ANALYTICAL FRAMEWORK FOR ASSESSMENT OF CORROSION AND FATIGUE IN FUSELAGE LAP JOINT

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ABSTRACT

This paper discusses the development and demonstration of the Corrosion Damage Assessment Framework (CDAF). Two specific concerns that could affect safety limits for aging aircraft are the effects of corrosion damage and widespread fatigue damage (WFD) on structural integrity. This project evaluated the capabilities of several advanced analysis tools for assessing these effects on the structural integrity of riveted lap joints. In constructing the framework, Boeing evaluated existing structural analysis tools capable of performing stress analysis, fatigue crack propagation analysis, and structural failure risk assessment. To validate the tools, analyses were conducted on and compared to experimental test data from a previous research effort. This paper summarizes the tools and procedures used in the analytical framework and the analysis results of the experimental test.

Under the CDAF project, the advanced structural analysis tools that were evaluated included:

- Finite-element code, FRANC2D/L for determining stress distributions and stress intensity factors of cracks,
- Crack growth analysis code, AFGROW, for estimating fatigue crack growth life, and
- Risk analysis code, PROF, for determining the probability of fracture,

The framework outlines the approaches used to provide the input data for each analytical tool, the procedures required to accomplish the analyses, and the processes to transfer data between the various analytical tools.

These existing structural analysis tools were evaluated for their capabilities to address crevice corrosion and multiple site damage (MSD) associated with WFD in fuselage lap joints. To validate the analysis tools, one of the case studies performed compared analysis results to experimental test data on lap joint coupon specimens with and without corrosion. The evaluations investigated the tools' capabilities to account for two primary effects of crevice corrosion - material thinning and corrosion pillowing- and for two primary effects of WFD – MSD cracks and small cracks (cracks less than 0.05-in). The tools demonstrated the capabilities to perform stress analysis, crack growth analysis, and risk analysis on thin structural components with multiple layers of material and multiple cracks. Analysis results showed good agreement between predicted and experimental fatigue life for both the baseline and corroded configurations. Evaluations showed that analysis tools could account for material thinning and MSD cracks, but limitations in some of the tools prevented a complete evaluation that accounted for corrosion pillowing or small cracks. With further improvements in analysis tools and techniques, the analytical framework would be useful in assessing the impact of corrosion damage and MSD on the integrity of an aircraft structural component.

1. INTRODUCTION

The extended use of many aircraft results in increased maintenance and repair costs because of structural cracking and corrosion problems. In most cases, older aircraft spend longer times undergoing depot maintenance, resulting in a severe impact on readiness. Furthermore, extended aircraft service places increased importance on forecasting when the system must be replaced. The U.S. Air Force must be able to accurately determine the expected structural life and evaluate the structural integrity of aircraft systems. Two primary mechanisms that can affect the longevity and structural health of the metallic structures are corrosion and fatigue cracking, including the onset of widespread fatigue damage (WFD). Overall, improvements in the predictions and estimations of the effects of corrosion damage and WFD can help reduce costs, extend service life, and enhance aircraft readiness.

This paper discusses a portion of the development and demonstration of the Corrosion Damage Assessment Framework (CDAF). This project evaluated the capabilities of several advanced analysis tools for assessing the effects of corrosion damage and WFD on the structural life and strength of riveted lap joints. In constructing the framework, Boeing evaluated advanced structural analysis tools capable of performing stress analysis, fatigue crack propagation analysis, and structural failure risk assessment. As part of validating the tools, analyses were conducted on and compared to experimental test data on lap joint specimens from a previous research effort. This paper summarizes some of the tools and procedures used in the analytical framework and the analysis results of the experimental test.

2. ANALYTICAL FRAMEWORK

The analytical framework incorporated several existing structural analysis tools to address crevice corrosion and fatigue cracks associated with WFD in fuselage lap joints. Analyses investigated the tools' capabilities to account for two primary effects of crevice corrosion - material thinning and corrosion pillowing- and for two primary effects of WFD – cracks from multiple site damage (MSD) and small cracks (cracks less than 0.05-in). The following types of structural analysis tools were evaluated in context of this analytical framework.

a. A finite-element analysis tool, FRANC2D/L, which gage the effects of corrosion damage and MSD on structural parameters such as stress level and stress intensity factor (SIF). (Swenson and James, 1997)

b. A crack growth analysis tool, AFGROW, which estimates the crack growth life for an assumed crack geometry when various levels of corrosion damage are present. (Harter, 1998)

c. A structural failure risk assessment tool, PROF, which defines the relative risk of structural failure for assumed levels of corrosion damage. (Berens and Papp, 1995)

A brief description of each analysis tool is provided below. The overall analysis approach is discussed in detail in Cope et al (1998), which identifies the input data required by each tool, outlines the procedures required to accomplish the analyses, and identifies the data that is transferred between the various analytical tools.

2.1 Finite-Element Analysis Tool, FRANC2D/L

FRANC2D/L (FRacture ANalysis Code) is a finite element analysis program for the simulation of crack growth in two-dimensional layered structures. The strength of FRANC2D/L lies in its ability to perform the following tasks in an automated fashion: (1) calculate stress intensity factors for cracks through the thickness at multiple crack tips; (2) determine the trajectory and magnitude of crack growth under fatigue loading for each crack tip; and (3) implement crack growth at each crack through local remeshing around the crack tip. The program can represent layered structures, such as lap joints or bonded repairs, where each layer is modeled by a separate mesh. The layers can be connected in overlap regions with rivet or adhesive elements. The code is limited to considering planar geometry only. Plane stress or plane strain elements are available. In addition, a linear bending option is also available, which allows out-of-plane displacements and accounts for the off-set distances which may exist between layers. When the bending option is used, bending stresses/strains and out-of-plane displacements are automatically calculated in addition to the standard in-plane stress, strain and displacement distributions. However, since the bending option is limited to linear behavior (not accounting for geometric nonlinearity), this option could greatly overestimate the bending effects due to pillowing or load eccentricity in fuselage lap joints. Furthermore, the presence of linear bending does not significantly affect the SIF calculation in FRANC2D/L. The SIF values are calculated based on stress distributions at the element mid-plane where the stresses due to bending are zero.

2.2 Crack Growth Life Analysis Tool, AFGROW

The crack growth life analysis tool estimates crack propagation for an assumed crack geometry when defined damage conditions from corrosion and/or MSD are present. AFGROW calculates fatigue crack growth life. It has the capability to account for the effect of corrosion damage and/or MSD using the appropriate stress intensity factor (or stress level) which characterizes the physical and/or geometrical effect associated with the damage scenario. This tool was used to predict the behavior of cracks that were generally larger than 0.05 inches long in airframe alloys. Inputs include: choice of 21 crack cases - including user defined through crack and part through crack configurations, initial flaw size, choice of several materials - including user defined tabular data input, and a load schedule. Outputs include a graphical or text version of crack size vs. cycle directly viewed in the analysis code or it may be exported into Excel via a pull down menu option in AFGROW. Material da/dN vs. ΔK tabular data may also be plotted and viewed in the software to check material properties. AFGROW provides users a simple procedure to edit individual elements in the model as well.

2.3 Structural Failure Risk Assessment Tool, PROF

The structural failure risk assessment tool (PROF) is a risk analysis computer program. The acronym PROF stands for PRobability Of Fracture. PROF evaluates structural safety and life in terms of fracture probabilities of equivalent details in any airframe in a fleet. The inputs for a PROF run consist of the following: (1) table of crack size versus the number of cycles, (2) stress intensity factor versus the crack length, (3) initial crack size distribution, (4) fracture toughness, (5) Stress distribution profile, (6) constants related to the number of locations, (7) inspection intervals, (8) a probability of detection function for inspections, and (9) crack size distribution of the repaired crack sites. With these inputs, the fracture probabilities are calculated for single flights as a function of spectrum hours and for entire intervals between maintenance actions. PROF evaluates durability by calculating the expected number of cracks to be detected at each inspection cycle. This information can be used to estimate the cost effectiveness of planned maintenance scenarios. PROF can define the relative risk of structural failure when various levels of corrosion damage are postulated to exist in the structural locations of interest. This tool has the capability for analyzing the effect of different damage scenarios.

3. VALIDATION OF ANALYTICAL FRAMEWORK

The analysis methods are validated with results from experimental coupon-level tests. These test coupons contained material and geometric features representative of typical lap joint structure; however, they were not components of a full-scale fuselage structure. Specific objectives in these tests included the study of corrosion and MSD effects on fatigue crack growth. The tests consisted of lap joint specimens, both corroded and uncorroded, that were fatigue tested at the National Research Council (NRC) of Canada for crack growth. The results of these experimental coupon tests are summarized and discussed relative to the impact that corrosion damage and MSD had on fatigue life and risk of failure of the test coupons, where applicable. Analytical predictions of the test conditions are compared to the test results and summarized along with the assumptions used to make the predictions.

3.1 Corrosion and Fatigue Testing

Several fatigue tests have been completed at NRC on lap joint specimens, which included lap joint specimens with no corrosion (8 specimens) and specimens corroded prior to testing (6 specimens). Scott (1997) and Eastaugh et al. (1995) discuss in detail the testing of these lap joint specimens. Figure 1 shows the geometry and material, i.e., configuration, for a lap joint specimen. It is constructed of two 0.040 inch sheets of 2024-T3 clad aluminum with three rows of 5/32 inch 2117-T4 rivets. The test specimens were 10 inches wide with 8 fasteners in each row across the width.

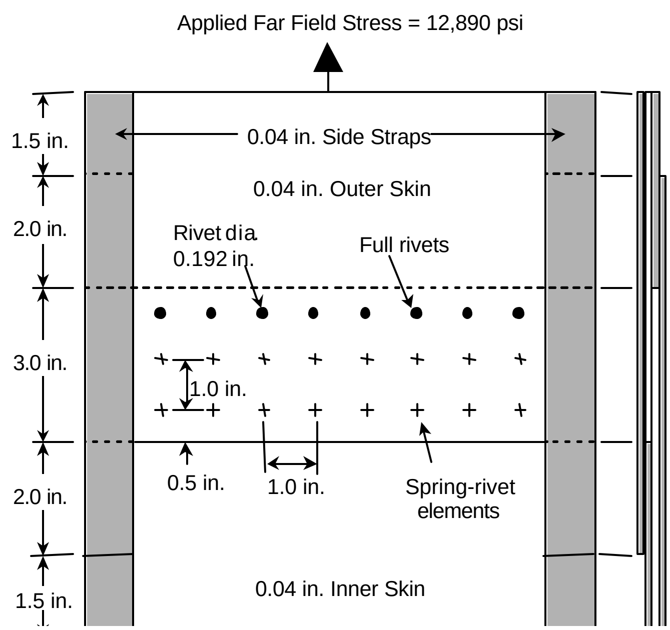


Figure 1. NRC Lap Joint Specimen Configuration.

Test data included crack growth measurements (a vs. N) during fatigue testing of both uncorroded and corroded specimens along with measurements of pillowing distortion and thickness loss on corroded specimens (Scott, 1997). Crack growth measurements of naturally occurring cracks were visually recorded when the crack had grown through the skin thickness from underneath the rivet head. The pillowing distortion is due to the buildup of corrosion byproducts in the lap joint, and the thickness loss estimated in the corroded specimens was about 2% (Scott, 1997).. In analyzing the crack growth test data, it was observed that 95% or more of the joint life was controlled by the lead crack behavior. The joint life was defined as a single crack spanning all eight rivets in the upper row of fasteners (Scott, 1997). The lead crack occurrences ranged from a single crack on one side of a rivet to double cracks of equal length on each side of a rivet. 50% of the occurrences were a single crack (Scenario 1), 10% were double cracks with equal length on each side of a rivet (Scenario 2), and the remaining 40% were double cracks with different lengths on each side of a rivet (Scenario 3). (Cope et al, 1998)

3.2 Analysis of MSD Lap Joint Specimens

The framework's analysis tools are used to model and analyze these lap joint specimens to validate the analysis approach in the framework. A stress analysis was performed to determine crack tip SIF values; a fatigue crack growth analysis was performed to predict the life of the lap joint; and risk analysis was performed to determine the probability of fracture. Analysis was only performed for the lead crack using three different scenarios, as observed in the test data. The stress analysis was performed to investigate capabilities for analyzing straight-front cracks outside the rivet head. From the stress analysis, SIF values were generated as a function of crack length. Crack growth analysis was then performed to determine the fatigue life of the lap joint (crack length versus cycles). These analyses were performed for specimens with no corrosion and specimens with 2% thickness loss, the estimated level in the corroded specimens. Results from the stress and SIF analyses along with the fatigue crack growth analyses were used in a risk analysis. For the risk analysis, crack growth analyses were also performed for scenarios that simulated 5%, 8%, and 10% thickness loss.

3.2.1 FRANC2D/L Model and Analyses

The first step in the analysis procedure was to perform a stress analysis of the lap joint. The crack was assumed to be through the thickness of the plate and have a straight front perpendicular to the plate surface. No countersink geometry was modeled, straight shank rivets and holes were used, and no plastic yielding was considered. The effect of the countersunk hole on SIF was approximated by a two-dimensional analysis of a straight shank hole, whose radius is the radius of the countersink at mid-thickness. Dawicke et al. (1992) showed that this approximation compared well (within 0.2%) with three-dimensional SIF solution of a countersunk hole with a 0.175-inch crack. Under these assumptions, the problem could be adequately modeled using two-dimensional geometry.

The FRANC2D/L model configuration was based on the geometry, materials, and loading of the experimental specimens (Figure 1). The model consisted of six-noded triangular plate elements. The inner and outer skins, modeled as discrete layers, were attached only at the rivet locations and along the side straps (which were adhesively bonded on the test specimen).

Rivets were modeled using two methods. In the first method, the rivets were modeled as circular, elastic plugs in both layers, and the plugs were attached to the surrounding structure using gap elements. The plugs were then attached from layer to layer using the adhesive element available in FRANC2D/L. This method was applied to the uppermost row of rivets as indicated in Figure 1, which was shown to be critical in the experimental test results. The second method of modeling rivets used a two-noded spring element. Each node of the element was attached to one of the two skin layers. This method was used to model each rivet in the lower two rivet rows, where the detailed stress distribution surrounding each rivet was less important.

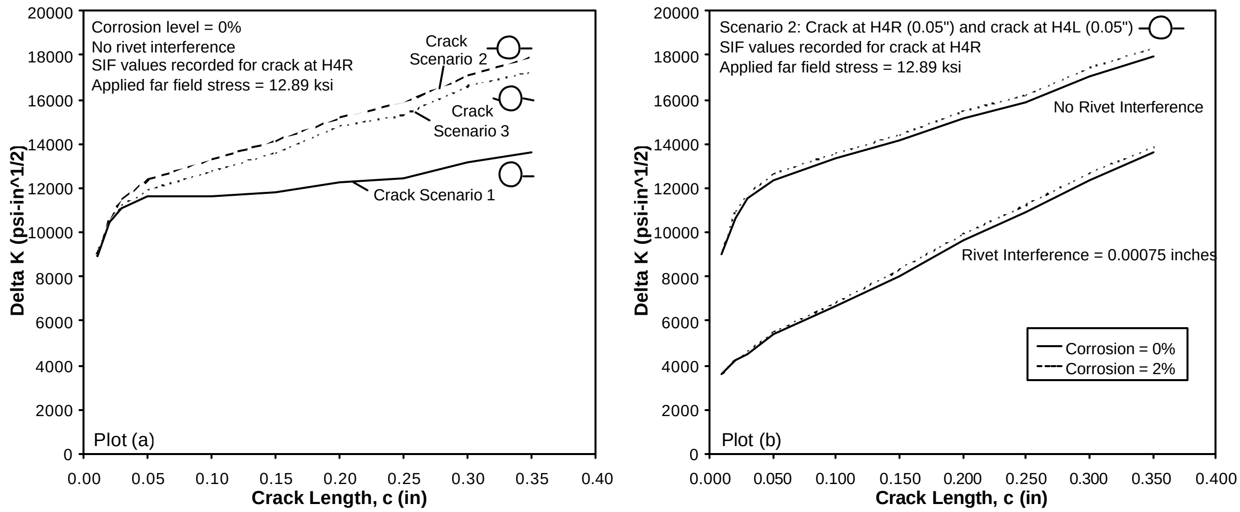
The gap elements used at the rivet/skin interface for the upper rivet row were also used to model rivet interference. The interface condition that governed the relative displacement between the rivet and skin was defined to generate nonzero stresses for a zero displacement. This technique modeled the effect of a slightly oversized rivet bearing against the rivet hole. The radial rivet interference level used in the finite element analysis was 0.00075-in (0.8% of the rivet radius), as measured in previous experimental testing (Dawicke et al, 1992).

Load eccentricity inherent to the single lap joint problem was introduced by offsetting the two skin layers. The offset produced bending in the lap joint. The bending stresses that resulted from this load eccentricity were compared with experimental strain gage data. The offset dimension was then adjusted to produce model bending stresses which generally agreed with the experimental data.

Two aspects of corrosion were considered in the FRANC2D/L analysis: material thinning and pillowing. The effect of material thinning was modeled through a uniform thickness reduction over the corroded region (faying surfaces of the lap joint). The presence of pillowing was modeled by introducing a transverse pressure acting against the faying surfaces of the lap joint in accordance with the NRC procedure for simulating pillowing (Bellinger et al, 1994).

Cracks were introduced into the outer skin in the upper rivet row according to three different scenarios. In Scenario 1, a single radial crack was located at the right hand edge of rivet hole number 4. In Scenario 2, cracks were located at both edges of rivet hole number 4. The initial crack lengths in this case were equal. In Scenario 3, cracks were once again located at both edges of rivet hole number 4. In this case, the initial crack length on the left side of the hole was one half of the initial crack length on the right side. The cracks were incrementally grown using the automated crack propagation routine. The crack tip SIFs were recorded at each propagation step.

The plots in Figure 2 summarize the results of the FRANC2D/L finite element analysis. These plots contain K-solutions for a range of crack configurations, corrosion conditions, and rivet interference levels. In each case, the K-solution is plotted for the lead crack which grows from 0.01 inches to 0.35 inches. The vertical axis in each plot contains ΔK which is given by, $\Delta K = K_{max} - K_{res}$, where K_{max} is the crack tip SIF for the lap joint under maximum hoop load and K_{res} is the crack tip SIF under no hoop load. For the cases of no rivet interference, K_{res} is zero, but for nonzero rivet interference, K_{res} is nonzero.



(a) (b)

Figure 2. FRANC2D/L SIF Predictions for (a) Different Crack Scenarios and (b) Different Interference and Corrosion Levels

Based on these results, several observations can be made regarding the effects of crack configuration, corrosion conditions, and rivet interference level on crack tip SIF. Figure 2a compares the SIF results for the three crack configurations corresponding to Scenarios 1 through 3. The plot shows a significant increase in SIF for the case of diametrically opposed cracks compared to that of a single crack, as observed in previous studies. Results for Scenarios 2 and 3 show very similar SIF values, which indicates that SIF values for the longer crack in Scenario 3 are not very sensitive to the length of the shorter crack on the opposite side of the hole. Scenario 2 provides an upper bound to SIF values in Scenario 3 if the shorter cracks were to increase in length to match the longer crack. Since Scenarios 2 and 3 yielded such close results, Scenario 3 was omitted from subsequent analyses.

Figure 2b compares K-solutions for two levels of rivet interference and two levels of corrosion. The effect of rivet interference was to increase substantially the residual SIF value under no applied hoop load (K_{res}), and to increase slightly the SIF value at maximum applied hoop load (K_{max}). The result was a large drop in ΔK over the entire range of crack growth. These results indicate how sensitive the ΔK-solution is to the level of rivet interference, which confirms similar results in previous studies (Dawicke et al, 1992).

The effect of corrosion was modeled through uniform thinning of the material in the corroded region. In this case, one would expect the average stresses in the corroded region, and therefore the SIF values, to increase by a factor of approximately t/t_{corr}, where t is the original thickness, and t_{corr} is the corroded panel thickness. The FRANC2D/L prediction yielded the expected result, as the SIF values for the 2% corrosion case were about 1.02 times higher than for the case with no corrosion. This result was consistently obtained for all analysis cases that had no interference.

For the analysis cases that included rivet interference, the effect of uniform material thinning was slightly different. For small crack lengths (less than 0.05 inches) the material thinning had a reduced impact on the SIF values, yielding an average increase of approximately 1% in ΔK. For crack lengths greater than 0.05 inches, the average increase in ΔK was back to the 2% level observed in the zero rivet interference case.

Initially, the effects of pillowing corrosion were also included in the analysis by applying a transverse pressure to the faying surfaces of the lap joint (Bellinger et al, 1994). The effect of the transverse pressure was to induce local bending stresses in the skins around each rivet, thereby producing non-uniform stresses through the thickness of the skin. However, SIF values calculated in FRANC2D/L were based on stresses at the mid-plane of each layer. The mid-plane stresses were, of course, unaffected by bending stresses, and therefore, the calculated SIF values saw no contribution from the pillowing pressure. Moreover, even if a method was used which captured the effect of bending on SIF, the resulting SIF distribution along the crack front would obviously become non-uniform. It follows that crack growth rate and crack length would also become non-uniform along the crack front. These conditions represent a complicated three-dimensional crack growth problem beyond the scope of this investigation. Therefore, pillowing corrosion effects were not considered further. In all the results presented herein, the effect of corrosion was accounted for solely through the method of thinning the material uniformly in the corroded region, a method commonly employed in previous studies to account for corrosion damage. Bellinger and Komorowski (1998) propose a nonlinear finite element analysis approach for investigating corrosion pillowing in fuselage lap joints.

The K-solutions obtained from the FRANC2D/L analysis were recorded and converted to beta factors for use in AFGROW. The conversion equation is given below:

$$\beta = \frac{K_{\max} - K_{res}}{\sigma_{ref}\sqrt{\pi c}}$$

where σ_{ref} is the reference stress set at 12.89 ksi based on experimental load level (Scott, 1997). Since $\Delta K = K_{max} - K_{res}$, variation in the load ratio, R, was implicitly accounted for by the variation of K_{res} as a function of crack length, c. K_{res} varied from about 0.6 to 0.3 as the crack length increased. The use of K_{res} rather than a residual stress is dependent on the analysis tool. Other crack growth programs may account for residual stresses differently, but they should provide the same or similar results. The resulting stress intensity factors and beta factors are tabulated in Cope et al (1998) for each crack scenario, rivet interference level, and corrosion level considered.

3.2.2 Crack Growth Analyses

Next, analysis was performed using the crack growth code AFGROW. Inputs included a constant amplitude of 12.89 ksi with an R ratio of 0.02. Since the SIF solutions used the far field stress of 12.89 ksi, this same load was used for the crack growth analysis. The material properties were for 2024–T3 clad aluminum with a da/dN lower limit of 10^{-9} inches/cycle. This lower limit was chosen as a first-order approximation of small crack effects.

To account for the different R ratios, the K_{res} was separated out of the K_{max} and K_{min} data for each crack length. The appropriate beta value was then calculated for the applied stresses and K values as discussed in Section 3.2.1. Each crack length had a corresponding beta and a K_{res} value, which was entered as a function of crack length in the residual K table (an option in AFGROW). Since the K_{res} was caused by an interference fit fastener that remains in the hole, this method only works for a constant amplitude loading scenario. The assumption is that the relationship between K_{res} and crack length is unique, which is only true for a given applied stress. A different input stress at a given crack length would result in a different K_{res}. The residual stress capability currently in AFGROW is designed to work for cases where you have pre-existing residual stresses (from machining or coldworking, etc). In general, an interference fit fastener must be handled differently - the K_{res} due to the interference fit fastener must be calculated real time as the crack grows for a variable applied stress spectrum.

The predictive analysis of cracks without interference grossly under predicted the normalized test data while the interference predictive analysis over predicted the test data, as shown in Table 1. Errors were calculated using

$$\left| \frac{\text{Predictive Results - Normalized Test Data}}{\text{Normalized Test Data}} \right| \text{ X } 100$$

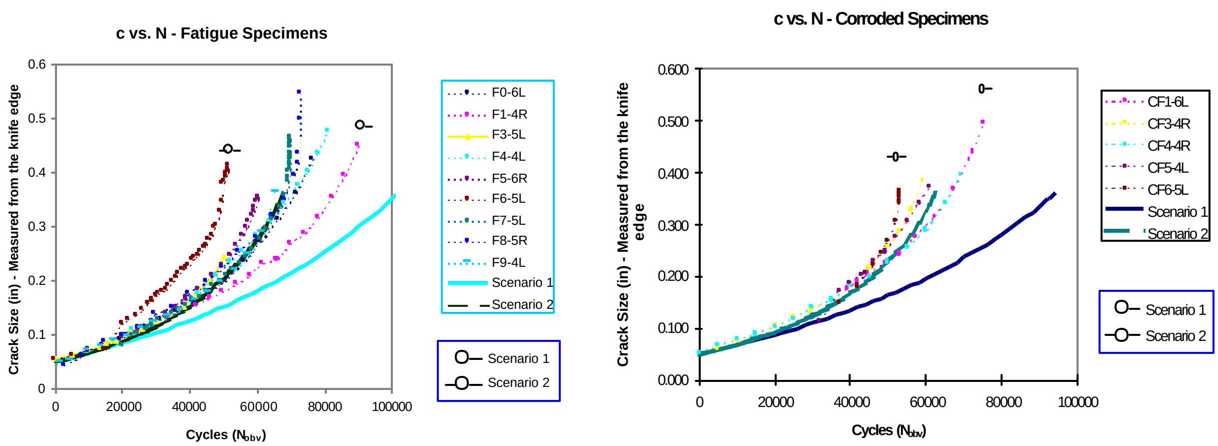
where the normalized test data used was the single case which best represented the appropriate scenario. As this is just a proof of concept analysis, the published amount of rivet interference was presumed close enough to show it had an effect on the life prediction of the crack, as shown in previous studies (Dawicke et al., 1992; Newman et al., 1997). A lengthy iterative process would be required to find a rivet interference value that would enable a closer prediction of the crack growth life.

TABLE 1. Prediction Estimation Errors.

		Specimen Crack Location	No Interference	Interference 0.00075-in
Scenario 1:	Fatigue	F1-4R	38% less	22% more

	2% Corrosion	CF4-4R	28% less	42% more
Scenario 2:	Fatigue	F6-5L	43% less	36% more
	2% Corrosion	CF3-4R	51% less	18% more

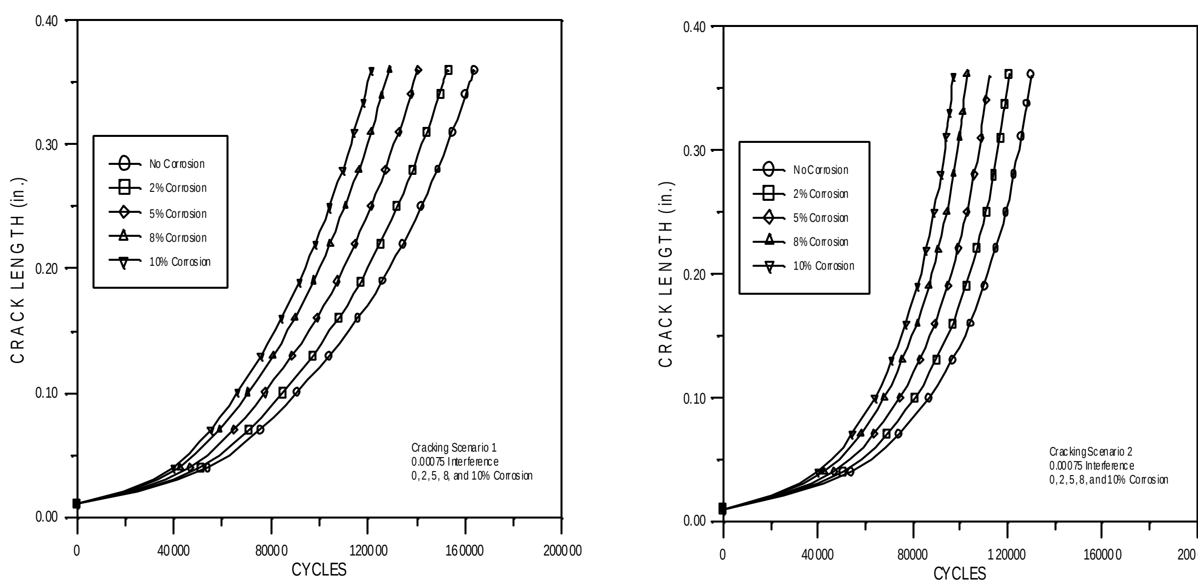
The next results (Figure 3) plot scenario 1 and scenario 2 (solid lines) with an interference of 0.00075 inches against all the fatigued and corroded normalized test data. The lead cracks' test data is identified in the figures by specimen number and crack location, i.e., F0-6L is the lead crack on the left side of rivet 6 in the fatigued specimen 0. (F = fatigue (no corrosion), CF = fatigue with prior corrosion, L = left, R = right). Comparing these two plots shows a definite loss in life when corrosion was present, as has been found in previous studies. Both the normalized test data points and the predictive analysis have a decrease in life of about 10% or more as a result of 2% thinning.



(a) (b)

Figure 3. Predicted Crack Growth for NRC Lap Joint
(a) Fatigue (No Corrosion) Specimens and (b) Corroded Specimens.

Analysis was then performed for the risk analysis using an initial short crack of 0.010 inches. Shown in Figure 4, crack growth curves were calculated for five corrosion levels (0%, 2%, 5%, 8%, and 10%) for both Scenario 1 and 2 using the 0.00075-in rivet interference. As discussed in Cope et al (1998), the risk analysis also used these analysis curves to extrapolate the first observed cracks to an estimated length at 50,000 cycles.



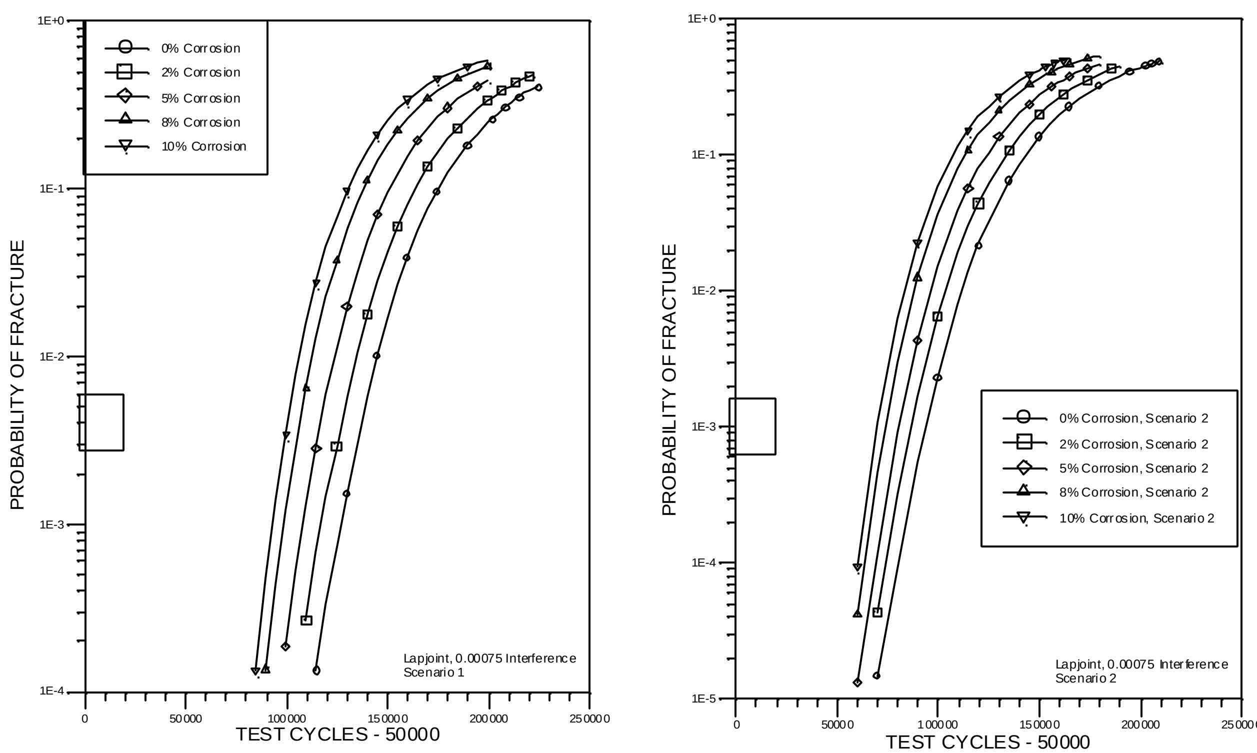
(a) (b)

Figure 4. Crack Size versus Cycles for 5 Corrosion Levels for (a) Scenario 1 and (b) Scenario 2

3.2.3 Risk Assessment

The risk assessment of the lap joints is based on the fracture probability of a randomly selected lap joint from the population being analyzed. One run of PROF produces a time history of fracture probability for an initial crack population with a fixed geometry and stress history. However, the population of lap joints to be modeled will not have a fixed geometry when the possibility of MSD is permitted. Further, the introduction of corrosive thinning will change the expected stress history and crack growth projections of a lap joint. If the distribution of these factors is known, the fracture probability can be evaluated from multiple PROF runs at conditions representative of percentiles of the distributions. The conditional fracture probabilities can then be combined or interpreted in terms of their relative frequencies of occurrence.

To perform the risk analyses that correspond to 0%, 2%, 5%, 8%, and 10% thinning, ten individual runs of PROF were required – five levels of stress (corrosion severity) for each of two MSD scenarios. Probability of fracture as a function of cycles was calculated for each of the ten combinations of cracking scenario and corrosion severity. These calculations do not account for any additional corrosive thinning after the start of the analysis. Fracture of the lap joint specimens was defined as the lead crack exceeding 0.35 in., as previously discussed. Figure 5 presents the conditional fracture probabilities for Scenarios 1 and 2. Time zero in the PROF analyses corresponds to 50,000 cycles in the test data. The fracture probabilities behave as expected - Scenario 2 increased risk of fracture over Scenario 1, and the risk of fracture increased as stress levels increased due to corrosion material loss.



(a) (b)

Figure 5. POF versus Cycles for for (a) Scenario 1 and (b) Scenario 2

4. CONCLUSIONS

This project evaluated advanced structural analysis tools for addressing the effects of corrosion damage and MSD cracks on stress distributions, stress intensity factors, fatigue life, and risk of fracture of a skin lap joint. The analysis tools included:

- Finite-element code, FRANC2D/L, for determining stress distributions and stress intensity factors of cracks,
- Crack growth analysis code, AFGROW, for estimating the fatigue crack growth life, and
- Risk analysis code, PROF, for determining the probability of fracture with a defined damage scenario.

4.1 Summary of Analysis Results

The analysis of the skin lap joint was based on the lap joint specimens tested with no corrosion and with 2% corrosion. These specimens were fatigue tested, allowing multiple cracks to form naturally in the joint. A finite element analysis was performed to determine crack tip SIF values and a fatigue crack growth analysis was performed to predict the life of the lap joint. Analysis was performed for the lead crack using three different cracking scenarios, as observed in the test data. Then, results from the finite element analysis and fatigue crack growth analysis were used in a risk analysis. Analysis of the MSD lap joint specimens showed several conclusions.

First, two-dimensional analysis was sufficient to generate results which generally followed the long crack growth test data (i.e. crack length greater than 0.05 inches) for both the baseline and corroded configurations. However, due to the fact that only 2% corrosion was exhibited, the bending stresses associated with pillowing were not as significant as corrosion levels seen in typical aircraft lap joints. Therefore, in the more extreme case of, say 10% corrosion, the bending stresses due to pillowing may be high enough to render a two-dimensional analysis inaccurate. Although analyses attempted to account for both pillowing and thinning effects in the joint, only the thinning effects of corrosion damage were successfully accounted for.

Second, the presence of rivet interference produced a significant impact on the SIF and crack growth predictions. Rivet interference could be manipulated to match the test data, but would require a time-consuming iterative process. Without rivet interference, crack growth analysis was conservative, but with rivet interference of 0.00075-in., the crack growth analysis overestimated the life. These results highlight the apparent sensitivity of fatigue crack growth rate to rivet interference.

Third, the risk assessment showed the relative impact of thinning on the probability of fracture. The lap joint fracture probability for the severity characterized by ten percent thinning can be 70 times greater than that of an uncorroded lap joint. If maintenance scheduling were based on keeping the fracture probability below 0.0001 to 0.001 when compared with an uncorroded lap joint, a lap joint with ten percent corrosion thinning would have a 25 to 50 times greater chance of resulting in fracture. Risk assessments require not only test data, but also historical corrosion data to generate meaningful results. The more data collected in the future at various corrosion levels and initial crack distributions, the more realistic the predicted results will be.

4.2 Assessment of Structural Analysis Tools

This project developed and demonstrated an analytical framework for estimating the effects of corrosion damage and WFD on structural integrity. The analytical framework incorporated a number of advanced analysis tools that, when taken together, have the capabilities to perform stress analysis, crack growth analysis, and risk analysis on thin structural components with multiple layers of material. Accounting for the thinning effect of corrosion and multiple cracks in these analyses were straight forward. However, the modeling and analysis of corrosion pillowing and small cracks demonstrated some of the limitations of the tools. With further improvements in analysis tools and techniques, the analytical framework would be useful in assessing the impact of corrosion damage and MSD on the integrity of an aircraft structural component.

Based on characterization of corrosion damage and fatigue cracking, the deterministic structural analysis tools can determine stress intensity factors and fatigue crack growth life of structural components with damage conditions from uniform material thinning due to corrosion, and multiple cracks in multi-layered structure. With defined initial quality or crack size distributions and deterministic information, the probabilistic structural analysis tool can predict the risk of failure accounting for the probability of detecting the damage condition. This capability allows the reliability of inspections to be assessed along with analysis methods to determine the probability of fracture in a structural component.

From this study, it was concluded that the finite element analyses and risk assessment analyses were labor intensive and could not easily be streamlined. Minimal automation from the output of FRANC2D/L to the input of AFGROW and from the output of AFGROW to the input of PROF could be achieved. However, it is recommended that each module be kept separate since distinct modules would allow greater flexibility for the engineers. The separate analyses also create individual checkpoints for the application of engineering judgement.

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