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Corrosion Pillowing in Aircraft Fuselage Lap Joints

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This paper presents the results of studies that have been carried out at the National Research Council Canada on the effect that corrosion pillowing has on the structural integrity of fuselage lap joints. Modeling of corrosion pillowing using finite element techniques showed that the stress near the rivet holes increased to the material (Al 2024-T3) yield strength when the corrosion present was above 6% thickness loss. In addition, the analysis showed that pillowing resulted in a stress gradient through the skin thickness, which suggested that semi-elliptical cracks with high aspect ratios could form. During teardowns of service-exposed lap joints, these types of cracks were found at numerous holes and a closer examination of the fracture surfaces revealed the presence of fatigue striations. Therefore, a new source of multisite damage, other than fatigue, was identified.

I. Introduction

IN THE 1980s, it became apparent that commercial transports would remain in service well beyond their original design life, which raised concerns that corrosion combined with fatigue could lead to catastrophic failures of fuselage lap joints. Although there are multiple lap joint designs present in a single fuselage, for older aircraft the majority of them consist of an outer and inner skin fabricated from aluminum 2024-T3 joined together with multiple rows of countersunk rivets (Fig. 1), as well as an adhesive layer. During the operation of an aircraft, the adhesive layer can deteriorate and disbond allowing moisture to migrate between the skins. This moisture can, in turn, breakdown the material protective system resulting in the formation of crevice corrosion. As the corrosion forms, the skins between the rivets are forced apart due to the presence of the corrosion products resulting in a bulging or "pillowing" of the skins. This phenomenon is referred to as corrosion pillowing and is the feature used to detect corrosion in lap joints using visual (flashlight) nondestructive inspection techniques.

This paper reviews the results to-date of studies that were carried out to determine the effect that corrosion pillowing has on the structural integrity of fuselage lap joints. The results indicate that corrosion pillowing can cause the formation of semi-elliptical cracks with high aspect ratios, which were found in a number of service-exposed corroded lap joints. These cracks formed at a number of different rivet holes and thus are considered to be a new source of multisite damage (other than fatigue), which could significantly affect the residual life and strength of a lap joint.

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II. Corrosion Pillowing Analysis

A. Mathematical Model

The visual nondestructive inspections used to detect corrosion pillowing in fuselage lap joints are not capable of determining the level of corrosion that is present within a joint. Therefore, to determine if a correlation existed between the amplitude of the pillowing deformation of the outer skin of a lap joint to the degree of corrosion inside the joint, a mathematical model was developed. This model presumed that after the lap joint disbonds the aircraft skin between the rivets deforms perpendicularly to the lap joint surface to accommodate the additional volume required by the corrosion product. A chemical analysis on corrosion samples taken from service-exposed lap joints indicated that the insoluble product mainly consisted of aluminum oxide trihydrate (aluminum hydroxide), which has a molecular volume ratio of 6.454 times that of pure aluminum [1].

The model assumed that the corrosion product was distributed within the joint so as to exert a uniform lateral pressure on the fuselage skins. It was also assumed that the joint was symmetrical about its midplane and thus only the outer skin was modeled. The closed-form classical plate theory of Timoshenko and Krieger was used to calculate the deformation of the outer skin supported by equidistant rivets and subjected to a uniform lateral pressure [2]. This deformation was used to calculate the pillowing ratio given by the ratio of the central deflection to the volume under the deformed plate [3]. From this model, the central deflection was determined to be approximately 3.3 times the thickness loss for a rivet spacing ratio of one. To better understand the effect that the rivet spacing ratio had on corrosion pillowing, the deformed shapes of plates with various rivet spacing ratios were calculated and the results are plotted in Fig. 2. The results showed that as the rivet spacing increased, the relative deflections at the shorter edges decreased, whereas those at the longer edges increased, which can significantly reduce the probability of detecting the corrosion visually. This suggests that the detection limit for joints with a high rivet spacing ratio, may be significantly larger than the maximum allowed 10% thickness loss.

B. Stress Analysis

Because actual lap joints contain free edges and stiffeners, which cannot be modeled using the closed-form solution, finite element techniques were developed to model an actual aircraft lap joint (Fig. 1). This model included the effects of the hoop stress from the pressurization of the fuselage, the rivet prestress caused by the rivet installation as well as the corrosion pillowing stress. The fuselage curvature was ignored for all the analyses that were performed during this program. Because it was assumed that a linear relationship existed between the different loads, three finite element models were

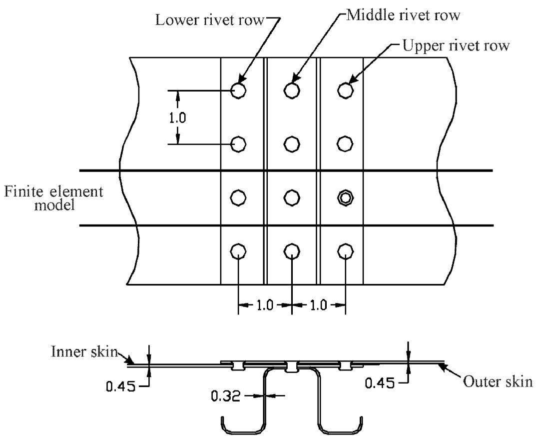


Fig. 1 Schematic of a typical longitudinal lap joint.

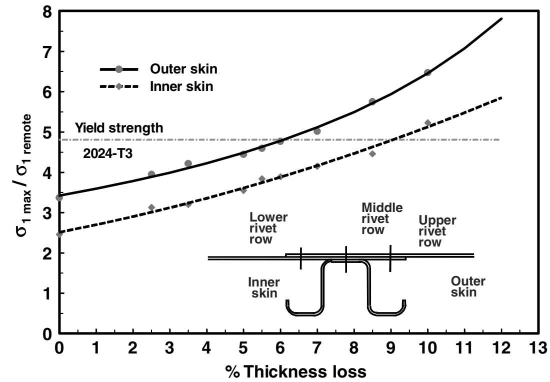


Fig. 3 Effect of increased corrosion pillowing on critical rivet row of respective skins [4].

generated for each load and the resultant stresses were added together.

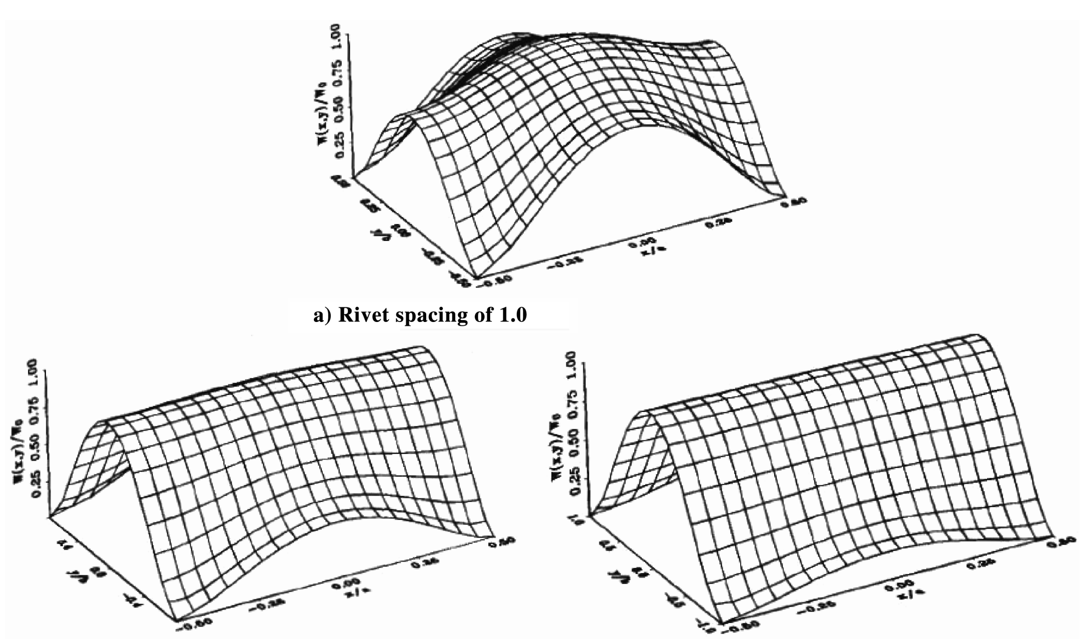
All the finite element models were generated with first-order brick element. It was assumed for the hoop stress model that some of the load transfer would be due to friction under the rivet heads, which was simulated by merging the nodes in these areas. The details of the modeling techniques developed are given elsewhere [4]. The results indicated that the stress in the vicinity of the upper rivet row in the outer skin and the lower rivet row in the inner skin, which are the critical locations in terms of cracking for the respective skin in a typical two-layer aircraft joint, increased as the pillowing increased, as shown in Fig. 3. To verify the finite element analysis, a photoelastic coating was placed on the outer surface of a simulated lap joint before being exposed to the National Research Council (NRC) artificial lap joint corrosion protocol (Fig. 4). The lap joint was periodically removed from the salt fog chamber and the maximum shear strain determined using an automated technique developed at NRC [5]. The results compared very well with the finite element analysis [6].

A comparison was also made between the increase in stress caused by an equivalent thinning of the outer skin and that caused by pillowing (Fig. 5). The results showed that pillowing had a greater influence on the stress in a joint, as compared with the effective thickness loss alone. This larger influence is a significant finding because it has been previously assumed that by reducing the skin thickness and increasing the crack growth rate, the effect of corrosion on fuselage lap joints can be taken into account. However, this simple assumption can result in nonconservative life estimates that can increase the risk of premature cracking. The finite element results also showed that pillowing could change the location of the maximum principal stress within a lap joint [4]. This finding has raised concerns, because the new critical location could occur in an area that is not normally inspected for cracks, again increasing the risk that these cracks could remain undetected. These pillowing models were refined using nonlinear material and geometric finite element methods [7]. More recently, Komorowski and Leski developed a new pillowing model using thermal techniques [8].

Using the pillowing models for various levels of thickness loss, the evolution of the pillowing stress states in a lap joint has been developed by Brooks et al. by considering the progressive build up of sustained bending stresses as the corrosion products accumulate [9].

C. Fracture Mechanics Analysis

The finite element analysis showed that the stress along the outer surface of the outer skin, in the vicinity of the critical rivet row, could become compressive at the holes when the thickness loss in a corroded lap joint increased to above 10% [10] (Fig. 6). This smaller stress, along the outer surface, raised concerns about the nucleation and growth of cracks in the presence of corrosion pillowing. To examine this effect, a fracture mechanics analysis was carried out

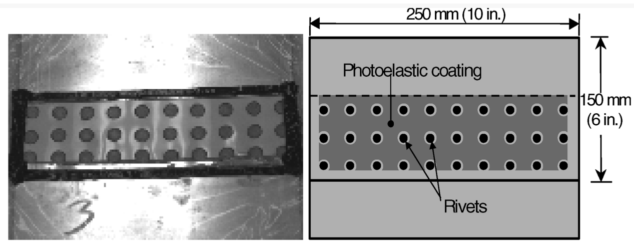


a) Rivet spacing of 1.0

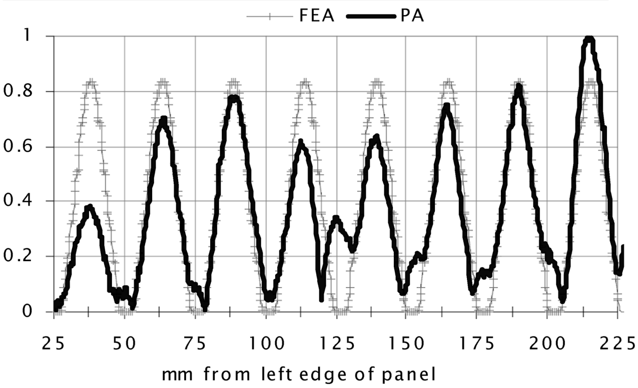
b) Rivet spacing of 1.5

c) Rivet spacing of 2.0

Fig. 2 Effect of rivet spacing ratio on pillowing ratio [1].



a) Photo of lap joint **b) Schematic of lap joint**



c) Fringe order along horizontal line between middle and lower rivet rows

Fig. 4 Lap joint corrosion pillowing specimen [6].

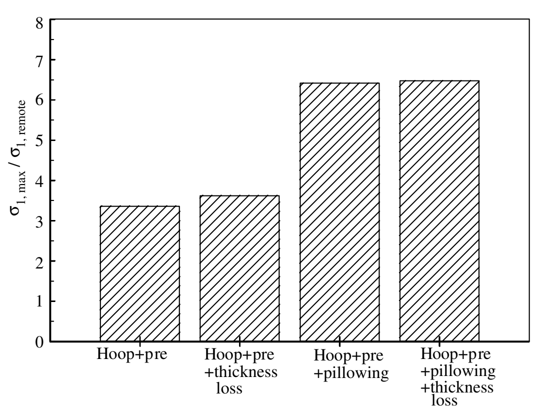
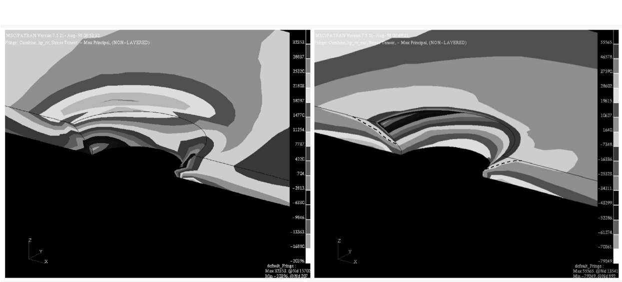


Fig. 5 Effect on stress caused by reduction of outer skin thickness as compared with pillowing (10% thickness loss) [4].

using finite element techniques [11]. A number of straight-fronted-through cracks were examined for joints containing two levels of corrosion, 5% and 10% thickness loss, and with a crack located at the critical rivet row. The results showed that the stress intensity factors along the inner and outer surface of the outer skin diverged as the



a) Noncorroded lap joint **b) Corroded lap joint**

Fig. 6 Stress plot from finite element analysis for lap joints; a) includes hoop stress and rivet interference, and b) shows approximate location of neutral axis (dashed line) for 10% thickness loss. Loading includes hoop stress, rivet interferences, and corrosion pillowing [10].

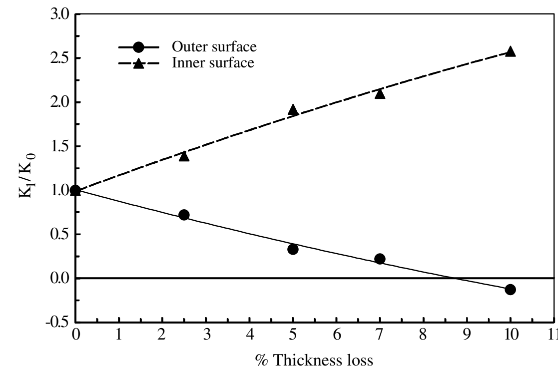


Fig. 7 Nondimensional stress intensity plot of outer surface ($z = 0.000$) and inner surface (1.14 mm) of outer skin for single crack length of 3.84 mm, where K_0 is the stress intensity factor of a through crack without corrosion ($K_0 = \sigma\sqrt{\pi a}$ [11].

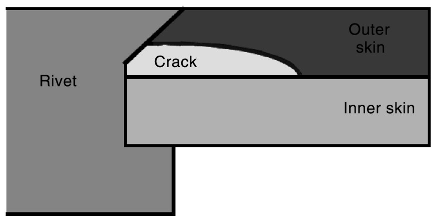


Fig. 8 Suggested shape of cracks in the presence of pillowing [11].

thickness loss increased (Fig. 7). As can be seen from this figure, the stress intensity factor for the crack edge along the faying (inner) surface increased as the pillowing increased, whereas the crack edge along the outer surface decreased. This difference in the two surfaces suggests that the crack edge located along the faying surface would grow more rapidly in the direction of the row of rivets than through the thickness, resulting in a semi-elliptical crack front with a high aspect ratio as shown in Fig. 8.

III. Pillowing Cracks

Following the finite element analysis, nonsurface breaking cracks were found in a number of naturally corroded joints removed from both retired and operational aircraft, Table 1. These cracks were identified using either x-ray nondestructive inspection techniques or when some of the joints were disassembled and the corrosion products removed. As can be seen from this table, cracks were found in a number of different locations on various aircraft with diverse operating lives. For the A300 incident, a service bulletin was found that was issued in 1982 by Airbus Industries [12]. The bulletin described the discovery of numerous cracks around the rivet holes of a corroded lap joint that resulted in a "star-shape" pattern.

The presence of these nonsurface breaking cracks, referred to as pillowing cracks, has raised concerns into the effect they could have on the structural integrity of corroded fuselage lap joints [13]. Visual examinations of lap joint faying surfaces that were cleaned of corrosion products revealed that pillowing cracks could extend to approximately one-quarter to one-half the rivet pitch.

A. Failure Investigation

To determine the failure mode of these pillowing cracks, a failure investigation was carried out on cracks found (using x-ray techniques) in a portion of a longitudinal lap joint that was recovered from a retired Boeing 707 aircraft [14,15]. To study these cracks, a section of the lap joint was disassembled and the corrosion products removed (Fig. 9). The pillowing cracks, which had not penetrated through the thickness, were found in the inner skin (Fig. 10). Given their location (second layer), these cracks would have had a very low probability of detection using conventional nondestructive inspection techniques (eddy current or ultrasonic). Figure 10 clearly

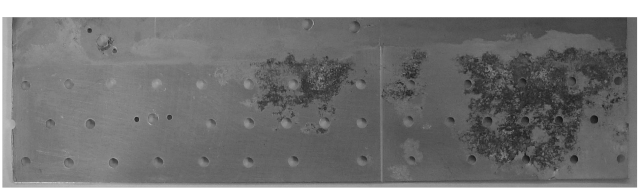
Table 1 Recorded incidences of pillowing cracks

Type of aircraft	Hours/cycles	Location of crack	Layer	WFU[a]/CUT[b]
L1011	38,040/31,370	33R/BS589-609	First	Dec. 92/Sept. 93
B727-235	55,640/48,660	4R/BS1100	Second	Sept. 92/May 93
B727-200	D check	S30/BS1090	First	in service/Aug. 95
B727-100	61,890/54,150	S19R/BS600-640	Second	July 94/July 96
B727-90C	72,400/56,700	S19-26L/BS440	First	in service/Oct. 95
B727-235	56,870/49,530	S19R/BS700-720	First	Mar. 92/Feb. 93
A300(AD)	10,400/6940	S31L/FR26-31	First	in service/Oct. 81
B727-295	61,854/55,465	S19R/BS660-680	First	Jan. 90/Feb. 98
B727-295	63,349/55,676	S19R/BS720A-720B	First	Aug. 89/Feb. 98
B707(Bueno)	——	floor to skin joint	First	in service
B707-3J6C	26,545/11,448	S20R/BS590–600H +10	——	Feb. 97/Jan. 99

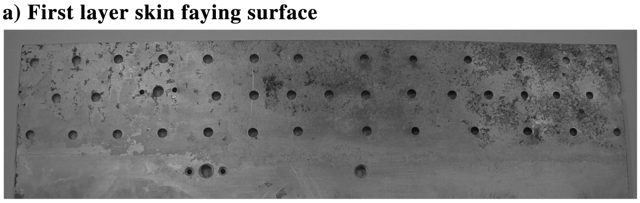
[a]WFU: date aircraft was withdrawn from service.
[b]CUT: date when lap joint was cut from aircraft.

shows the characteristic star-shape cracking pattern that occurs in the presence of corrosion in lap joints. A few of the cracks had grown in the direction parallel to the rivet pitch at approximately 90 deg to the hoop stress. The location of these particular cracks could indicate that some may have propagated under cyclic loading. One of the cracks, which had a length of 3.94 mm (0.155 in.) and a maximum depth of 1 mm (0.039 in.), labeled "1" in Fig. 10, was pried open. A scanning electron micrograph of the fracture surface is shown in Fig. 11. As can be seen from Fig. 11a, there are at least four distinctive nucleation sites, as well as a large secondary crack present on this fracture surface. The exact locations for these sites could not be determined due to the presence of corrosion products on the fracture surfaces. Fatigue striations were also found near the crack tip indicating that this crack was growing under cyclic loading (Fig. 11b and 11c). A cavity was also present on the fracture face (Fig. 11e), which appeared to have intergranular cracks originating from it. This cavity may have formed as a result of intergranular corrosion dissolving a constituent particle that was located at a grain boundary. This scenario was found during a study to determine the faying surface damage caused by corrosion in the vicinity of the rivet holes [14,15]. During this study, sections were taken from naturally corroded lap joints and progressively polished to document the damage present. Some of these sections were taken from areas that contained pillowing cracks. An example of intergranular corrosion dissolving a constituent particle is shown in Fig. 12. As can be seen from this figure, extensive intergranular cracking was present.

To verify the observations that resulted from the one study, five additional cracks from two aircraft were examined using both optical and scanning electron microscopy, three from a Boeing 727 (B727) and two from a Lockheed 1011 (L1011). The following observations were made [10,14,15]:



a) First layer skin faying surface



b) Second layer faying surface

Fig. 9 Optical images of cleaned B707 longitudinal lap joint.

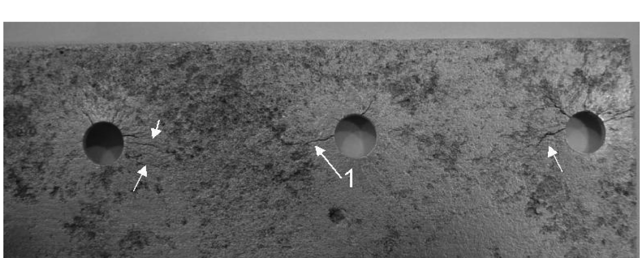
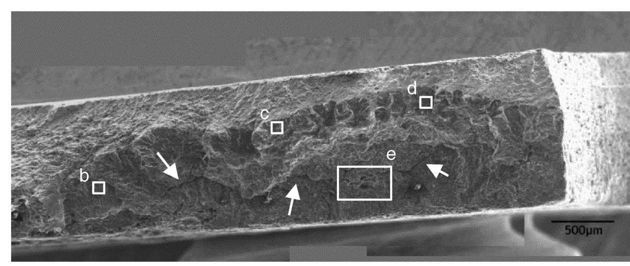
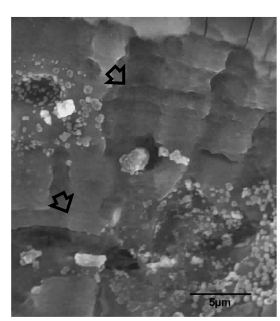


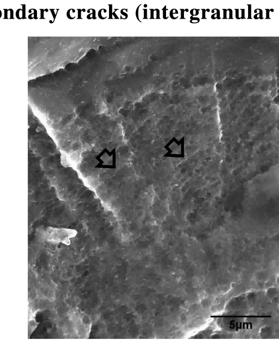
Fig. 10 Close-up of pillowing cracks present in second layer. Crack labeled "1" was pried open [14,15].



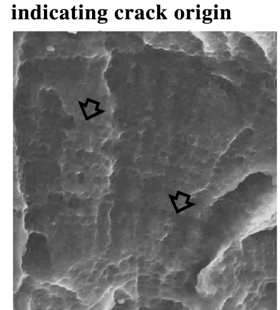
a) Overall view of fracture surface showing distinct fracture regions. Boxes indicate areas where close-ups were taken. Arrows show location of secondary cracks (intergranular cracks)



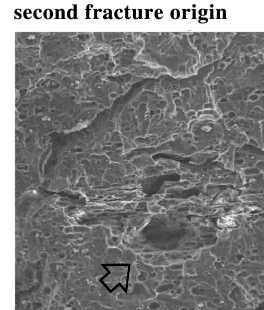
b) Fatigue striations were found near edge of crack indicating crack origin



c) Fatigue striations found on fracture surface indicating second fracture origin



d) Fatigue striations found indicating third crack origin



e) Close-up of cavity and intergranular cracks

Fig. 11 Scanning electron micrographs of fracture surface from crack "1" in Fig. 10 [14,15].

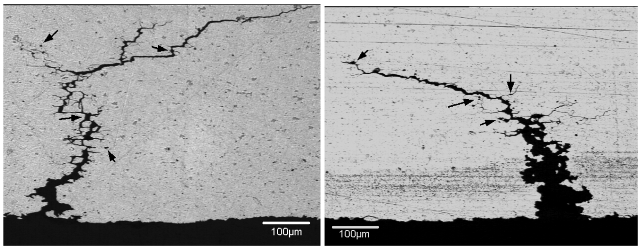


Fig. 12 Optical micrographs of environmentally assisted cracks found in cut sections of corroded lap joints. Arrows indicate constituent particles affected by intergranular corrosion (discoloration) [14,15].

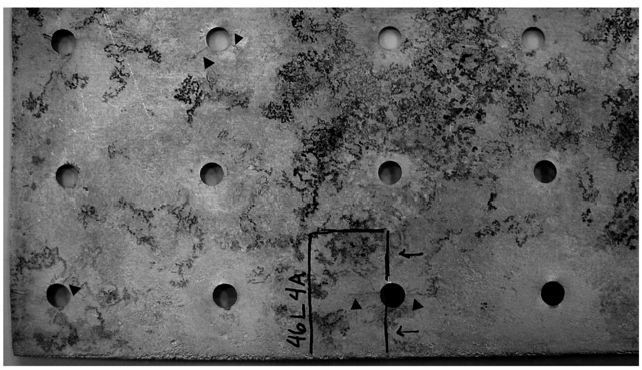


Fig. 13 Optical image of faying surface of artificially corroded lap joint containing pillowing cracks (arrows).

1) Pillowing cracks tended to occur in groups (i.e., star-shape pattern cracks at more than one hole), which did not normally penetrate through the thickness. The cracks always occurred on the side of the hole that was affected by the increased stress due to the pillowing and tended to propagate into the pillowed region.

2) The crack faces that were pried open contained corrosion products and showed extensive intergranular fracture with numerous secondary cracking.

3) The crack growth through the thickness was not perpendicular to the faying and outer skin surfaces but occurred at an angle.

4) A number of the cracks had multiple nucleation sites. Although these sites could not be determined, they were evident based on the different crack planes present.

5) Some of the fracture surfaces contained fatigue striations near the crack edge where the corrosion was light.

At the start of this study, lap joints were subjected to an artificial accelerated corrosion protocol that was developed at NRC to simulate corrosion pillowing. One of these lap joints was stored at NRC for four years after which it was disassembled and the corrosion products removed. Pillowing cracks were discovered that were similar to those found in service-exposed lap joints (Fig. 13). Because these cracks formed only in the presence of the sustained stress caused by corrosion pillowing, it strongly suggests that they nucleated and grew due to environmentally assisted cracking. However, the presence of striations found along the crack front of the pillowing crack pried open from several service-exposed joints suggests that once these cracks form, they may grow further under fatigue loading.

Based on these results and the fact that Wanhill discovered pillowing cracks at every fastener hole in an area of about one-bay length (500 mm) [16], it is proposed that the term multisite damage (MSD) include corrosion, because the effect that pillowing cracks may have on structural integrity could be similar to fatigue crack MSD.

IV. Summary and Future

Corrosion pillowing is present in any area of an aircraft where corrosion is contained between two fixed surfaces such as lap joints and has been shown to increase the stress in the area where the material is restricted from deforming such as at rivets. The resulting high-sustained stress level can cause the nucleation and growth of environmentally assisted cracks, which can grow to significant lengths without being detected. These cracks, which occur at more than one hole depending on the extent of the corrosion contained within the area of interest, are a form of multisite damage. This damage, which is difficult to detect using standard nondestructive inspection techniques, can potentially decrease the residual strength of the component below its design limit.

A test program is presently being carried out to determine the residual life and strength of corroded lap joints containing pillowing cracks. Specimens have been cut from service-exposed lap joints that contain various levels of corrosion, some of which also contain pillowing cracks. These specimens will be subjected to constant amplitude loading until two cracks link-up, at which time some of the specimens will be subjected to an overload to determine the residual strength. The results from the various tests will determine whether pillowing cracks have an effect on the structural integrity of fuselage lap joints.

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