Experimental Study on Fatigue Life of Wide Bolted Lap Joint

Da-zhao YU*, Wen-lin LIU, Lin WANG and Li XU

Aeronautical Foundation College, Naval Aviation University, Yantai, 264001, P.R. China
*Corresponding author

Keywords: Bolted lap joint, Multiple site damage, Fatigue life, Fretting fatigue.

Abstract. Due to the complexity of the geometrical configuration and loading conditions, especially for multiple site damage (MSD). In this paper, four fatigue tests of wide bolted lap joint with MSD inserted along the upper row were carried out under two different constant amplitude loading with marker band. The simultaneous propagation of multiple cracks in the test was monitored continuously by aid of a specially developed image analysis technique. Through fractographic examination, MSD initiation characteristic, crack front shape, and growth course were determined. The results show that the crack initiation stage and early crack growth (up to visible cracks) cover the major part of the fatigue life. When crack grows beyond the bolt heads, the residual lives only have 15%~30% of total fatigue life. The greater the stress level is, the smaller the relative residual life will be. When the crack was linked up for the first time, the residual lives are only 0.7%~2.1%. After the second linked up, fatigue lives are only remaining 0.01%~0.03%.

Introduction

Since Alha Airlines accident over Hawaii in April 1988, MSD phenomena have drawn much attention to safety of aircraft lap joint structure. For MSD behavior, some researches [1-3] have been based on an open-hole type model or wide flat panel with many closely spaced collinear cracks model used to simulate the aircraft structure. In reality, aircraft structure is much more complicated than the open-hole model or collinear cracks model because the airframe is joined by fasteners and reinforced by stiffeners or crack stoppers. Joint structure involves very complicated mechanisms such as the load transfer through the fasteners, residual compressive stress at fastener hole due to fastener installation process, interface contact problem, corrosion degradation in strength, and bending effect due to the efficiency of lap joint.

For MSD damage, the core of problems is the initiation of MSD, MSD fracture crack growth and fatigue life of lap joint. Although the riveting process and squeeze force can be well controlled in the laboratory, they are very difficult and impractical to control or measure. The riveting process cannot eliminate human errors, and provide a consistent installation quality of the rivet joints. These will lead to the inconsistent result [4-5]. Because bolted lap joint is easier to control the installation quality than the riveted lap joint, the objective of this study was to identify fatigue crack initiation sites, the subsequent fatigue crack growth rate, and fatigue life of bolted lap joints that contain MSD made of aluminum alloy LY12CZ.

Experimental Procedure

Fatigue Specimens

A total of 4 fatigue test specimens were machined from aluminum alloy LY12CZ with thickness 4mm. They were pre-stretched along the longitudinal direction, which was the direction of the applied load on the specimens. The main mechanical properties, determined by standard coupon tensile tests were: Yield stress $\sigma_y = 322\text{MPa}$, Young’s modulus $E = 69850\text{MPa}$, Poisson’s ratio $\nu = 0.33$.

The dimension and schematic of specimen are shown in Figure 1. The size of the lap joint specimen resembles the span between two adjacent stiffeners of an aircraft fuselage structure. A jeweler’s saw
blade with thickness of 0.3mm was used to cut a small notch with average width of 0.5mm at each side of 8 holes in column A of sheet 1 except two holes near the free edge of the specimen as shown in Figure 2. This purpose was to prevent early fracture at the free edge since more load is transferred through the edge rivet than by the other parts of a wide lap joint specimen [6-7]. Small saw cuts were made to ensure that a corner crack initiation should occur at both sides of the hole.

Fatigue Test

In order to predict the growth of coalescence of MSD cracks, four fatigue tests were performed under constant amplitude loading at a frequency of 20 Hz and a stress ratio of 0.1 with marker load. The maximum stress level of 100 and 150MPa were used for two specimens respectively. All tests were carried out on a 100kN MTS servo hydraulic. During all tests, the temperature and the relative humidity were recorded to determine that all tests were carried out under similar environmental conditions.

Crack Measurements

In general, crack length measurements were made by visual observations while the shape of crack front was studied by post-test fractographic analysis in the SEM. For through crack that propagating outside bolt head, a traveling optical microscope (40X) mounted to the loading frame was used to monitor the cracks at various stages of the propagation life. For crack under the bolt head, efficient crack detection methods are not available for a lap joint at this time being. The geometry of the crack front cannot be ascertained from the SEM observations under constant amplitude (CA) loading 26. Marker band analysis is recommended to investigate the short crack propagation behavior. The application of marker loads is based on the assumption that the marker cycles can perturb the striation spacing created by the CA loading. Of course it is desirable that the marker load cycles should have a negligible effect on the fatigue crack propagation during the baseline cycles. Crack growth or acceleration should be avoided.

The marker loads used here were a “6-4-10”pattern spectrum. This sequence generates sets of 6, 4 and 10 striations on the fracture surface at every 5170 cycles. An SEM example is shown in Figure 3.
Test Results and Analysis

Specimen Teardown and Examination

Four specimens fatigue tests were run to failure in order to estimate the approximate time for crack appearance and final failure. Whenever the crack tip emerges from under the bolt head, a traveling optical microscope was used to measure the crack tip positions on the visible.

All fatigue cracks grew, linked-up, and finally failed along the upper bolt hole in the specimen 2# as shown in Figure 4.

All specimens were disassembled after the fatigue tests were completed. Fretting was evident at all holes but was heavier at crack initiation locations in the critical row than elsewhere. Figure 5 shows the evidence of fretting fatigue was noted by a black oxide deposit on the mating surface between the inner and outer skin around each bolt hole of column A and C. There is little fretting around hole of middle row. This shows that the main reason of fretting is out of plane bending. The role of fretting is not clear. It may be the result of cracking or the cause, increasing the local stress and hence the crack driving force during early crack growth.
**Analysis of Crack Propagation**

Table 1 gives the corresponding cycles vs surface crack length that growing out bolt head. There is a period of relatively slow growth under the bolt heads followed by faster growth beyond the bolt heads. Table 1 show that crack growth under bolt head cover 73.2% of the total specimen fatigue life for specimen 1#. These mean that the crack initiation stage and early crack growth (up to visible cracks) cover the major part of the fatigue life. When crack grow beyond the bolt heads, the residual life only have 15%~30% of total fatigue life. The greater the stress level is, the smaller the relative residual life will be. The two adjacent cracks will link-up to form a lead crack. This lead crack grows faster than other unlinked cracks and tends to dominate subsequent crack growth. There is a relatively short period between the first link-up and the development of a linked crack across the full specimen. When the crack was linked up for the first time, the residual lives are only 2.1%. After the second linked up, fatigue lives are only remaining 0.03%. In other words, the life of the crack linked up for the first time can be seen as the total fatigue life.

<table>
<thead>
<tr>
<th>N/(cycles)</th>
<th>Crack length/(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>79393</td>
<td></td>
</tr>
<tr>
<td>82329</td>
<td></td>
</tr>
<tr>
<td>84722</td>
<td></td>
</tr>
<tr>
<td>94729</td>
<td></td>
</tr>
<tr>
<td>101260</td>
<td></td>
</tr>
<tr>
<td>101870</td>
<td></td>
</tr>
<tr>
<td>105362</td>
<td></td>
</tr>
<tr>
<td>105942</td>
<td></td>
</tr>
<tr>
<td>106962</td>
<td></td>
</tr>
<tr>
<td>107492</td>
<td></td>
</tr>
<tr>
<td>108302</td>
<td></td>
</tr>
<tr>
<td>108399</td>
<td></td>
</tr>
<tr>
<td>108442</td>
<td></td>
</tr>
<tr>
<td>108474</td>
<td>failure</td>
</tr>
</tbody>
</table>

**Analysis of Fracture Surface**

The crack fronts for the right and left side of hole 6# obtained for specimen 1# and 3# by microscope inspection are shown in Figure 6. The figure shows that all cracks initiated from faying surface at the bolt hole horizontal center-line and the crack shape is roughly quarter- or semi-elliptical. The cracks tend to grow faster in direction of the row of the bolt holes than through the skin towards the outer surface. When cracks reach the out surface of a lap, they become through cracks [9]. However, the crack fronts remain slanted to some extent. The main reason is the out of plane bending of lap joint. Although all for the hole 6#, the cracks shape are different for two specimens. The possible reasons are different initial fatigue quality of lap joint and stress level used in fatigue test.
Summary

MSD fatigue cracks tend to initiate on the faying surface near or at the rivet hole corners and grow in the thickness and longitudinal direction. The MSD cracks are hidden for 73.2% (specimen 1#) to 85.7% (specimen 3#) of the total fatigue life; therefore, the number of cycles required to achieve initial failure did not differ significantly from that to final failure of the specimen. The life of the crack linked up for the first time can be seen as the total fatigue life. Fatigue crack growth could be reconstructed from the fracture surface morphology based on the location and direction of the fatigue striations under CA loading with marker. But the marker bands were hard to detect under the SEM for the first 30,000 cycles.

Acknowledgement

This research was financially supported by the National Science Foundation of China (No.51375490).

References


