The Fatigue Behavior and Delamination Properties in Fiber Reinforced Aramid Laminates
— Case (I): AFRP/Al Laminates —

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The fuselage-wing intersection suffers from the cyclic bending moment of variable amplitude. Therefore, the influence of cyclic bending moment on the delamination and the fatigue crack propagation behavior in AFRP/Al laminate of fuselage-wing was investigated in this study. The cyclic bending moment fatigue test in AFRP/Al laminate was performed with five levels of bending moment. The shape and size of the delamination zone formed along the fatigue crack between aluminum sheet and aramid fiber-adhesive layer were measured by an ultrasonic C-scan. The relationships between da/dN and ΔK, between the cyclic bending moment and the delamination zone size, and between the fiber bridging behavior and the delamination zone were studied. As results, fiber failures were not observed in the delamination zone in this study; the fiber bridging modification factor increases and the fatigue crack growth rate decrease; and the shape of delamination zone is semi-elliptic with the contour decreasing non-linearly toward the crack tip.

Key Words: Cyclic Bending Moment, AFRP/Al Laminate, Crack Bridging Effect, Delamination Zone, Fiber Bridging Modification Factor, Crack Growth Rate(da/dN), C-Scan image

1. Introduction

The delamination property on the fatigue crack propagation in aluminum/aramid fiber laminates is closely related to the crack bridging behind the crack tip. When fatigue cracks occur in the aluminum sheets, fibers may remain intact and bridge the crack. Therefore, understanding of delamination during the fatigue crack propagation in AFRP/Al laminates is essential in predicting the fatigue life.

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Recently, Marissen (1984; 1988) reported that the relationship between fatigue crack growth rate and delamination were inter-dependent by reciprocal action, and suggested a model for the crack growth behavior in AFRP/Al laminates. Lin et al. (1991) and Macheret et al. (1989) reported that the fiber bridging in the triangular delamination zone was superior to that of in the elliptical delamination zone. Roebroeks (1987) reported that the plastic zone size in the aluminum layer could be increased by the overload, which might reduce the fatigue crack growth and expand the delamination zone. Kim (Kim and Sohn, 1999; Song and Kim, 2000; 2001) reported that the superior fiber bridging occurred in case of the resin mixture ratio at 1 : 1 : 0.2 (the contents of epoxy resin : curing agent : accelerator).

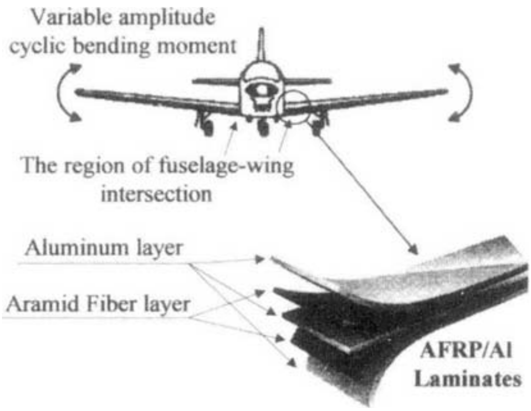


Fig. 1 Schematic of applied cyclic bending moment and AFRP/Al laminates in aircraft

However, since most of previous researches are carried out under the cyclic uniaxial load such as tension-tension or tension-compression, the investigation on bending fatigue behavior is needed to accomodate the usage of AFRP/Al laminates such as the fuselage-wing intersection which suffers from cyclic bending moment during the service (see Fig. 1) (Gunnink et al., 1984).

In this study, the delamination and fatigue crack propagation behavior of AFRP/Al composite under cyclic bending moment are investigated and compared with those of uniaxial test. The details of investigation are as follows: (1) The amplitude effect of cyclic bending moment on the fatigue life; (2) The relationship between da/dN and ΔK under various amplitude of cyclic bending moment; (3) The comparison between da/dN and ΔK under the cyclic uniaxial load versus da/dN and ΔK under the cyclic bending moment; (4) The behavior of delamination zone under cyclic bending moment.

2. Experimental Procedure

2.1 Material and specimen

2.1.1 Fabrication of prepreg

Prepreg consists of aramid fiber (Twaron®, type-2200) made by AKZO Co. (Arnhem, Netherlands) and epoxy resin, curing agent, accelerator made by KUKDO Chemical (Seoul, Korea). Mechanical properties of Twaron 2200 are listed in Table 1. Component and the mixture ratio of AFRP/Al laminates are as in Table 2. The prepreg was manufactured by UD (uni-directional) aramid fiber wetted by resin system. The mixture of resin system was 1 : 1 : 0.2 (the contents of epoxy resin : curing agent : accelerator). Which was recommended by Song and Kim (2001).

Table 1 Mechanical properties of Twaron® 2200

Tensile modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)	Density (g/cm³)	Coeff. of thermal expansion (10^{-6}/K)	Filament diameter (μm)
115	3150	2.6	1.44	−3.5	12

Table 2 Component and the mixture ratio of AFRP/Al

Factor / Name	Component	Mixture ratio#		Thickness (mm)
		Equivalence ratio	Volume ratio**	
AFRP/Al	Al5052	−	−	0.5
	Prepreg*	1 : 1 : 0.2##	312 : 150 : 76	0.3

* Prepreg=matrix (epoxy resin+curing agent+accelerator) +aramid fiber
** Volume ratio=(molecular weight/specific gravity) ×equivalence ratio
# Mixture ratio=epoxy : curing agent : accelerator
20% of epoxy content

Table 3 Chemical composition of Al5052

Composition	Fe	Mg	Si	Cu	Mn	Cr	Zn
wt%	0.40	2.60	0.25	0.10	0.10	0.25	0.10

Table 4 Material properties of Al5052

Alloy	Tensile strength (MPa)	Yielding strength (0.2% offset) (MPa)	Thickness (mm)
Al5052	283	228	0.5

2.1.2 Lamination and curing

Aluminum alloy sheet and prepreg were laminated in shape of 3/2 shown in Fig. 2. Tables 3 and 4 show the chemical composition and mechanical properties of Al5052. The laminate was cured at 120℃ for 90 minutes using the hot-plate-press in which the pressure was 1.2 MPa. In order to obtain a chemically stable laminate, it was preheated for 30 minutes and quenched.

2.1.3 Specimen

Figure 2 depicts the geometry of AFRP/Al laminate specimen for the bending fatigue test. A pre-crack was introduced at the center of specimen by a wheel cutter, and four holes with diameter of 10.5 mm were drilled for gripping the specimen.

2.2 Experimental method

The fatigue crack propagation test was performed by a bending fatigue testing machine (TB-10, Shimadzu Co. (Kyoto, Japan)). The cyclic out-of-plane bending moment, of which the fatigue stress ratio on the specimen surface $R=0.1$. The maximum amplitude of bending moment is 98 N-m. The frequency of cyclic loading was 33.3 Hz. The crack length was measured by a traveling microscope with 100 times magnification. The stress intensity factor range (ΔK) was calculated by Eq. (1). Where $f(a/w)$ is the geometry correction factor (Anderson, 1994).

$$\Delta K = f(a/W)\,\Delta\sigma\sqrt{\pi a} \quad (1)$$

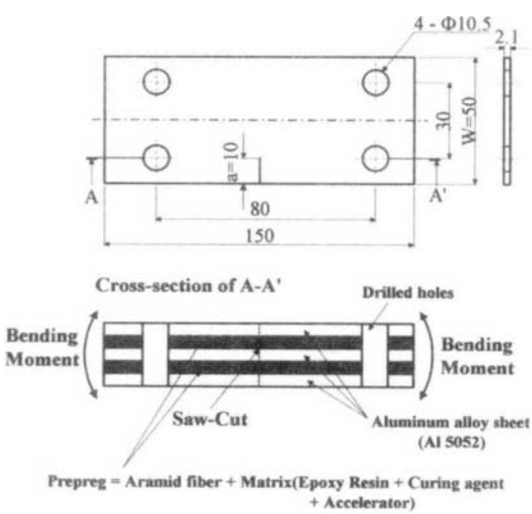


Fig. 2 Geometries of specimen (unit : mm)

where,

$$f(a/W) = \frac{\sqrt{2\tan\frac{\pi a}{2W}}}{\cos\frac{\pi a}{2W}}\left[0.752 + 2.02\left(\frac{a}{W}\right) + 0.37\left(1 - \sin\frac{\pi a}{2W}\right)^3\right]$$

The measurement of shape of delamination zone and the observation of fibers in AFRP/Al laminates were carried out by an ultrasonic C-scan images (Mi-SCOPE exla, Hitachi Co.).

3. Results and Discussion

3.1 The effect of variable amplitude cyclic bending moment on the fatigue life

When the AFRP/Al laminates are applied by cyclic tensile stress, the fiber bridging behind the crack tip reduces the stress intensity near a crack tip in aluminum layer. Consequently, AFRP/Al laminates is remarkably improved in fatigue life more than monolithic aluminum (Song and Kim, 2000).

However, under the cyclic bending moment, the delamination tends to be easily initiated at the interface between aluminum layer and fiber layer in AFRP/Al laminates by the shear stress. The delamination behind the crack tip reduces the bonding stiffness. As the amplitude of cyclic bending moment increases, the increased shear stress promotes the delamination and makes the

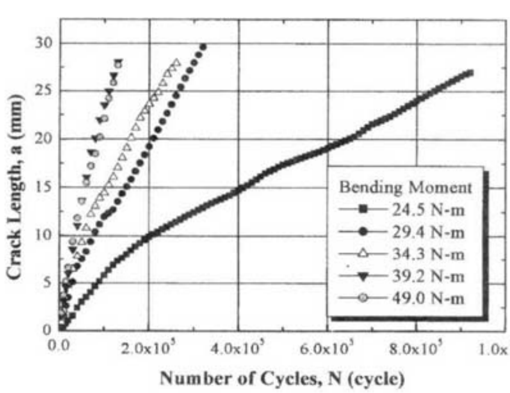


Fig. 3 Influence of the cyclic bending moment level on the relationship between crack length and cycles in the AFRP/Al laminates

fiber bridging less effective. As a result, the fatigue life will be shorten.

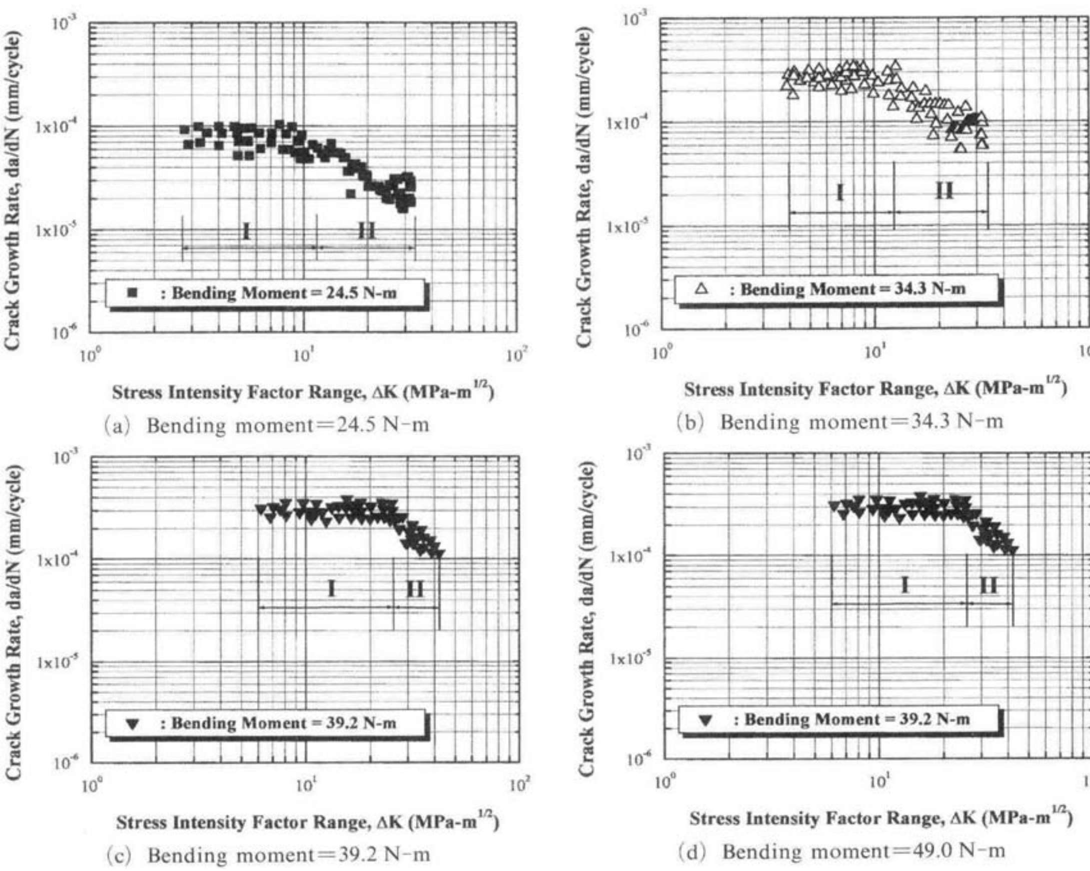
Figure 3 represents the relationship between crack length in the aluminum layer and number of cycle of bending moment with various amplitudes (24.5, 29.4, 34.3, 39.2, 49.0 N-m) regarding AFRP/Al laminates. In general, the crack grows faster with the larger amplitude. The shorter life is expected by the higher amplitude of cyclic moment. However, the difference becomes smaller with the increment of amplitude, and the discrepancy finally disappears in case of high amplitudes: 39.2 and 49.0 N-m.

Since the crack growth is influenced by the delamination between aluminum layer and fiber layer, the shear stress at the interlaminar, the efficiency of fiber bridging, the breakage of fibers etc., the relationship between the crack growth rate and the aspect of delamination zone evolution need to be investigated.

3.2 The relationship between da/dN and ΔK under cyclic bending moment

In order to investigate the dependence of crack growth rate on the amplitude of bending moment, the crack growth rate, da/dN, and the stress intensity factor rage, ΔK, for various amplitudes is presented in Fig. 4. Since the crack growth rate is not uniquely dependent on the stress intensity factor range, the stress intensity factor as a parameter for the prediction of crack growth rate seems inadequate.

Moreover, the behavior of crack growth rate dependence on the stress intensity factor range can be classified by two regions, as regions I and II in this study (see Fig. 4). The crack growth rate is almost constant regardless of stress intensity factor range in region I in which the stress



(a) Bending moment=24.5 N-m

(b) Bending moment=34.3 N-m

(c) Bending moment=39.2 N-m

(d) Bending moment=49.0 N-m

Fig. 4 Relationship between da/dN and ΔK in the AFRP/Al laminates under cyclic bending moment intensity factor range is lower than that in region II. On the other hand, the crack growth rate decreases with increment of stress intensity factor range in region II. Such a typical transition behavior of crack growth rate appears same for all tested cyclic bending moments.

The transition may imply that it should be closely related with the non-monotonous evolution of process zone caused by the delamination or breakage of fibers.

3.3 da/dN and ΔK of the cyclic uniaxial load and the cyclic bending moment

The relationship between da/dN and ΔK under cyclic axial loading (tension-tension or tension-compression) is represented in Fig. 5 to be compared with that under cyclic bending moment in Fig. 4. The data in Fig. 5 regarding GLARE3-5/4 composed of Al7075/GFRP are by Takamatsu et al. (1999). Two regions (I and II) also appear in Fig. 5. The crack growth rate decreases with the increment of stress intensity factor range in region I, while the crack growth rate increases with the increment of stress intensity factor range in region II.

Takamatsu et al. (1999) explained that the decreasing tendency of fatigue crack growth rate in region I in Fig. 5 was attributed to the enhanced fiber bridging caused by unbroken fibers, while the increasing tendency of fatigue crack growth rate in region II was attributed to less effective bridging caused by the failure of fibers in process zone. The transition would be determined by occurrence of fiber failure in the process zone. Thus no increment of crack growth rate under cyclic bending moment in this study may be caused by unbroken aramid fibers in the process zone.

On the other hand, the fiber bridging modification factor, β_{fb}, is defined as the ratio of the ΔK of monolithic aluminum to the ΔK of AFRP/Al laminates by Toi (1996), which is expressed by Eq. (2).

Figure 6 represents that the fiber bridging modification factor, β_{fb}, increases with number of cycles of bending moment regardless of amplitude of bending moment. It implies that the fiber bridging is enhanced by the cycles of bending

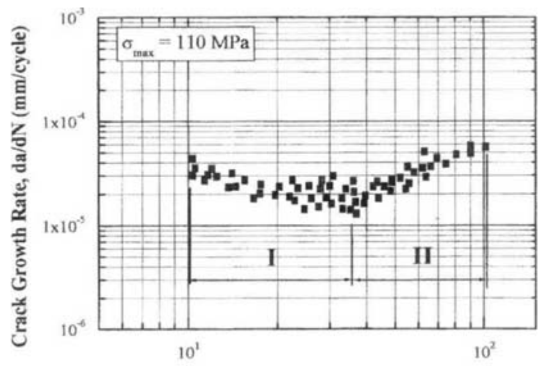


Fig. 5 Relationship between da/dN and ΔK in the GLARE3-5/4 under constant amplitude loading of σ_{max}=110 MPa by Takamatsu et al. (1999)

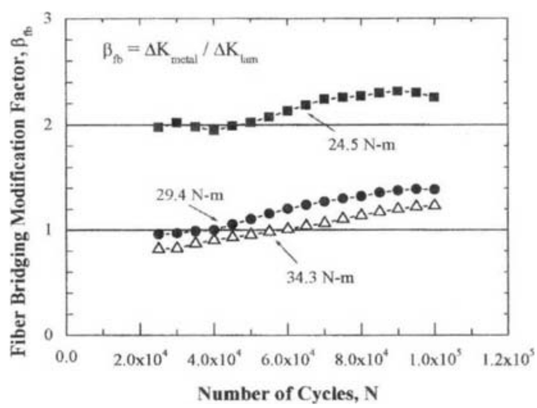


Fig. 6 Relationship between fiber bridging modification factor (β_{fb}) and cycles under cyclic bending moment

moment.

$$\beta_{fb}=\frac{\Delta K_{metal}}{\Delta K_{lam}} \tag{2}$$

where,

ΔK_{metal} : stress intensity factor range (monolithic Al)

ΔK_{lam} : stress intensity factor range (AFRP/Al)

3.4 The behavior of delamination zone under cyclic bending moment

The delamination zone between aluminum layer and fiber layer in AFRP/Al laminates is formed behind the crack tip. The discontinuity due to the delamination zone may make the load transmission between aluminum layer and fiber layer less effective. Moreover, if broken fibers exist in the delamination zone, the ability of load transmission get much worse. Thus the occurrence of broken fiber plays a important role in the crack growth rate.

Figure 7 represents a schematic diagram of delamination zone evolved in AFRP/Al laminates at different crack lengths as a/W=0.3, a/W=0.5, a/W=0.6 and a/W=0.8. Particularly, the delamination zones at a/W=0.8 by different cyclic bending moments were observed by C-scan images as shown in Fig. 8. The delamination zone area increases as the amplitude of bending moment increases. The shape of delamination zone is a semi-ellipse spreaded out behind the crack tip.

The expansion of delamination zone is momentarily arrested by stitches in the laminates. It is also conjectured that the delamination zone is initiated mainly by crack propagation and extended in the loading direction. Thus the height of delamination zone in the loading direction would be associated with number of cyclic loading. Marissen reported that the shape of delamination zone was semi-elliptical type under the uniaxial loading (tension-tension or tension-compres-

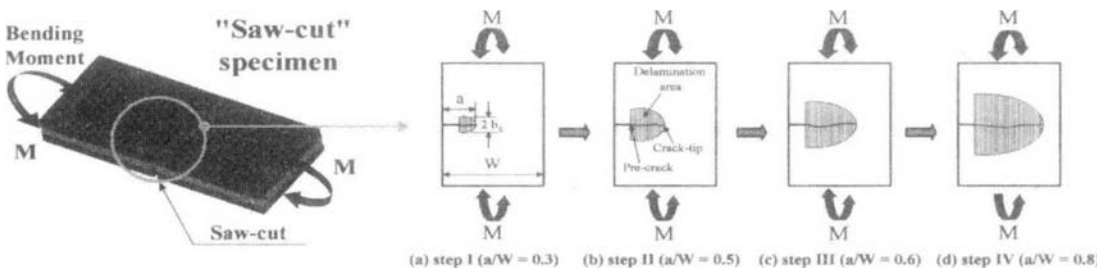


Fig. 7 Schematic of relationship between crack growth and delamination extension under cyclic bending moment

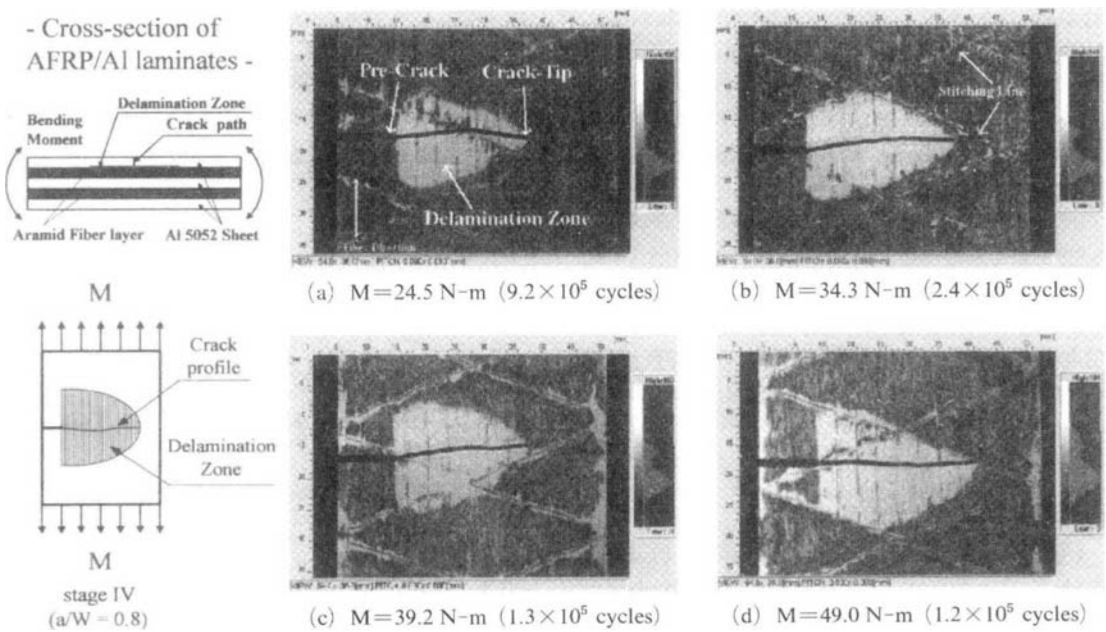


Fig. 8 Ultrasonic C-scan images of the shape of crack and delamination in the AFRP/Al under cyclic bending moment at stage IV (a/W=0.8)

sion), which coincides with that under cyclic bending moments in this study.

No delamination behind the pre-crack tip was observed. The cracks shown in Fig. 8(a), (b), (c) and (d) indicate that cracks formed only in the aluminum layer. The broken fibers were not found in the delamination zone, which would induce the decrement of fatigue crack growth rate in Fig. 4.

4. Conclusions

The results of this study are drawn as follows:

(1) The crack grows faster with the larger amplitude of moment and the shorter life is expected by the higher amplitude of moment. However, the difference becomes smaller with the increment of amplitude, and the discrepancy finally disappears in case of high amplitudes, of 39.2 and 49.0 N-m.

(2) The behavior of crack growth rate dependence on the stress intensity factor range can be classified by two regions as the regions I and II. The crack growth rate is almost constant regardless of stress intensity factor range in the region I. On the other hand, the crack growth rate decreases with increment of stress intensity factor range in the region II.

(3) The delamination zone area increases as the amplitude of bending moment increases. The shape of delamination zone is a semi-ellipse spreaded out behind the crack tip. No broken fibers were observed in the delamination zone.

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