method. The nominal cured ply thickness of the prepreg was 0.2 mm. These prepregs were stacked unidirectionally, and the CFRP laminate was cured in an autoclave at 180 °C