KEY FACTORS FOR CHARACTERIZING DELAMINATION FATIGUE PROPERTIES IN TOUGHENED CFRP

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Abstract

Interlaminar fracture is still one of the major design limiting factors for composite structures. Several materials have been developed to enhance the delamination toughness both under static and fatigue loadings. These materials often try to modify matrix resin and microstructures. Since the delamination fatigue crack growth properties of CFRP laminates depend on the crack length and the crack pass locations, the characterization of the fatigue properties is quite important with clear mechanism consideration. The precise testing method and the influence of fiber architectures and matrix structures are reviewed for interlayer-toughened CFRP laminates.

1. Introduction

Demands for higher fuel efficiency require extensive use of advanced composite materials such as carbon fiber reinforced plastics (CFRPs) for the primary structures of the next-generation commercial aircraft, Boeing 787 and Airbus A350XWB. These aircraft have overcome difficulties in replacing main wing and fuselage with CFRPs, and the volume ratio of composite materials is about 70%. Although thirty years have passed since the importance of the interlaminar fracture was recognized, interlaminar strength is still one of the design limiting factors in composite laminate structures. Improving interlaminar fracture toughness and resistance to fatigue delamination is an eternal topic in composite laminate structures because traditional two-dimensional composites have no reinforcement in the through-the-thickness direction.

Thousands of research activities have been carried out to solve the problem of delamination. These are classified either as improvement of the materials (matrix resin systems and fiber/resin interface) or as modification of the fiber architecture. One of the established means of material improvement is to replace resin at the prepreg interface with a tougher system. A commercial carbon fiber (CF)/epoxy with a heterogeneous interlayer has been used in the primary structures of Boeing 777 [1]. Boeing 787 has increased the use of interlayer-toughened CF/epoxy in its fuselages and main wings. Thorough-the-thickness reinforcement is another expected method to increase interlaminar strength with minimal effects on in-plane properties.

In these toughened laminates, delamination crack path can be introduced both at interlayer and intralaminar regions. Moreover, bridged fibers bring increase in resistance, and this factor much depends on the location of delamination inside the laminates and the crack length. Then, the crack growth behavior is more complicated in conjunction with reinforcements. In the present study, the roles of fiber architectures, matrix resin and its structure on the delamination fatigue properties are summarized. The key factors to correctly evaluate the fatigue delamination are discussed from the view points of mechanism consideration.

2. Summary of key factors

Key factors are itemized below. While some factors increase the fatigue crack growth resistance, other factors also decrease the resistance. The complicated situation is that several factors overlap in experimental characterizations. We first summarize the key factors and then introduce examples of experimental results and understanding for toughened laminate systems.

2.1. Test method

The measurement of crack length by compliance method is important for the low growth rate region near the threshold

2.2 Macroscopic fracture mechanics approach

Load ratios (modes I, II and III), stress-ratio effects and related mechanisms should be investigated.

2.3 Microstructure

Influences of fiber and matrix architecture such as interlayer-toughened laminates, through-the-thickness reinforcement, and preform should be revealed.

2.4 Location of crack path

Interlaminar fracture properties are commonly investigated. However, intralaminar fracture properties are also important for the current developed new materials.

2.5 Crack length dependency

Fiber bridging is a popular source of the increase in fatigue crack growth resistance. For materials with complicated microstructures, location of the crack path changes with the crack growth, and this change influences the crack growth resistance.

2.6 Separation of contribution of resin, fiber and interface

Comparison between neat resin and composite laminates were rarely investigated. Micromechanical approaches were still on the way both in experiments and analysis.

3 Increase in resistance with crack length

The first possibility is that the fatigue crack growth resistance increases with the increment of the crack length similar to the rising R-curves under static loading (Fig.1). The bridged fiber is often the cause of this behavior specially for the intralaminar crack growth. If the standard load-shedding tests were carried out for these laminates, the evaluation of the fatigue threshold can be non-conservative as schematically shown by gray symbols in Fig. 2 [3].

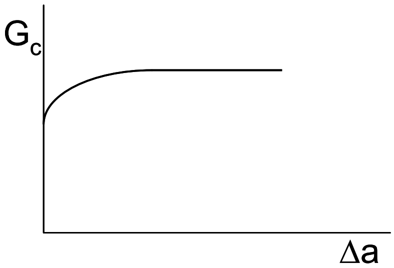

Figure 1 Schematic explanation of relationship between fracture toughness and increment of crack length.

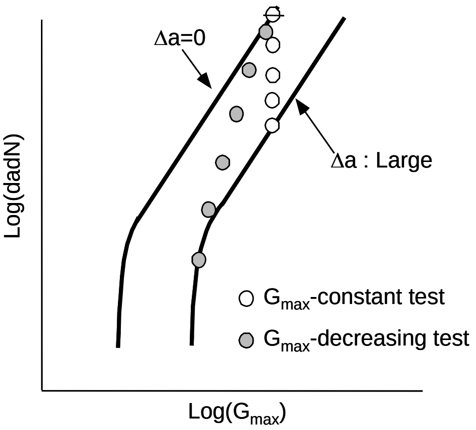

Figure 2 Schematic da/dN-G_{max} for rising R-curves.

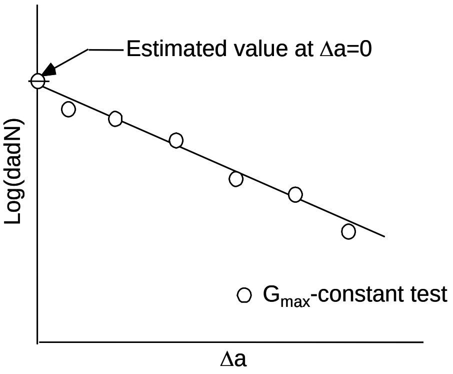

Figure 3 Change in da/dN in Gmax-constant test.

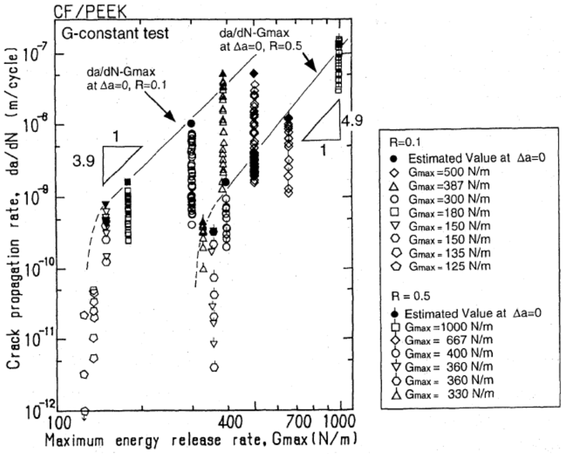

Figure 4 da/dN-Gmax in Gmax constant test and estimated relationship for Δa=0 in AS4/PEEK.

One of the possible ways to solve this problem is to carry out tests with constant maximum energy release rate during the fatigue tests [4]. When G_{max}-constant fatigue tests are carried out, da/dN values gradually decreases with the increment of the crack length as shown in Fig. 3. Then, the da/dN value at zero crack extension should be the correct value without respect to the bridged fiber effect and other factors. Very precise tests with sophisticated software are necessary to achieve proper characterization of these behaviors. The test results for AS4/PEEK laminates were shown in Fig. 4 [4]. A possible way to simplify this method was also proposed in [3].

4 Decrease in resistance with crack length

The second possibility is that the fatigue crack growth resistance decreases with the increment of the crack length. This can be possible because it is reported that the crack path deviates from the interlayer-toughened region to the interface between the interlayer-toughened region and the fiber-rich region, and to fiber-rich intralaminar region. Fig. 5 shows the example for T800H/3900-2 laminates in the normal load-shedding tests [5]. Here, monotonic decrease in da/dN is expected with the increment of the crack length when the fatigue crack growth resistance is constant without respect to the crack length. The results indicate higher da/dN from the monotonic decrease indicated by the dashed line, showing that the fatigue crack growth resistance decreased corresponding to the deviation of the crack path from the tougher interlayer-toughened region. da/dN starts to decrease again when the increment of the crack length is larger than 8mm indicating the re-increase in the crack growth resistance owing to the deviation of the crack path to the fiber- rich intralaminar region. Fig. 6 indicates the corresponding complicated relationship between da/dN and G_{max} under the stress ratio, R, of 0.5 [5].

The results in Fig. 6 clearly indicate that both factors exist to increase and decrease the crack growth resistance with the increment of the crack length for interlayer-toughened laminates. Then, the correct characterization both for interlayer region and intralaminar region is necessary by using the G_{max}-constant tests. Fatigue delamination test results using newly developed initial crack introduction method, "interlaminar film insertion method" [6] will be shown in the presentation together with G_{max}-constant tests.

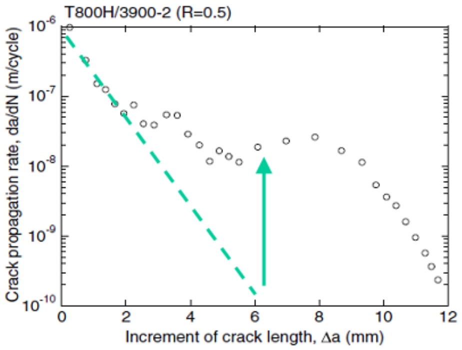

Figure 5 Change in da/dN with Δa for load-shedding test in T800H/3900-2.

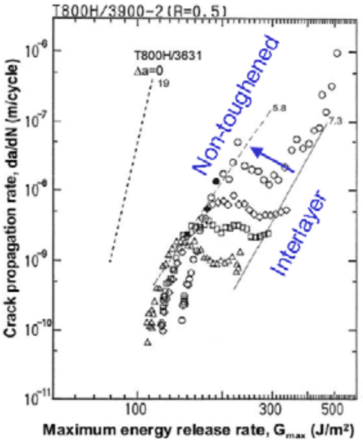

Figure 6 da/dN-Gmax in T800H/3900-2

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