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Corrosion Pillowing Stresses in Fuselage Lap Joints

Nicholas C. Bellinger* and Jerzy P. Komorowski†
National Research Council, Ottawa, Ontario K1A 0R6, Canada

Finite element techniques were used to determine the effect that pillowing, caused by the presence of corrosion products, has on the stress in fuselage lap joints. The stress caused by the internal pressure and the riveting process were taken into account, and the fuselage curvature was ignored. The results show that the joint stress increases as the pillowing increases (i.e., material loss increases). It is shown that pillowing can significantly increase the stress in a lap joint for material loss below the detection limit of current nondestructive inspection techniques, thus increasing the risk of premature cracking.

Introduction

THE damage from environmental attack can lead to early crack initiation, enhanced crack growth rates (corrosion fatigue), thickness loss (increased stresses), intergranular and stress corrosion cracking, and pitting (stress risers). It has been assumed that these corrosion effects can be approximated in a fracture-based analysis in terms of thickness reductions, corrosion equivalent crack sizes, and accelerated crack growth.[1] However, one parameter that has been ignored thus far is the effect that the out-of-plane deformation caused by the buildup of corrosion products between the fasteners, better known as pillowing, has on the structural integrity of the joint.

In 1992, the Institute for Aerospace Research of the National Research Council Canada (IAR/NRCC), the Transportation Development Centre of Transport Canada, and the Technical Center of the U.S. Federal Aviation Administration agreed to jointly fund a project to develop the application of D Sight[2] for corrosion detection in transport aircraft fuselage joints. This work is being carried out by the Structures, Materials and Propulsion Laboratory of the IAR/NRCC and Diffracto, Limited, under a collaborative agreement. D Sight is a surface inspection technique that uses a simple optical arrangement and is capable of detecting changes in surface topography of greater than 10 μm. During this program, it was established that the volumetric increase associated with the corrosion products was 6.454 (molecular volume ratio) times greater than the volume of parent material lost,[3] which is much higher than was originally thought. This large volumetric increase, in turn, raised concerns about the possible effect of pillowing on the structural integrity of corroded fuselage joints.

This paper presents the results of a study to determine the effect of corrosion pillowing on the structural integrity of fuselage lap joints. Finite element techniques along with a mathematical model[4] were used to simulate the presence of corrosion products within a lap joint. The prestress caused by the rivet-fastening process, the stress resulting from the internal pressure (hoop stress), and the reduction in thickness caused by the material loss were all taken into account. The results indicate that the stress in a joint caused by pillowing is significantly higher than that caused by the material loss alone. This finding suggests that approximating corrosion by simply reducing the thickness of the skins may significantly underestimate the residual static strength and life of a corroded joint.

Finite Element Model

A typical lap joint configuration was chosen for this study and 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 by using three rows of rivets with a 25.4-mm (1.0 in.) spacing. Each rivet had a nominal shank diameter of 3.96 mm (0.156 in.) and a rivet-head diameter of 5.8 mm (0.232 in.). A hat-section stringer was attached to the middle rivet row through the hat crown, as shown in Fig. 1. Three finite element models were generated by using the commercial finite element package NISA (Numerically Integrated Elements for System Analysis) to simulate the different loads present within a corroded joint (fuselage curvature was ignored). These loads were 1) prestress caused by the riveting process, 2) hoop stress caused by the internal pressure, and 3) stress due to corrosion pillowing. To save computation time and storage space, only three rivets were modeled as shown in Fig. 2.

All the finite element models were generated with first-order brick elements to accommodate the gap elements, which, for the finite element code used, were not recommended for use at edges or faces of elements with midside nodes. Symmetrical boundary conditions were applied along the centerline of the joints, and clamped boundary conditions were applied along one or both short edges, depending on the load case being modeled.

In the first model, the prestress caused by the rivet clamping force was simulated by applying a pressure to each rivet head. All the nodes were merged in this particular model to prevent the surfaces from overlapping. In the second model, pressure was applied along a skin edge to simulate the hoop stress; the opposing edge was fixed in all directions. Gap elements were used to simulate the rivet/skin interaction. The skins directly under the rivet heads were assumed to transfer some of the load, which was modeled by merging the nodes in these areas.

To simplify the third model (corrosion), it was assumed that the material loss due to corrosion was constant throughout the entire joint. An initial finite element run was carried out in which a pressure of 6.89 kPa (1 psi) was applied to the faying surfaces. The volume

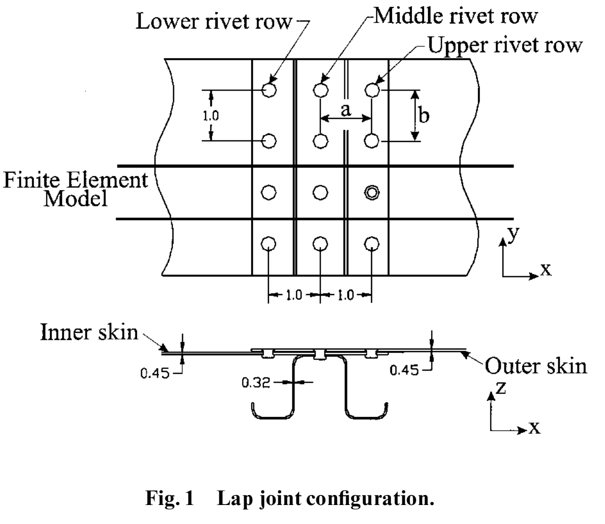

Fig. 1 Lap joint configuration.

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*Associate Research Officer, Institute for Aerospace Research, Structures, Materials and Propulsion Laboratory, Building M-14, Montreal Road.

†Senior Research Officer, Institute for Aerospace Research, Structures, Materials and Propulsion Laboratory, Building M-14, Montreal Road.

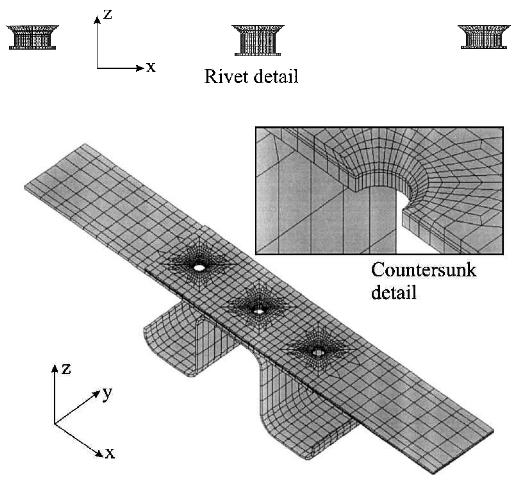


Fig. 2 Finite element model.

under the resulting deformed shape V_{fem} was then determined using an iterated integral:

$$V_{fem} = \int_{e}^{f} \left(\int_{c}^{d} f(x, y)\, dx \right) dy \tag{1}$$

where (c, d) and (e, f) are the intervals of integration along the x and y axes, respectively, over the length of the joint for which the volume was to be calculated (i.e., between the rivets, 25.4 mm). Simpson's $\frac{1}{3}$ and $\frac{2}{3}$ rules[5] were used to numerically integrate Eq. (1), depending on the number of nodes evaluated. A formula derived in a previous study[4] was then used to calculate the actual volume required V_{req} to accommodate the corrosion products given a specific material loss, t_{lo} (e.g., for $t = 0.1$, 5% material loss $t_{lo} = 0.005$):

$$V_{req} = abt_{lo}[(V_{mr}/2) - 1] \tag{2}$$

where V_{mr} is the molecular volume ratio, 6.454, and a and b are the rivet spacing, 25.4 mm in this case. On the basis of the results of the chemical analysis,[3] the products of corrosion were considered to be incompressible (i.e., Young's modulus of the products was significantly higher than that of aluminum). On this basis, a linear relationship was assumed to be present, and thus the pressure-to-volume ratios for the mathematical and finite element models were set equal:

$$(P_{req}/V_{req}) = (P_{fem}/V_{fem}) \tag{3}$$

From this equation, the pressure necessary to obtain the required volume was determined, which was then reapplied to the faying surfaces in the corrosion model and the corrosion finite element analysis was rerun. In the case in which the seal has deteriorated, or was not applied, around the free edges of an actual lap joint, the corrosion products in that area could seep out, thus reducing the pillowing effect in that area. D Sight images of fuselage lap joints have shown that only a small amount of pillowing occurs at the free edges compared to the area between each pair of rivet rows. To accommodate this smaller volume, the pressure was progressively decreased from the rivets to the free edges in the finite element model.

Because pillowing is governed by the total volume of corrosion products contained within a joint, the material converted to form these products could originate from the outer skin (first layer), inner skin (second layer), or both. For the purpose of this study, it was decided that the percentage of material loss would refer to the amount of material converted from the thinnest skin present within the joint.

Results and Discussion

Convergence Study

A number of finite element models were generated in which the mesh was progressively refined in the vicinity of the upper rivet row. The resulting stress values were compared from one run to another; when the stress varied by less than 3%, the results were assumed to have converged. To further verify these results, second-order elements were used in the vicinity of the maximum stress (instead of first order), which resulted in stress values that were less than 1% of the previous results. Because the time required to complete a run using second-order elements was more than double that required for the first-order elements, it was decided to use only first-order elements in the model.

Effects of Modeling Assumptions

The installation pressure applied to the rivet heads resulted in a hole diameter increase in the skins of approximately 0.5%. This interference fit generated a compressive stress under the countersink, which decreased the maximum tensile stress in the vicinity of the rivet holes.

Merging the nodes under the rivet heads resulted in lower stress values compared to those values obtained from a situation in which only the rivets transferred the load (worst-case scenario). This case represents a load path that is partly through the faying surfaces and partly through the rivets, which would be the situation given the high prestress caused by the riveting process.

Corrosion is known to be a random phenomenon that affects different areas of a lap joint at different rates. C-scan eddy current inspections of lap joints obtained from retired aircraft show that the material loss varies considerably within a joint as shown in Fig. 3. Therefore, the constant material loss assumed for the corrosion model results in higher stress values than might normally occur in service. These higher stress values can be considered an upper-bound limit of the effect of pillowing on a joint.

In a previous study, the out-of-plane displacements obtained from corrosion models alone (that is, no rivet prestress or hoop stress was applied) were used in a ray tracing routine to obtain simulated D Sight images.[6] Because D Sight images are a measure of the severity of the curvature caused by the corrosion products, comparing these simulated images to images obtained from naturally corroded lap joints would be a good indication of the accuracy of the finite element models. Such a comparison was made and the images compared very well.[6] The naturally corroded lap joints were also inspected by using shadow moiré techniques to estimate the out-of-plane displacements caused by pillowing, which compared fairly well with the displacements obtained from the finite element results.

Stress Analysis

To determine the resultant stress that would occur from a combination of the three load cases, the nodal displacements obtained from each case were added together and the analysis was rerun.

To determine the effect that skin thickness loss has on the stress in a joint, four conditions were studied: 1) no corrosion, 2) corrosion simulated by decreasing skin thickness, 3) corrosion simulated by pillowing, and 4) corrosion simulated by pillowing with effective skin thickness reduction. A 10% material loss was assumed to be present in all the corrosion models. For the effective thickness loss models, only the outer skin thickness was reduced. The resulting maximum principal stress is shown in Fig. 4 for the upper rivet row (which is known to be the critical row in terms of cracking) and at the location where the maximum pillowing deflection occurs. As shown in this figure, pillowing has a greater influence on the stress throughout the joint compared to the effective thickness loss alone.

On the basis of the thickness reduction study, a number of models were generated to simulate pillowing representing material loss between 0 and 10% with and without the outer skin reduced in thickness. Stress plots of the maximum principal stress for material

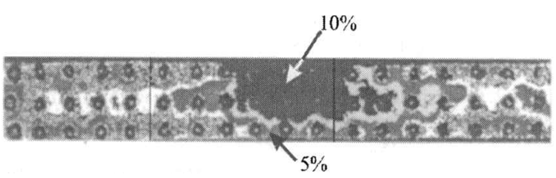


Fig. 3 C-scan eddy current image of a corroded lap joint. Note the variation in percentage thickness loss throughout the joint.

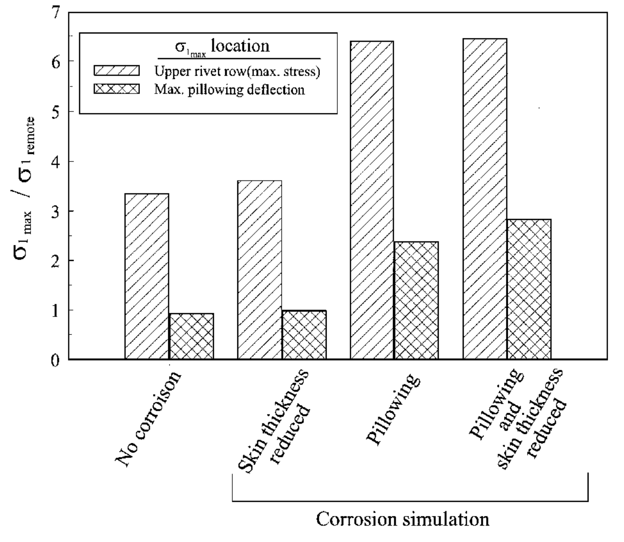


Fig. 4 Effect on stress in certain locations caused by reduction of outer skin thickness compared to pillowing (10% thickness loss).

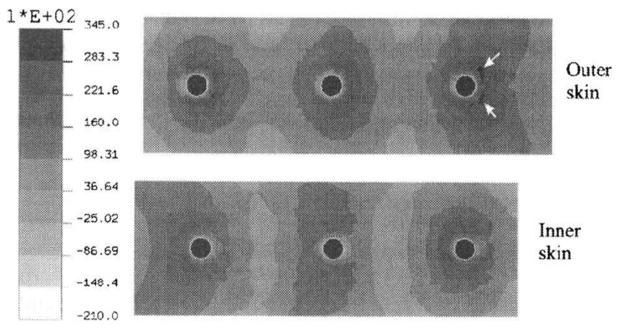


Fig. 5 Stress plot of maximum principal stress σ_1 (psi) for fuselage lap joint containing 2.5% material loss.

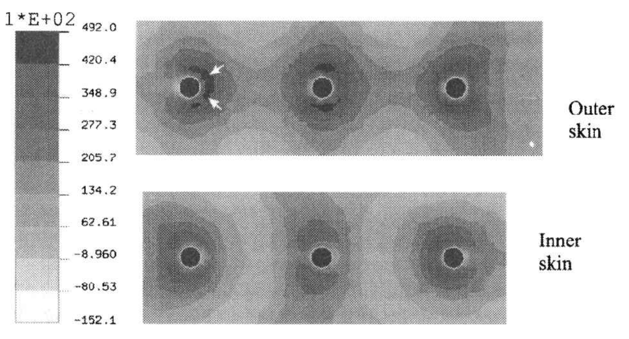


Fig. 6 Stress plot of maximum principal stress σ_1 (psi) for fuselage lap joint containing 7% material loss.

losses of 2.5 and 7% are shown in Figs. 5 and 6, respectively. These figures indicate that the location of the maximum stress changes as the material loss increases. The maximum principal stress is located at the upper rivet row until approximately 5% material loss. Below 4%, the maximum stress at this row occurs along a line approximately 45 deg to the loading direction. However, as the pillowing increases because of a higher material loss, the maximum stress along this rivet row shifts to a line approximately 90 deg to the loading direction as shown in Fig. 7. For material loss greater than 5%, the maximum stress is located at the lower rivet row along a line approximately 45 deg to the loading direction. The maximum stress in all cases occurred along the inside surface of the outer skin. As the pillowing increases above 10% material loss, cracking may shift to another row in some joint configurations; however, in most cases the upper rivet row remains the critical row.

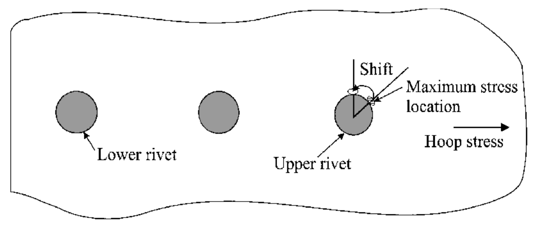
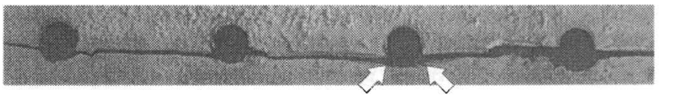
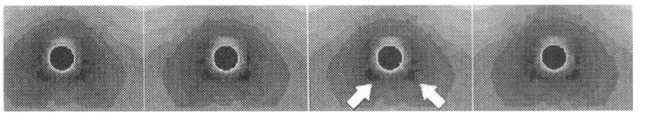


Fig. 7 Shift in maximum stress location at upper rivet row due to increase in corrosion pillowing increases.



a) Crack located along upper rivet row in precorroded specimen. Arrows indicate crack initiation sites



b) Maximum principal stress location obtained from finite element analysis

Fig. 8 Comparison of crack initiation sites in multisite damage specimens and maximum principal stress locations.

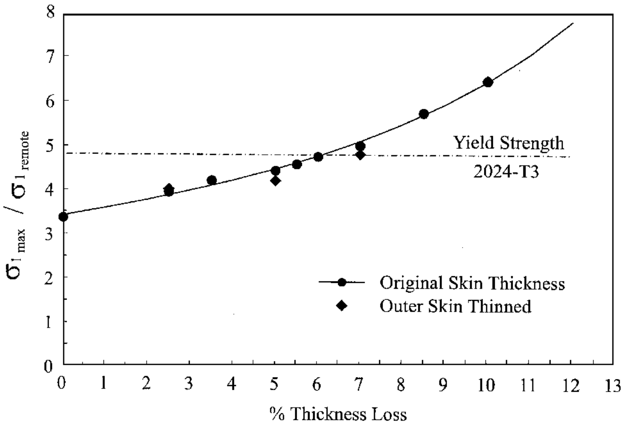


Fig. 9 Effect of increased corrosion pillowing on the stress in the vicinity of the upper rivet row.

In an independent study,[7] constant amplitude loading tests were carried out on three multisite damage specimens, which were precorroded in an accelerated corrosion chamber. The specimens were subjected to constant amplitude loading until failure and all developed cracks in the upper rivet row. An examination of these specimens indicated that cracks initiated in the area predicted by the finite element analysis as shown in Fig. 8.

Plots of the maximum principal stress at each rivet row in the outer skin, nondimensionalized with respect to the remote principal stress, are shown in Figs. 9–11 for both the original and the reduced thickness cases. The horizontal lines represent the yield stress for the material studied (Al 2024-T3), nondimensionalized with respect to the remote principal stress. As shown in these figures, the maximum stress increases as the percentage of material loss increases. Decreasing the outer skin thickness by the effective material loss did not appear to have a significant effect on the stress in the critical rivet row; however, significant change did occur in the middle and lower rivet rows. The stress in the inner skin, on the other hand, did not increase as rapidly as in the outer skin, as shown in Fig. 12. This difference was due to the presence of the stringer, which is located along the middle rivet row.

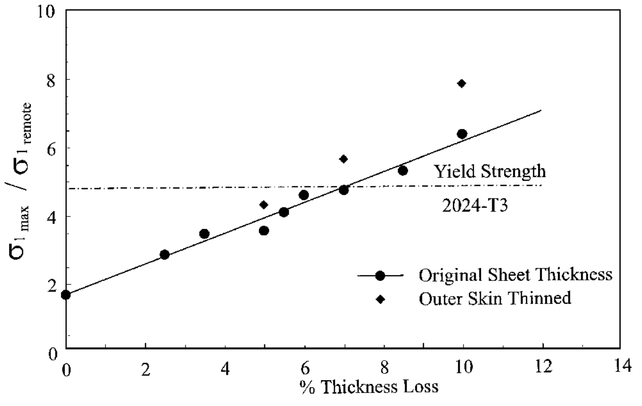


Fig. 10 Effect of increased corrosion pillowing on the stress in the vicinity of the middle rivet row.

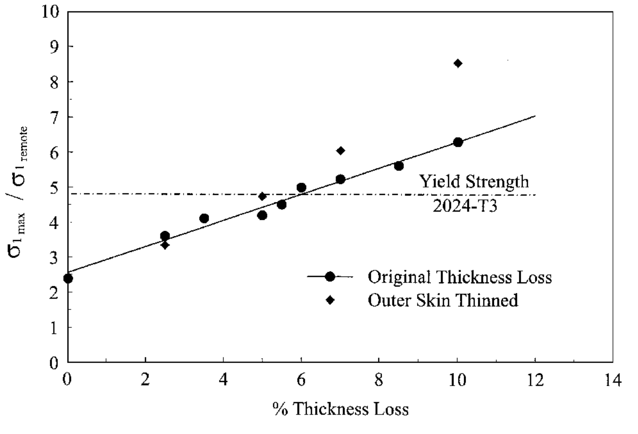


Fig. 11 Effect of increased corrosion pillowing on the stress in the vicinity of the lower rivet row.

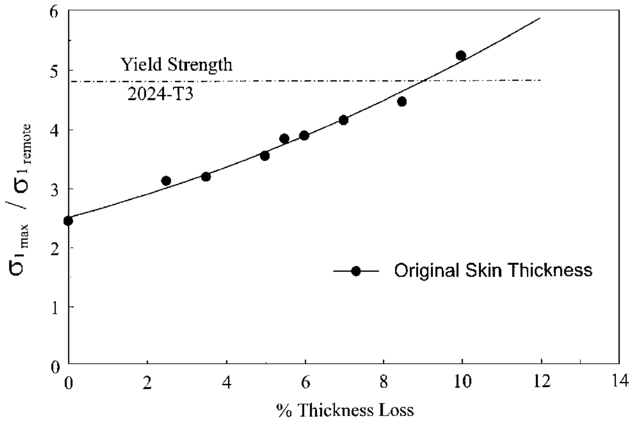


Fig. 12 Effect of increased corrosion pillowing on the stress at the lower rivet hole in the inner skin.

Tear-down inspections of corroded lap joints being carried out in parallel with this study indicate that pillowing results in permanent skin deformation, providing support for the high stress levels shown in Figs. 9–11.

Present maintenance practices indicate that 10% material loss is generally the maximum amount of lap joint corrosion allowed in a single skin before repairs must be made.[8] Generally, if corrosion is suspected from close visual inspections, single-frequency eddy current techniques are used to estimate the percentage material loss in the outer skin. If this value is less than 10%, then it has been proposed that dual frequency eddy current techniques, which are capable of detecting second layer corrosion, be used to estimate the loss in the inner skin.[8] If neither of the skins has greater than 10% material loss, the aircraft may be returned to service but reinspected after a specified period of time. Given the results obtained from this study, the pillowing caused by a 10% material loss within the entire joint (i.e., both skins) could significantly increase the mean stress in the joint, thus increasing the risk of premature cracking. Also, even if corrosion affects only the inner skin, the resultant pillowing of the outer skin caused by the presence of corrosion products will still increase the stress, causing premature cracking in the first layer.

Conclusions

The results can be summarized as follows.

1) The stress in a fuselage lap joint increases as the pillowing caused by the corrosion by-products increases.

2) Simulating the effect of corrosion on a fuselage lap joint by reducing the skin thickness and increasing the crack growth rates only could result in nonconservative life estimates if pillowing is ignored.

3) Pillowing can change the location of the maximum principal stress. However, in most cases the critical row in terms of cracking will remain the upper rivet row.

4) Pillowing can significantly increase the stress in a lap joint for a material loss below the maximum allowable (i.e., 10% loss per skin), thus increasing the risk of premature cracking.

5) If new, more sensitive nondestructive inspection methods, such as D Sight, capable of detecting small amounts of corrosion were to be deployed, aggressive corrosion prevention methods and revised maintenance procedures could be implemented.

Acknowledgments

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