Chapter 14 – MODELING CORROSION STRUCTURAL IMPACT: PILLOWING

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14.1 INTRODUCTION

Since actual lap joints contain free edges and stiffeners, which cannot be modeled using the closed-form solution, finite element techniques have been developed to model an actual aircraft lap joint. This model included the effects of the hoop stress from the pressurization of the fuselage, the rivet pre-stress 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. Since it was assumed that a linear relationship existed between the different loads, three finite element models were generated for each load and the resultant stresses were added together.

14.2 MODEL DEVELOPMENT

All the finite element models were generated with first-order brick elements. 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. Since lap joints contain stiffeners, the joints were not symmetrical about their mid-planes and thus both skins had to be modeled. Initially, a constant pressure of 6.89 kPa (1 psi) was applied to both the outer and inner skins of the joint. The resulting volume under the deformed shape, V_{fem}, was determined using an iterated integral:

$$V_{fem} = \int_c^d \left(\int_a^b f(x,y)\,dx \right) dy \tag{1}$$

where (a, b) and (c, d) 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. In computing the iterated integrals, y was held constant while integrating with respect to x (vice-versa in the second case). Simpson's 1/3 and 3/8 rule [1] were used depending on the number of nodes to be evaluated. Then, assuming a thickness loss, t_{lo}, given a specific percentage of corrosion, the actual volume required by the corrosion products, V_{req} can be determined using Equation 2:

$$V_{req} = abt_{lo}\left[\frac{V_{mr}}{2} - 1\right] \tag{2}$$

To obtain this volume, the pressure between the rivets in the initial finite element analysis was multiplied by the ratio, P_{req}, given in Equation 3:

$$P_{req} = \frac{V_{req}}{V_{fem}} \tag{3}$$

Since the free edges of a lap joint are usually sealed (either by paint or a sealant) to prevent moisture from entering the joint, the volume of corrosion products is less than that present around the rivet. Therefore, the pressure is decreased from the rivets to the free edge to simulate this reduction in corrosion products [2].

14.3 RESULTS

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 skins in a typical two layer aircraft joint, increases as the pillowing increased, as shown in Figure 14-1.

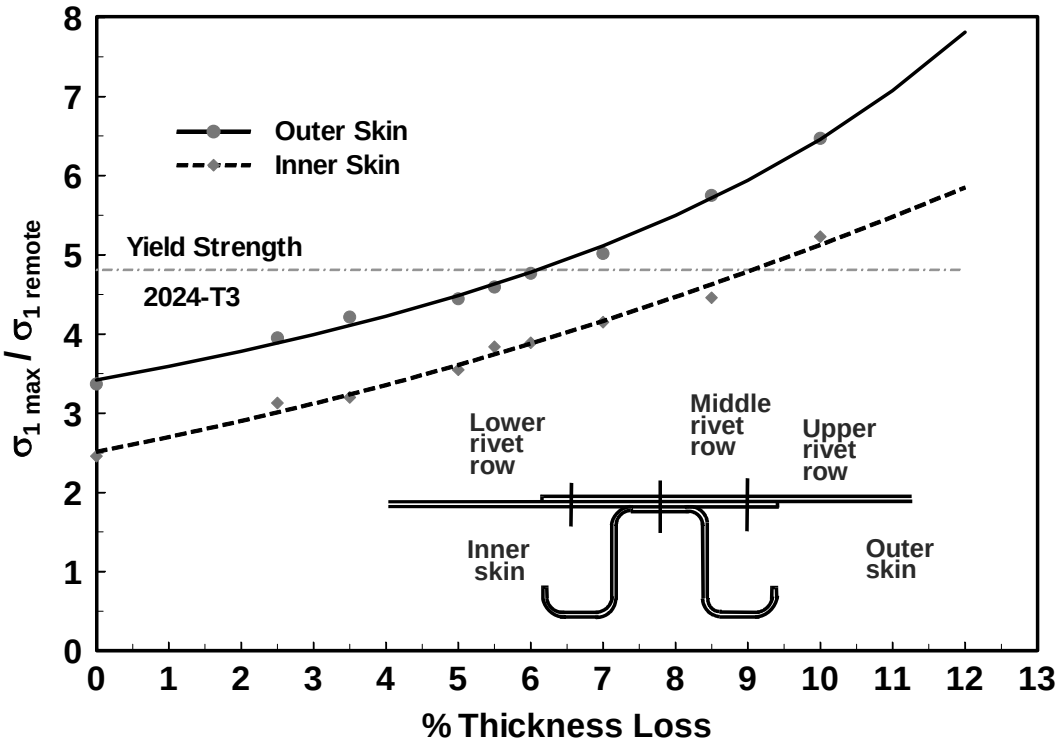


Figure 14-1: Effect of Increased Corrosion Pillowing on Critical Rivet Row of Respective Skins [1].

A comparison was also made between the increase in stress caused by an equivalent thinning of the outer skin and that caused by pillowing, Figure 14-2. The results showed that pillowing had a greater influence on the stress in a joint as compared to the effective thickness loss alone. This larger influence is a significant finding, since 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 adequately taken into account. However, this simple assumption can result in non-conservative 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 [2]. This finding has raised concerns since 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.

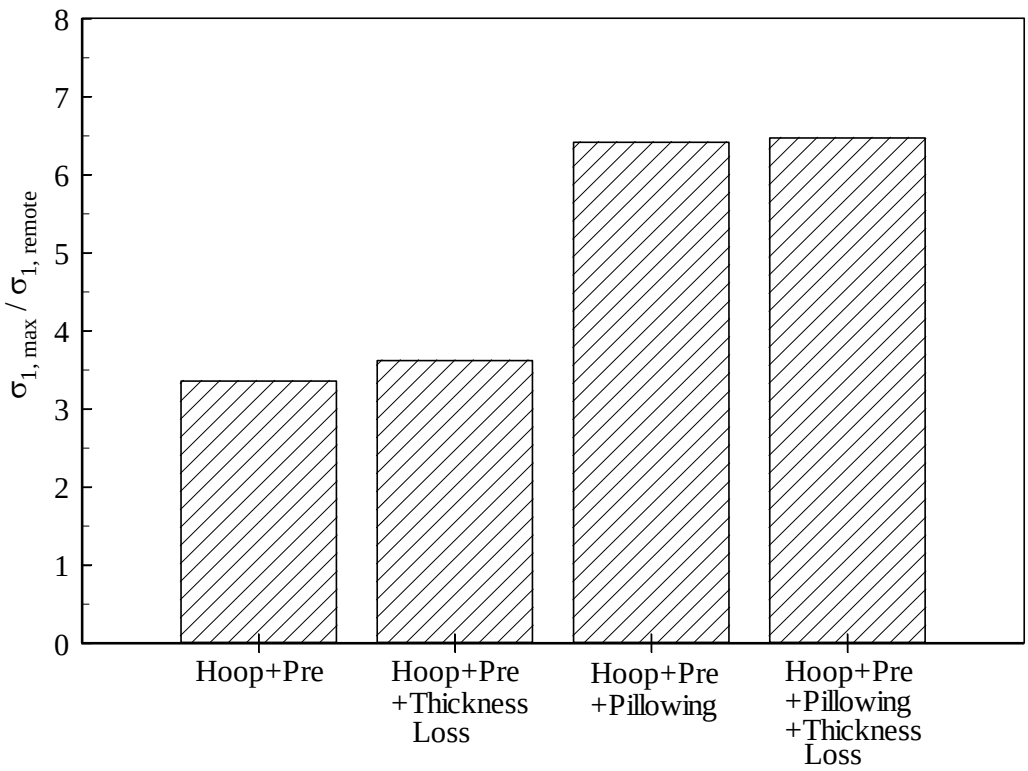
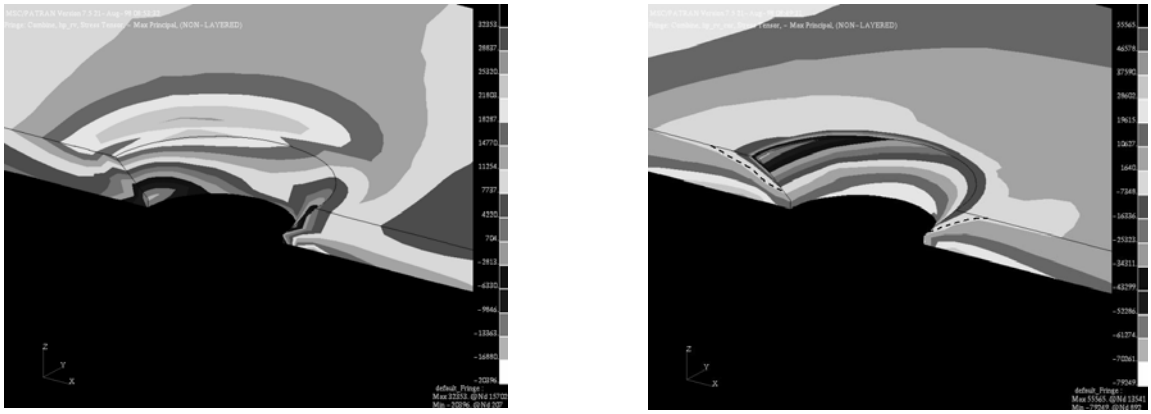


Figure 14-2: Effect on Stress Caused by Reduction of Outer Skin Thickness as Compared to Pillowing (10% Thickness Loss) [2].

The finite element results also 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%, Figure 14-3 [3]. This smaller stress along the outer surface raised concerns about the nucleation and growth of cracks in the presence of corrosion pillowing.



(a) Non-corroded lap joint, includes hoop stress and rivet interference.

(b) Corroded lap joint showing approximate location of neutral axis (dashed line) for 10% thickness loss. Loading includes hoop stress, rivet interferences and corrosion pillowing.

Figure 14-3: Stress Plot for Non-Corroded and Corroded Lap Joints.

To examine this effect, a fracture mechanics analysis was carried out using finite element techniques [4]. 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 thickness loss increased, Figure 14-4. 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 while that at 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 Figure 14-5.

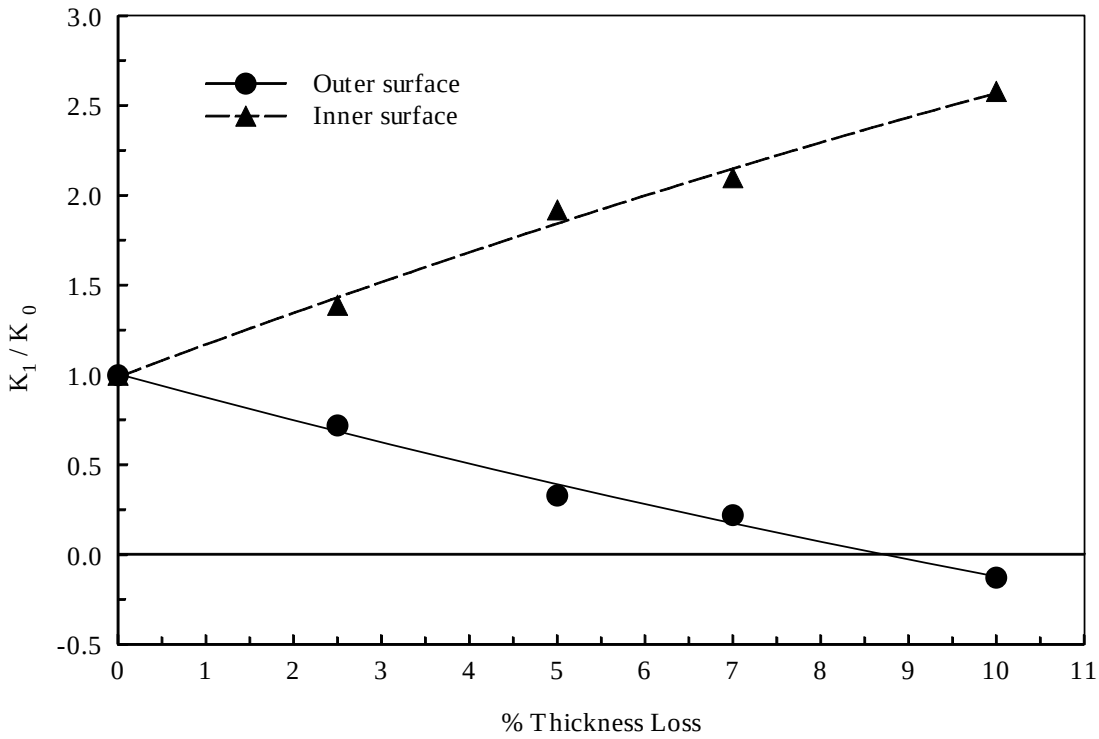


Figure 14-4: Non-Dimensional Stress Intensity Plot of Outer Surface, z = 0.00 and Inner (Faying) Surface, 1.14 mm (0.045 inch) of Outer Skin for Single Crack Length of, 3.84 mm (0.151 inch), where K_0 is the Stress Intensity Factor of a Through Crack Without Corrosion ($K_0 = \sigma\sqrt{\pi a}$) [4].

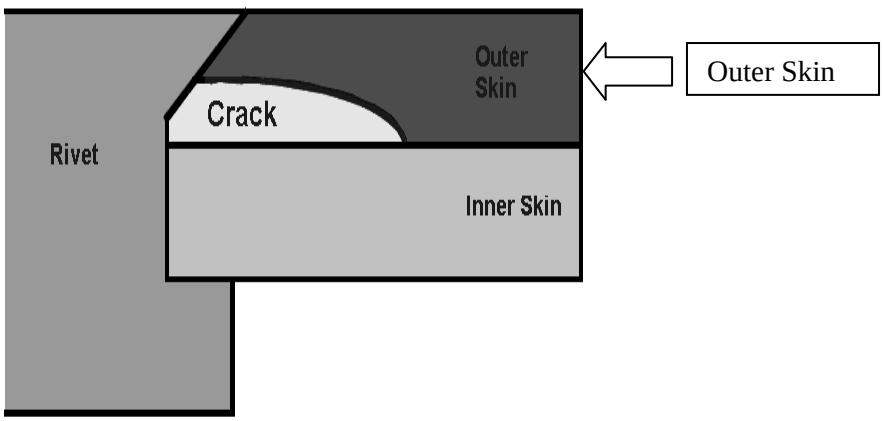


Figure 14-5: Suggested Shape of Cracks in the Presence of Pillowing [4].

14.4 REFERENCES

[1] Gerald, C.F. and Whearley, P.O., “Applied Numerical Analysis”, 3rd Ed., Addison-Wesley Publishing Company, 1985.

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

[3] Bellinger, N.C., Komorowski, J.P. and Gould, R.W., “Corrosion Pillowing Cracks in Fuselage Lap Joints”, Proceedings of the Second Joint NASA/FAA/DoD Conference on Aging Aircraft, NASA/CP-1999-208982/Part 2, Williamsburg, VA, USA, pp. 535-544, 31 August – 3 September 1998.

[4] Bellinger, N.C., Komorowski, J.P. and Gould, R.W., “Damage Tolerance Implications of Corrosion Pillowing on Fuselage Lap Joints”, Journal of Aircraft, Vol. 35, No. 3, pp. 487-491, May – June 1998.