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Damage Tolerance Implications of Corrosion Pillowing on Fuselage Lap Joints

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A previous study showed that pillowing, caused by the presence of corrosion products, can significantly increase the stress in fuselage lap joints, which raises concerns about the effect on aircraft safety. In the present study finite element techniques were used to determine the effect that pillowing has on the stress-intensity factor for cracks located at rivet holes in lap joints. The stress caused by the internal pressure and riveting process was taken into account while the fuselage curvature was ignored. The results indicate that corrosion pillowing increases the stress-intensity factor for the crack edge along the skin-faying surface with a concurrent decrease on the opposite side. This difference suggests that a crack will grow more rapidly along the faying surface than in the through-the-thickness direction, thus forming a semielliptical crack front with a very high aspect ratio. This type of crack is more difficult to detect.

Introduction

TRADITIONALLY, corrosion has been treated as a durability issue in aircraft structures with the primary objective being the prevention of the initiation of corrosion through the proper use of materials, coatings, and maintenance. However, a recent study has determined that the out-of-plane deformations caused by the build-up of corrosion products between fasteners in aircraft fuselage lap joints, better known as pillowing, significantly increases the stress in these joints, which in turn increases the risk of early crack initiation.[1–3] The study also showed that, depending on the location of the corrosion and the severity of the pillowing, the maximum stress in a joint could shift to other locations. These locations could include second or third skin layers and/or previously noncritical rivet rows, which are typically not subject to regular inspections for cracks. The increased risk of early undetected cracking raises concerns over the possible effect corrosion pillowing has on aircraft safety.

This paper presents the results of a study to determine the effect that corrosion pillowing has on the stress-intensity factor of a crack that is present at a rivet hole in a lap splice. Finite element techniques in conjunction with a mathematical model[1] were used to simulate the presence of corrosion products within a lap joint. The prestress caused by the rivet-fastening process and the stress resulting from the internal pressure (hoop stress) were all taken into account while fuselage curvature was ignored. The results suggest that corrosion pillowing could cause the formation of a semielliptical crack front with a high aspect ratio, which could make detection difficult, increasing the risk of in-service failure.

Finite Element Modeling

Corrosion Pillowing Stress

In a previous study finite element techniques were developed to determine the effect that corrosion pillowing has on the stress in a fuselage lap joint.[2,3] Three models were generated to simulate the different loads that were present within a corroded joint. These loads were 1) hoop stress caused by the internal pressure, 2) prestress caused by the riveting process, and 3) stress resulting from corrosion pillowing. All models were generated using first-order brick elements and the material properties were E = 71,016 MPa (10,300 ksi), ν = 0.33 for the skins, and E = 73,774 MPa (10,700 ksi), ν = 0.33 for the rivets. Corrosion pillowing was modeled using a three-stage process:

1) A 6.89 kPa (1 psi) pressure was initially applied to the faying surfaces and the resulting volume determined.

2) Given a specified constant thickness loss in one skin the volume required to accommodate the corrosion products was calculated using a previously derived formula.[1]

3) Assuming a linear relationship between the applied pressure and volume caused by the incompressibility of the corrosion products the pressure necessary to obtain the required volume was calculated and then reapplied to the faying surfaces.[1–3]

The finite element analysis was then rerun and the resulting displacements obtained. The rivet/skin interaction was simulated using nonlinear gap elements. To simplify the model, the elements used to model the skins and rivets were considered to be linear and thus neither geometric nor material nonlinearity was considered. Friction was also not considered at this time.

Corrosion Pillowing Verification

To verify the relationship between maximum pillowing deflection and the calculated induced stress determined in the previous study,[2,3] an experiment was carried out using a lap joint consisting of two skins joined together with four rivets spaced 25.4 mm (1-in.) apart as shown in Fig. 1. The outer skin had a thickness of 1.02 mm (0.04 in.) while the inner skin was 3.175 mm (0.125 in.) thick. Pillowing was simulated by hydraulically pressurizing the faying surfaces. Because it was difficult to place strain gauges at the location of maximum stress, indicated previously to be along the faying surface of the outer skin,[3] it was decided to place three rosette strain gauges on the outer surface of the skin instead. One gauge was placed at the location of maximum pillowing deflection and the other two were located between the rivets. Because the experimental lap joint had a different configuration than previous finite element models, a new model was generated with a constant pressure applied to the faying surfaces.

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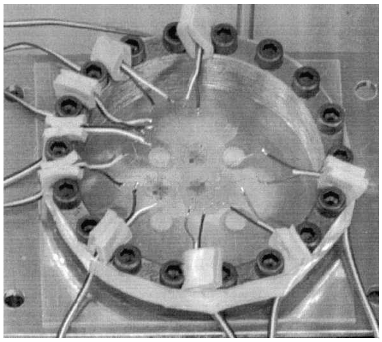

Fig. 1 Experimental apparatus for corrosion pillowing verification.

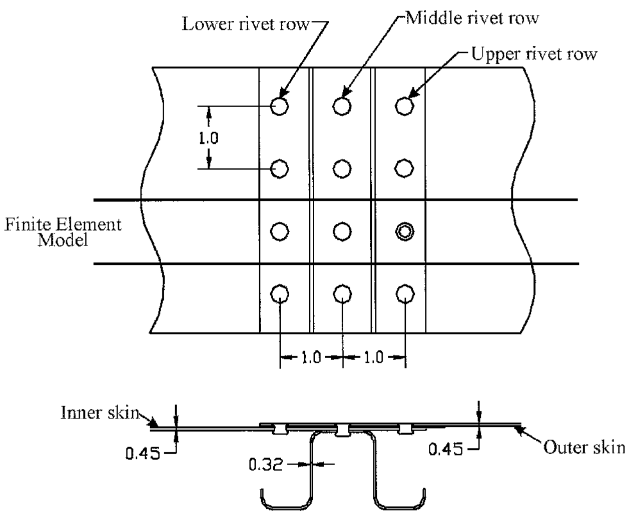

Fig. 2 Fuselage lap-joint configuration.

Fracture Mechanics Analysis

The finite element stress models generated in the previous stress study[2,3] were modified for this analysis. Second-order elements, i.e., elements with midside nodes, were generated in the area of the critical rivet row (upper row). The lap joint examined consisted of two skins (outer and inner) of equal thickness, 1.14 mm (0.045 in.) fabricated from Al 2024-T3. The skins were joined using three rows of rivets with a 25.4 mm (1.0 in.) spacing. A hat-section stringer was attached to the middle rivet row through the hat crown as shown in Fig. 2. The finite element model is shown in Fig. 3. A straight fronted through the thickness crack perpendicular to the hoop stress loading was assumed to be present on one side of the upper rivet hole (Fig. 4). The midside nodes for the elements surrounding the crack tip were moved to the quarter-point to simulate the stress singularity at this location. A number of crack lengths were examined starting at the rivet hole and extending outward beyond the rivet head. Cracks under the rivet head were not examined in this study. The resulting quarter-point and corner nodal displacements were used in the following equation to calculate the mode I stress intensity factor[4]:

$$K_I = [4(u_1 - u_2) - (u_3 - u_4)](E/8)\sqrt{2\pi/L} \tag{1}$$

where u_1 and u_2 are the displacements for the quarter-point nodes perpendicular to the crack face, u_3 and u_4 are the corresponding displacements for the corner nodes, and L is the length of the crack tip element. Because of the thickness of the skins plane stress conditions were assumed to exist ahead of the crack front.

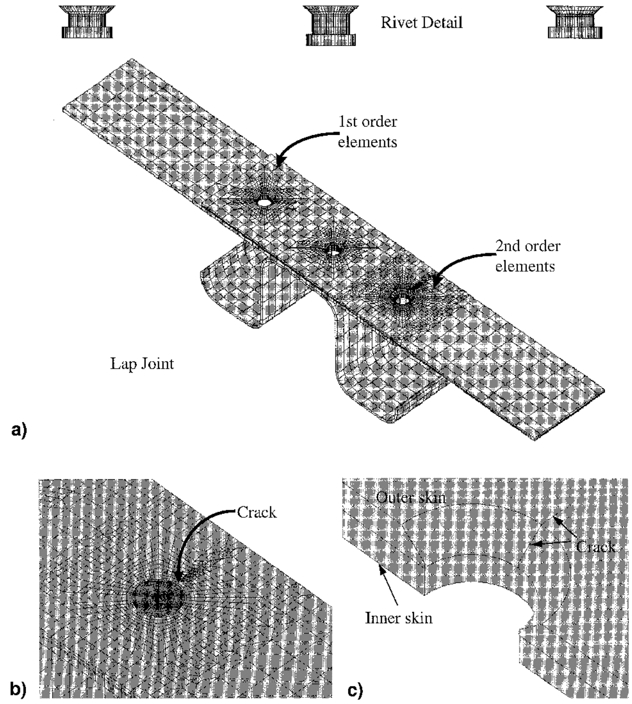

Fig. 3 Finite element model for fracture mechanics analysis: a) overall lap-joint model, b) critical rivet row detail, and c) boundary line plot showing crack.

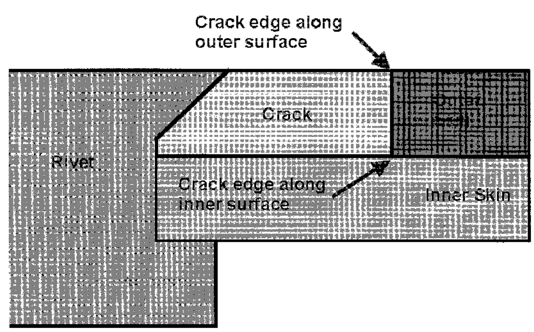

Fig. 4 Assumed crack shape used in finite element model.

Results and Discussion

Corrosion Pillowing Verification Experiment

In an initial test the pressure was increased until the maximum pillowing deflection was 0.254 mm (0.01 in.), which corresponds to a total thickness loss of 5% estimated by using a procedure described elsewhere.[5] The purpose of this test was to obtain shadow moirè images of the deformed joint for comparison to the finite element results. One such comparison is shown in Fig. 5. Figure 5 shows that the out-of-plane contours compare very well.

In a subsequent test the pressure was slowly increased to a maximum deflection of 0.508 mm (0.02 in.) corresponding to a total thickness loss of 10%. A plot of the principal stress calculated from the strain gauge readings vs the maximum pillowing deflection is shown in Fig. 6 along with the finite element results. Included in Fig. 6 is the corresponding maximum stress along the inner surface of the outer skin obtained from the finite element results. Good agreement is shown between the experimental stress values and the finite element results, indicating that the finite element model used in the previous study[2,3] produces reasonable results. The maximum stress values in Fig. 6 show just how rapidly stress increases in a corroded joint. The stress in the joint increases to above yield with less than 5% thickness loss. It should be emphasized

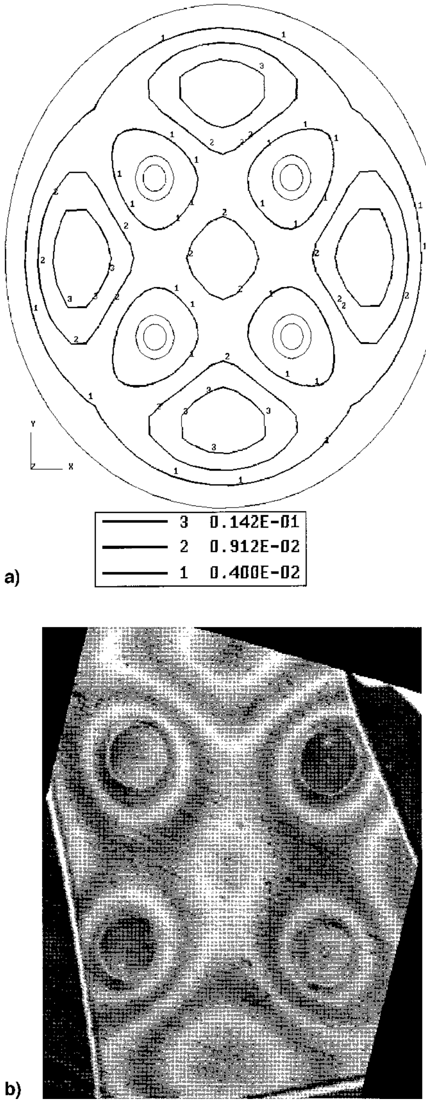

Fig. 5 Out-of-plane displacement contours for a maximum pillowing deflection of 0.01 in. (0.254 mm): a) finite element results (legend in inches) and b) shadow moirè results (fringe separation —0.005 in.).

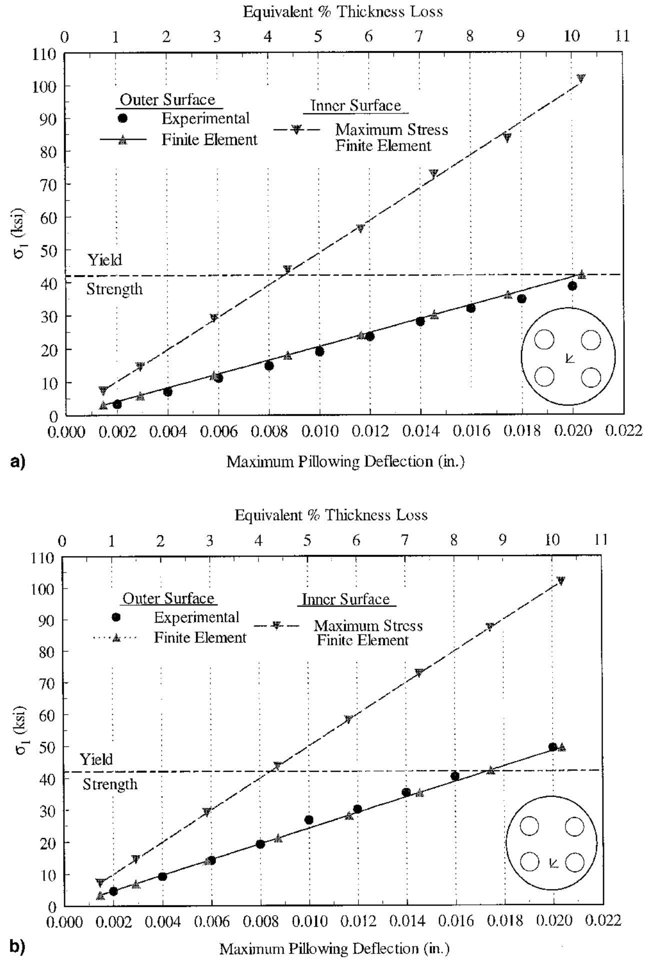

Fig. 6 Comparison between experimental and finite element results: a) center strain gauge location and b) strain gauge location between two rivets.

that the thickness loss refers to the total loss in the outer skin only, which can be considered a worst-case senario.

Fracture Mechanics Analysis

To calculate the mode I stress-intensity factor the nodal displacements from the three loading cases were added together and substituted into Eq. (1). A number of crack lengths were examined for joints containing two levels of corrosion thickness loss, 5 and 10%. The results were nondimensionalized with respect to the noncorroded stress-intensity factor and plotted against crack length (Fig. 7). It should be pointed out that the crack length was measured from the center of the rivet hole to the crack tip. The stress-intensity factors for the crack edge along the outer surface (Fig. 7a) are consistently lower than the noncorroded value ($K_I/K_0 = 1.0$), but steadily increase as the crack length increases. At higher corrosion levels, i.e., 10% thickness loss, the stress-intensity factors have negative values for cracks close to the hole edge. It is recognized that negative values are unrealistic, which strongly suggests that the assumed crack shape used in the model is incorrect. This is explored further in the next paragraph.

The stress-intensity factors for the crack edge along the inner (faying) surface (Fig. 7b) are significantly higher for small crack lengths, i.e., near the rivet hole, and steadily decrease as the crack length increases. This suggests that the effect pillowing has on a joint is highest near the hole edge and slowly decreases. The divergence in the stress intensity factors for the two surfaces suggested in Fig. 7 is shown more clearly in Fig. 8. In Fig. 8 the stress-intensity factor for a single crack length of 3.84 mm (0.151 in.) was nondimensionalized and plotted against the percentage thickness loss. As can be seen from Fig. 8 the stress-intensity factor for the crack edge along the faying surface increases as the pillowing increases while the crack edge along the outer surface decreases. This is understandable because the bending in the skin caused by pillowing produces a compressive stress in the rivet area on the outer surface while a high tensile stress is present on the faying surface. The difference in the stress-intensity factor for the two surfaces suggests that the crack edge on the faying surface would grow more rapidly in the direction of the row of rivets than through the skin toward the outer surface. This should result in a semielliptical crack front with a high aspect ratio, as demonstrated in Fig. 9.

Following this analysis nonsurface breaking cracks were identified in many naturally corroded joints removed from retired aircraft as well as in skins removed from operational aging aircraft.[3,6,7] Figure 10 shows an x-ray image of a disassembled joint showing these nonsurface breaking cracks. Numerous cracks were detected at the four rivet holes in this lap joint in the area where maximum pillowing occurred. This joint had an average thickness loss of 14%. Given that the corrosion was confined to a very localized area of the joint and that the skin thickness was approximately 1.78 mm (0.07 in.), it is unlikely that this damage would have been detected under normal maintenance procedures. More importantly is the fact that all of the cracks present had not penetrated through the thickness to reach the outer surface, although some had lengths greater than 6.35 mm (0.25 in.).

One approach to decreasing the risk of aging aircraft failure caused by multiple site damage (MSD) is to perform special inspections of selected critical areas at predefined intervals (Fig. 11).[8] If corrosion is present cracks could nucleate earlier than in a noncorroded joint and these cracks would be typically high aspect ratio semielliptical in shape for the reasons discussed previously. They would also be subsurface and difficult to detect. It is estimated that these cracks could extend to approximately one-quarter to one-half the rivet pitch along the faying surface before becoming visible on the exterior surface. This would significantly reduce the probability of detection before first link-up in an MSD situation and therefore could increase the risk of in-service failure. To reduce this risk the special inspections to detect MSD might have to be started earlier, as shown in Fig. 11, and may have to include previously noncritical areas. These inspections should include corrosion detection, and if corrosion is found then special nondestructive inspection techniques, such as x ray or lower frequency eddy current, should be used to find the high aspect ratio cracks.

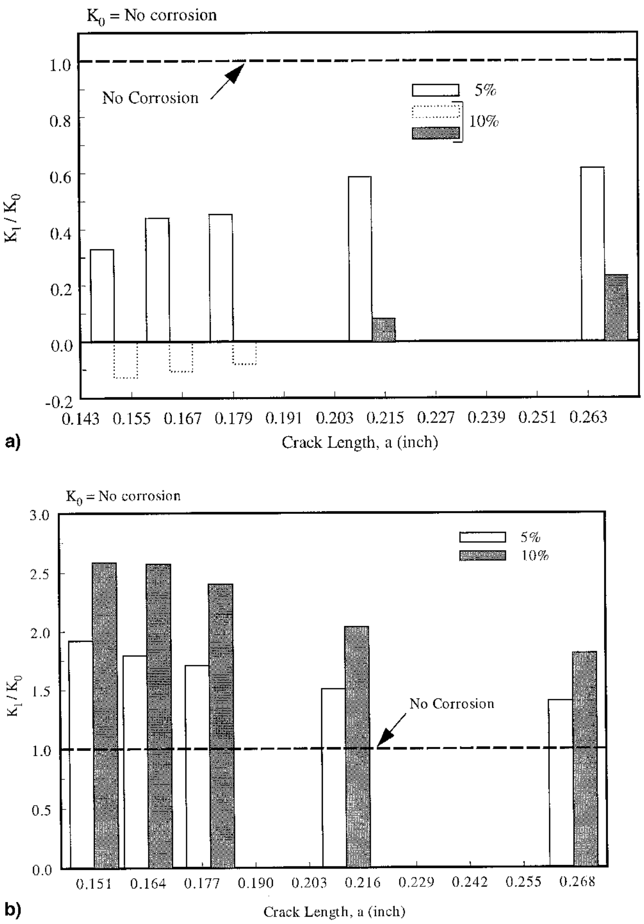

Fig. 7 Stress-intensity factor ratios for various crack lengths present in joints containing two levels of corrosion, 5 and 10%. Stress-intensity ratio for crack edge along a) outer surface and b) inner faying surface.

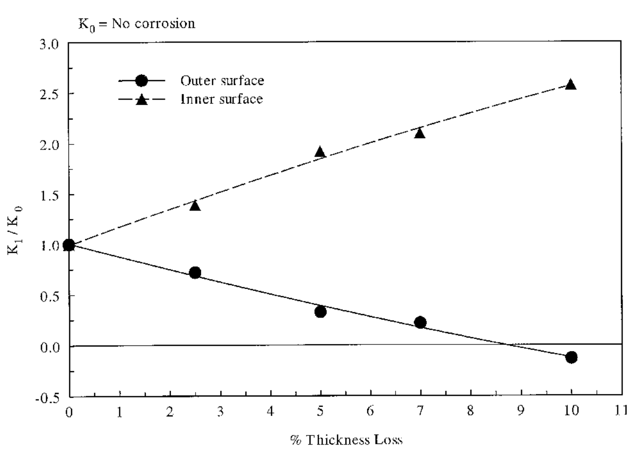

Fig. 8 Comparison of stress-intensity factor for crack edge along inner and outer surfaces.

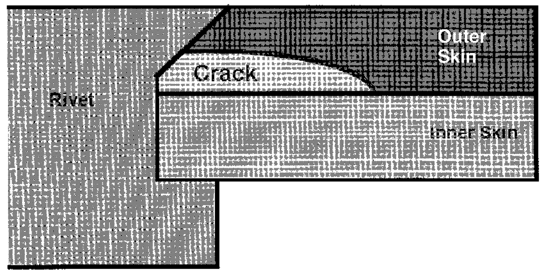

Fig. 9 Suggested shape of crack under influence of pillowing.

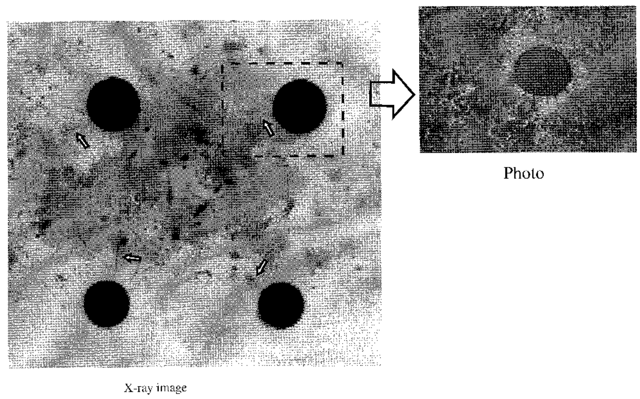

Fig. 10 Image of disassembled fuselage lap joint obtained from retired aircraft showing cracks around rivet holes in the area with corrosion pillowing. All cracks present have not penetrated through the thickness.

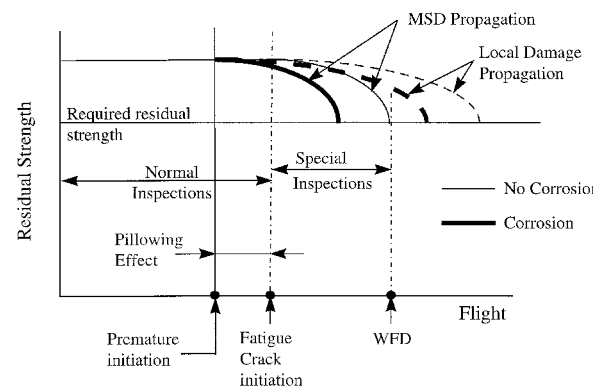

Fig. 11 Implications of corrosion pillowing on structural integrity of fuselage lap joints. Graph modified from Ref. 8.

Conclusions

1) The relationship between the maximum pillowing deflection and stress has been verified using experimental techniques. The stress in this simulated joint with only corrosion present increases to above the yield strength of Al 2043-T3 with as little as 5% total thickness loss of the outer layer.

2) Corrosion pillowing significantly increases the stress-intensity factor for the crack edge along the skin faying surface with a subsequent decrease on the opposite side. This suggests that a crack will grow more rapidly along the faying surface than through the skin thickness, resulting in a semielliptical crack front with a high aspect ratio. Such cracks have been found in several aircraft joints during teardown inspections.

3) High aspect ratio cracks make detection difficult because they do not break through to the exterior surface until late in the growth phase. This decreases the probability of detection and increases the risk of in-service failure. This is particularly true if corrosion pillowing occurs in an area previously considered noncritical, where inspections are not carried out on a regular basis.

4) Special inspection programs to detect MSD may have to be initiated earlier and include early corrosion detection to below the currently accepted levels. If corrosion is found, then special nondestructive inspection techniques should be used to detect the high aspect ratio cracks that could be present in these areas. It should be emphasized that such cracks have recently been found in operational aircraft.

Acknowledgments

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References

[1]Bellinger, N. C., Krishnakumar, S., and Komorowski, J. P., "Modelling of Pillowing Due to Corrosion in Fuselage Lap Joints," *CAS Journal*, Vol. 40, No. 3, 1994, pp. 125–130.

[2]Bellinger, N. C., and Komorowski, J. P., "Corrosion Pillowing Stresses in Fuselage Lap Joints," *AIAA Journal*, Vol. 35, No. 2, 1997, pp. 317–320.

[3]Bellinger, N. C., and Komorowski, J. P., "Implications of Corrosion Pillowing on the Structural Integrity of Fuselage Lap Joints," *Proceedings of the FAA-NASA Symposium on Continued Airworthiness of Aircraft Structures* (Atlanta, GA), Vol. 2, DOT/FAA/AR-97/2, II, 1996, pp. 391–402.

[4]Gruber, M. L., Mazar, C. J., Wilkins, K. E., and Worden, R. E., "Investigation of Fuselage Structure Subject to Widespread Fatigue Damage," DOT/FAA/AR-95/47, Final Rept., Feb. 1996.

[5]Komorowski, J. P., Bellinger, N. C., Gould, R. W., Marincak, A., and Reynolds, R., "Quantification of Corrosion in Aircraft Structures with Double Pass Retroreflection," *Canadian Aeronautics and Space Journal*, Vol. 42, No. 2, 1996, pp. 76–82.

[6]Bueno, C., Barker, M. D., Barry, R. C., and Betz, R. A., "Corrosion Detection and Characterization Using High Resolution Real-Time Radiography," SAMPE 41st International Symposium and Exhibition, March 1996.

[7]Komorowski, J. P., and Gould, R. W., "DAIS-250C Field Inspections at First Air," LTR-ST-2073, Sept. 1996.

[8]Swift, T., "Widespread Fatigue Damage Monitoring—Issues and Concerns," *FAA/NASA International Symposium on Advanced Structural Integrity Methods for Airframe Durability and Damage Tolerance* (Hampton, VA), Pt. 2, NASA-CP-3274-PT-2, 1994, pp. 829–870.