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Delamination and fatigue crack growth behavior in Fiber Metal Laminates (Glare) under single overloads

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ABSTRACT

Delamination extension and fatigue crack growth behaviors under single overloads were investigated for GLARE 2-2/1-0.3 with fiber direction of 00/00. The results indicate that the stress intensity factor at the crack tip in metal layer while overload applied, $K_{tip,ol}$ is a key controlling variable which influences fatigue crack growth and delamination behaviors. When $K_{tip,ol}$ becomes bigger and exceeds a critical value, an obvious kink in the delamination shape is observed nearby the location of overload applied. Crack growth rate after application of overload could not return to its original level even the crack grows beyond the overload plastic zone. The reduction magnitude of the crack growth rate becomes bigger with the overload ratio (intrinsically $K_{tip,ol}$) increasing. These new results for the crack growth behavior have never been reported before, which can be well explained by the delamination extension behavior observed after overload applied.

1. Introduction

Fiber Metal Laminates (*FMLs*), as an advanced aerospace material, composed of metals and composite, exhibiting excellent fatigue and damage tolerant properties, have been developed and successfully used in aircraft structures [1]. Several studies [2–9] have focused on the fatigue performances of *FMLs* under constant amplitude (*CA*) loading and confirmed that *FMLs* present slow and almost constant crack growth rate under *CA* fatigue loading, which is the main advantage of *FMLs* [10]. In service, most of the airplane structures are loaded under variable amplitude (*VA*) fatigue loading [11]. Owing to this actuality, it is necessary to investigate the fatigue crack growth behavior under *VA* loading.

It is well known that the main difference between *CA* and *VA* loading for metal materials is the existence of interaction phenomenon connected with *VA* loading such as crack growth retardation caused by overloads [12]. Taking single overload for example, a large plastic zone forms in front of the crack-tip after overload applied and consequently residual compressive stress is created in this zone. The combination of residual compressive stress and applied tensile stress will reduce the crack-tip effective stress intensity factor range (ΔK_{eff}), which results in the retardation of crack growth rate (da/dN). After several delayed cycles (N_d), the crack grows out of this large plastic zone and crack growth rate gradually gets back to its original rate. The crack growth retardation is illustrated in Fig. 1.

In *FMLs*, except for crack growth in the metal layers, fatigue crack propagation also causes delamination growth at the metal/-fiber interfaces in wake of the metal crack [13,14], that are both concerned with bridging effect of fibers. When the fatigue crack grows in the metal layers, the fibers do not fracture and restrain the crack tip opening. The loads of crack region in metal layers are partly transferred to the fiber layer. These transferred loads are called bridging stress, as a result of which crack growth rate is reduced effectively. In the meantime, the delamination occurs because bridging stress causes shear deformation between metal layers and fiber layer. Therefore, unlike monolithic metal materials only with the retardation effect, both the retardation effect and the bridging effect of fibers in *FMLs* will be generated together when applying overload during the fatigue crack growth. That means not only crack growth rate may be retarded, but also the delamination will possibly change after overload.

Delamination shape and size are key factors to calculate the bridging stress, which determine the effectiveness of crack growth reduction. Compared to the extensively studies under *CA* loading, few works under *VA* loading can be found. Alderliesten [15] and Khan [16] have performed tests respectively on GLARE 3-3/2-0.3 and GLARE 3-5/4-0.4, both of which are cross-ply (0°/90°) laminates. In their studies, the kink phenomenon was observed in the delamination shape after application of overload, as shown in Fig. 2. Alderliesten [15] explained the transition may be attributed

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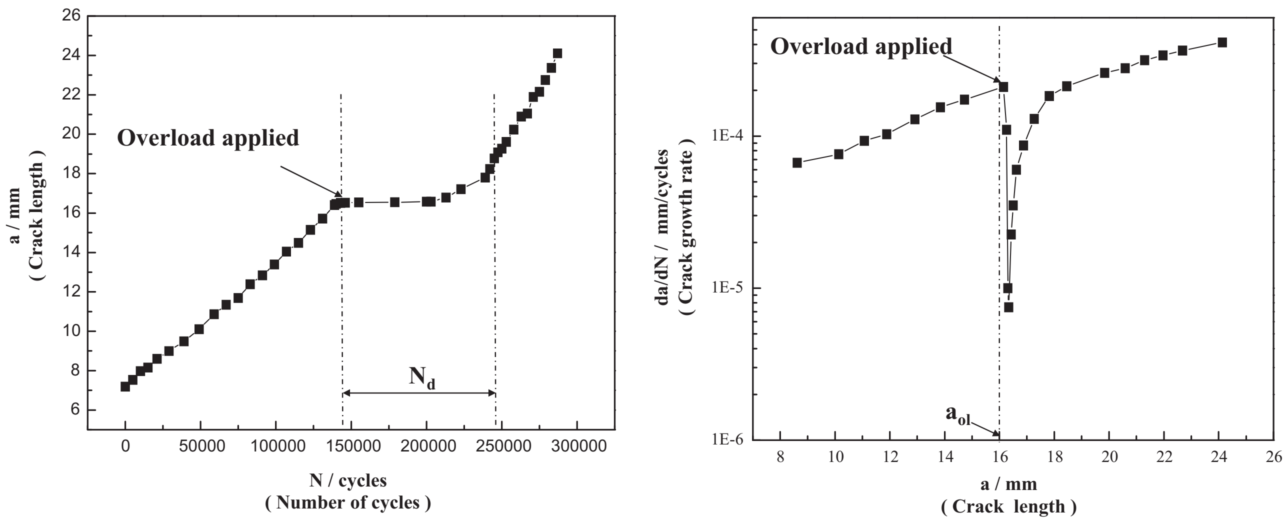

Fig. 1. Illustration of crack growth retardation with single overload in metals.

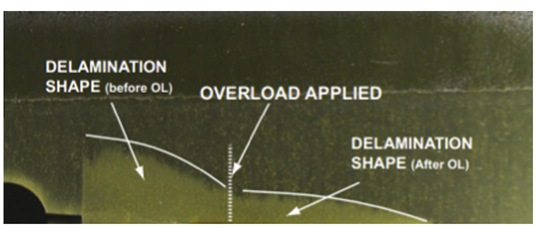

Fig. 2. Kink phenomenon in the delamination shape caused by overload [16].

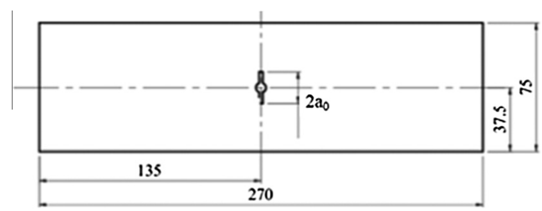

Fig. 3. The middle-tension ($M(T)$) specimen.

to plasticity induced stress re-distribution, while Khan [16] considered plasticity induced crack retardation by the overload may have a greater impact on this change in delamination shape. However, there are still many issues that need to be studied such as whether the delamination and fatigue crack growth after overload have the same behaviors in GLARE with different ply-up structures, whether the kink can be observed in all overload cases, etc. To better understand the effect of overload on delamination and fatigue crack growth behaviors, and develop an analytical prediction model under *VA* loading, in this paper GLARE 2-2/1-0.3 with fiber direction of 0°/0° was chosen to study both fatigue crack growth and delamination behaviors in various single overload conditions.

2. Experimental method

2.1. Test specimen

The middle-tension ($M(T)$) specimens were used to study the delamination and crack growth behaviors. The specimen was made of GLARE 2-2/1-0.3, consisting of two 2024-T3 Al alloy layers with 0.3 mm thickness and one 0°/0° direction fiber layer with 0.2 mm thickness. Detailed dimensions (mm) of the specimen are shown in Fig. 3. The starter notch was made by drilling a hole of 6 mm diameter with two saw-cuts perpendicular to the loading direction. The length of the starter saw-cut ($2a_0$) is approximately 10 mm.

2.2. Test matrix

All fatigue crack growth tests were performed on 10-tonne SHIMADZU low-frequency fatigue testing machine. The test frequency was 10 Hz. Details of the test program are given in Table 1. To determine the effect of overload on the delamination shape, comparison must be made between the cases without and with overload. For this reason, the tests were performed under constant amplitude load and single overload. Overload ratio (R_{ol}), the crack length while overload applied (a_{ol}) and the maximum baseline stress level (S_{max}) are considered as the loading controlling factors in this research. The *CA* stress ratio (R) of all tests is 0.06. Here, the overload ratio (R_{ol}) is defined as the ratio between the applied maximum overload stress (S_{ol}) and the *CA* maximum baseline stress (S_{max}), i.e., S_{ol}/S_{max}, in which both stresses are laminate stresses.

One set of specimens was tested using a *CA* baseline cycle with S_{max} = 120 MPa. Single overloads with R_{ol} = 1.3, 1.4, 1.6 were respectively applied to three specimens at a_{ol} = 12 mm. The other set of specimens was tested using a *CA* baseline cycle with S_{max} = 150 MPa. Single overloads with R_{ol} = 1.4, 1.6, 1.8 were respectively applied to three specimens at a_{ol} = 12 mm and another three specimens at a_{ol} = 16 mm.

2.3. Fatigue crack growth rate

Two JDX-B magnification microscopes with scale of 20× were used to observe the crack length respectively in the right front side and right back side of the specimen. The average value of the two measured values is taken as the crack length (a) under the corresponding number of cycles (N). Then the crack growth rate (da/dN) is calculated by means of seven point incremental polynomial method.

2.4. Delamination shape and size

Two measurement techniques were adopted to investigate the delamination shape and size.