Chapter 17 – CORROSION FATIGUE ANALYSIS OF AN F-18 LONGERON

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17.1 INTRODUCTION

A full scale F-18 wing test (FT245) was conducted at the National Research Council (NRC) Canada under the International Follow-On Structural Test Project (IFOSTP) supported by The Canadian Forces (CF) and The Royal Australian Air Force (RAAF). During the test, a long fatigue crack of 46 mm (1.81 inch) was discovered on the right hand upper Outboard Longeron (UOL) of the centre fuselage at 2932 Simulated Flight Hours (SFH), as shown in Figure 17-1. In this test, the fuselage was used as a transition structure, and was a retired United States Navy (USN) F-18 aircraft that had been in-service for ten years (1984 – 1994), Rutledge et al. [1]. Extensive corrosion was reported on the UOL by the US Navy (USN) during its service life, which was repaired (blended out) [1]. During the full scale wing test, the crack in the component was discovered after a fairing and sealant had been removed to perform a scheduled life enhancement procedure. Corrosion pits were found in the area near the apparent crack nucleation site. Since the full scale wing test was conducted in an environmentally controlled facility, it was reasonable to assume that these pits formed in-service and went undetected after the last maintenance cycle prior to the aircraft being retired. This cracking case was used to demonstrate and validate the applicability of a Holistic Structural Integrity Process (HOLSIP) based corrosion fatigue analysis methodology and tool.

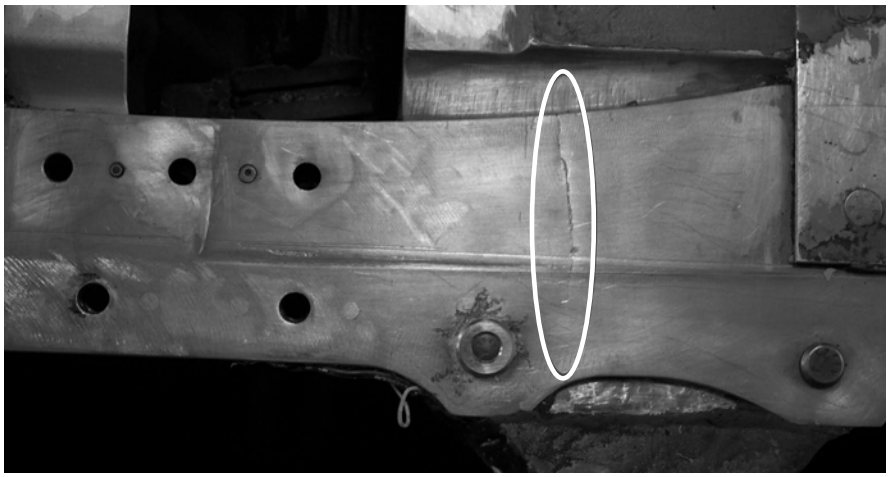

Figure 17-1: Fatigue Crack on the Right UOL of F18 Central Fuselage.

17.2 CORROSION FATIGUE MODELING FUNDAMENTALS

In HOLSIP, corrosion and fatigue can act not only *concurrently* but also *independently*. These effects are characterized by changes to the crack tip stress intensity. Based on the HOLSIP concept, a computer code ECLIPSE – Environmental and Cyclic Life Interaction Predictions for in-Service Evaluations has been developed by Analytical Process / Engineered Solutions (APES) Inc., Brooks et al. [2]-[3]. ECLIPSE uses fracture mechanics principles to formulate stress intensity factor solutions as follows, Brooks et al. [3]:

$$\Delta K_{cyclic} = \beta_T \Delta\sigma_{cyclic} \sqrt{\pi a/Q}\, \Psi(a,t,Env) \tag{1}$$

$$\Delta K_{time} = \beta_T \Delta E_{time} \sqrt{\pi a/Q}\, \Psi(a,t,Env) \tag{2}$$

where ΔK_{cyclic} and ΔK_{time} are driven by cyclic and time dependent mechanisms, respectively; β_T is the total geometry correction which is a function of geometry and crack length; $\Delta\sigma_{cyclic}$ represents the cyclic stress, and ΔE_{time} represents the environmental cyclic stress (environment spectrum) that is a function of time, sustained stress, environmental exposure, hydration cycles or potentially electro-chemical processes; Q is the crack shape parameter that is also a significant metric to accurately account for the aspect ratio of crack depth and width. Ψ (a,t,Env) is the total correction, which is a function of crack length, time, and environment. This parameter represents the effects of corrosion or corrosion fatigue interaction on ΔK, such as corrosion related thickness loss, local geometric stress risers, topography change, corrosion induced sustained stress, and corrosion pillowing stress, etc. Therefore, $\Psi(a,t,Env)$ has different expressions for different corrosion mechanisms.

The total crack growth is determined through the summation of the cyclic damage and other time dependent damage, which is used to grow an Initial Discontinuity State (IDS, treated as a crack in any fracture mechanics model) to final instability. Incremental growth rates from both the operational stress cycles and the age degradation effects are used to determine a combined incremental growth. Therefore the total crack length is expressed as:

$$a_{Total} = a_{IDS} + \sum \Delta a \text{ and } \Delta a = \Delta a_{cyclic} + \Delta a_{time} \tag{3}$$

where a_{IDS} is the material, geometric or manufactured IDS that is simulated as an active crack in HOLSIP, and:

$$\Delta a_{cyclic} = \left(\frac{da}{dN}\right)_{cyclic} dN = f(\Delta K_{cyclic})dN \text{ and } \Delta a_{time} = \left(\frac{da}{dt}\right)_{time} dt = g(\Delta K_{time})dt \tag{4}$$

Note that Δa_{cyclic} is expressed in the cyclic domain while Δa_{time} is in the time domain. Since a relationship exists between cyclic and time domains for each increment of crack growth, the summation in Equation (3) could be performed on either cyclic or time domains. For the cyclic domain, Equation (3) can be solved using the following equation, Brooks et al. [3]:

$$\begin{aligned} a_{Total} &= a_{IDS} + \int \left(\frac{da}{dN}\right)_{cyclic} dN + \int\int \left(\frac{da}{dt}\right)_{time} dt\,dN \\ &= a_{IDS} + \int f(\Delta K_{cyclic})dN + \int\int g(\Delta K_{time})dt\,dN \end{aligned} \tag{5}$$

In ECLIPSE, age degradation is applied at each integration interval and the relationship between cyclic and time domains has to be specified to determine the cycles per integration interval. The corrosion fatigue analysis procedure of ECLIPSE is schematically presented in Figure 17-2. The USAF program, AFGROW, is linked to ECLIPSE as a crack growth analyzer. For each integration interval, β_T and $\Psi(a,t,Env)$ are determined and updated in ECLIPSE, and then the appropriate time-dependent ΔE_{time} parameters (stress, beta corrections, etc.) are passed to AFGROW to calculate the crack growth for the next integration interval. The input parameters required by ECLIPSE are also shown in Figure 17-2.

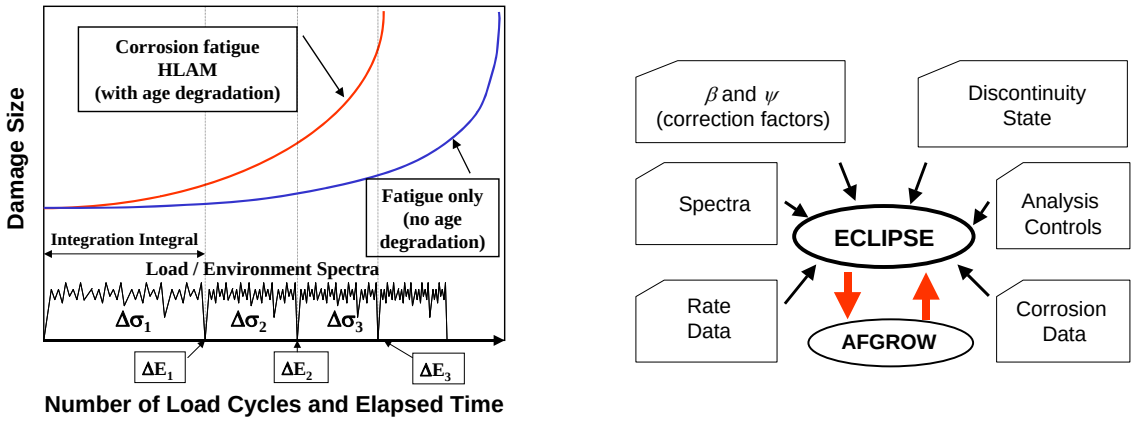

Figure 17-2: Corrosion Fatigue Analysis Procedure in HOLSIP/ECLIPSE [2]-[3].

17.3 INPUTS FOR CORROSION FATIGUE ANALYSIS

The input parameters for ECLIPSE were prepared based on the data and assumptions as follows.

17.3.1 Cracking Scenario

A replica was taken to verify that the crack nucleated from corrosion pits (see the dotted line in Figure 17-3) that were present at the round corner. A corner crack model was thus added to ECLIPSE in order to simulate this cracking scenario. The combined length of the pits along the thickness direction was approximately 0.63 mm (0.0248 inch), and the pit depth (shortest dimension), which occurred in the width direction was approximately 0.44 mm (0.0172 inch).

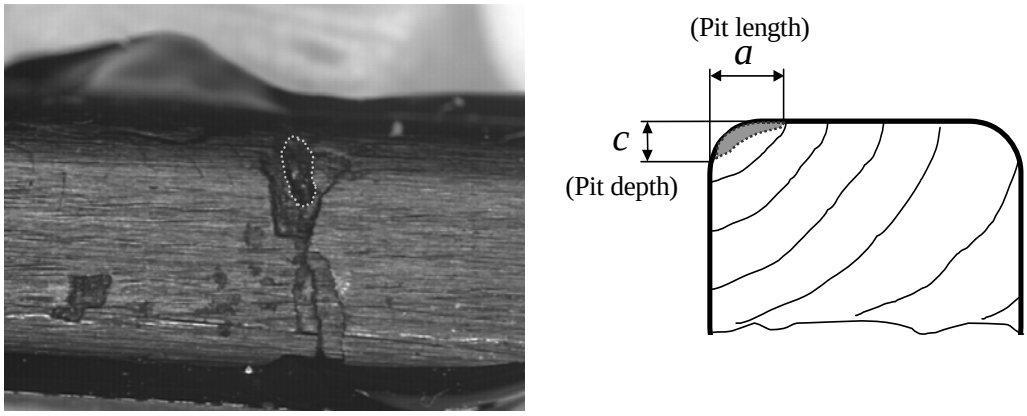

Figure 17-3: Corrosion Pits and Cracking Scenario.

17.3.2 Material Models (da/dN and IDS Crack)

The UOL material was 7149-T73511 aluminum extrusion (L-T). Ideally, HOLSIP would require physical measurements and a metallurigcal study to determine the IDS distribution presented in the alloy. However, due to the unavailability of pristine material, it was decided to use the existing fatigue life data to estimate the IDS value, i.e., initial crack size, of this alloy. Crack growth data from the full scale CF-18 fuselage test (FT55) conducted at Bombardier Aerospace were used to estimate the initial crack size, in which a

fatigue crack nucleated at the same location of the UOL but in that case, no corrosion was present. The crack growth data from the FT55 test are presented in Figure 17-7. Revised Crack Growth Rate (CGR) data for this alloy, which were originally taken from the NASGRO material database and modified by APES to include the small crack growth regime using the method developed by Brooks et al. [4], was employed to estimate the IDS value. The *geometry* for the initial crack on the corner of the UOL was assumed to have a quarter circle shape.

To determine the loading spectrum, the readings from one strain gauge, which was placed on the UOL in the full scale fuselage test (FT55) and very close to the crack nucleation site, was used. One block of this spectrum contained 8,369 cycles, which represented 326 SFH. The analytical results, labeled as HOLSIP (non-corroded) are presented in Figure 17-7, which indicates that, if an initial crack size of 0.18 mm (0.0071 inches) was used, the non-corroded analytical results are very close to the test (FT55). This initial crack size was then employed for the following corrosion fatigue analysis.

17.3.3 Corrosion Growth Rate and Topography ID

The corrosion pits were assumed to have developed under service environments and cyclic loading during the ten years of service in the USN. It has been shown that a cube root power law can effectively describe the corrosion pit growth in aluminum alloys, Godard [5] and Hoeppner [6]. Also, Harlow and Wei [7], and Turnbull [8] demonstrated that this power law could be derived based on pit growth kinetics and Faraday's law. Thus, the cube root power law was used in this work to describe the corrosion pit growth rates:

$$d = C(T)^{1/3} \tag{6}$$

where d is the maximum pit depth, T is the time, and C is a parameter related to the material/ environment combination. Based on the pit depth and time information given previously, the corrosion pit growth curve was estimated (Figure 17-4). It has been demonstrated that the topography, i.e., surface roughness of a corroded surface, has an effect on the local stress states around a pit/crack, Brooks, et al. [2]. The effect was quantified using the StressCheck finite element model and converted to stress intensity factor beta factors library. The software ECLIPSE used what is termed the 'Topography ID' to represent different beta factors. The topography IDs are in increasing order of severity from 0 (0.0 mm pit in depth or no topography correction) to 9 (1.0 mm (0.040 inch) pit in depth). From the corrosion pit growth curve (Figure 17-4), the pit depth for every year was obtained, then the corresponding ID for this pit depth at this year was interpolated using the pre-defined IDs in ECLIPSE. The resulting topography ID used in ECLIPSE is shown in Figure 17-5.

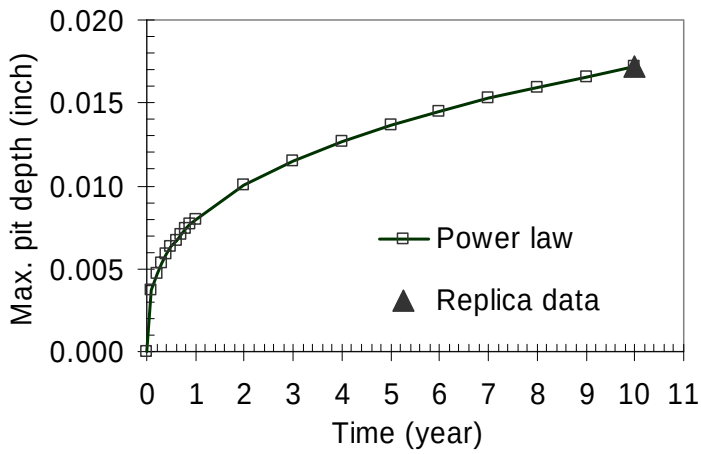

Figure 17-4: Corrosion Pit Growth Rate.

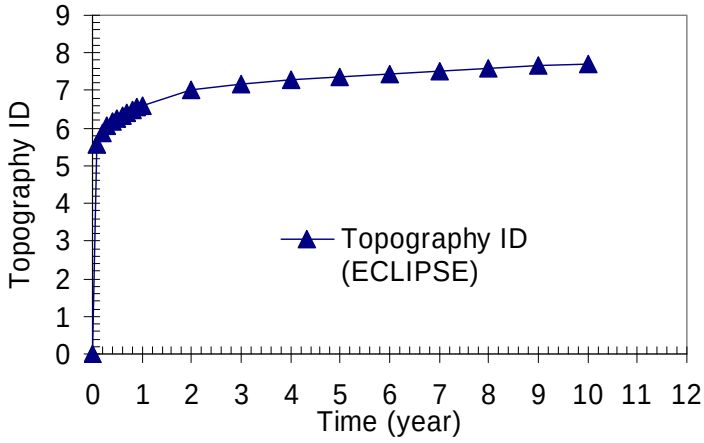

Figure 17-5: Topography ID Used in ECLIPSE.

17.3.4 Thickness Loss

The thickness loss effect is included in ECLIPSE through the time related correction, Ψ (*a*,*t*,*Env*). Although the UOL surface had been blended out to remove damage (surface corrosion) during its service life, no blending marks were found along the crack path. It was thus decided that no thickness loss would be taken into account in the corrosion fatigue analysis. To accurately measure the thickness of the present UOL along the crack path, an ultrasonic technique was employed. The average thickness along the crack path was determined to be 3.12 mm (0.123 inch).

17.3.5 Loading Spectrum

During the NRC full scale test, two aluminum alloy (7075-T6) straps were used to repair the cracked UOL and the test resumed. The readings from two strain gauges, placed on the two straps, were then processed to determine the loading spectrum. A two step process was used:

1) The nominal stress level was first determined based on the total loads that by-passed the UOL, which can be calculated by assuming that the UOL was completely broken; and

2) The stress level at the fillet where the pits and crack nucleated was determined by applying a combined (tension and bending) stress concentration factor of 1.35 determined by Bombardier Aerospace during the repair disposition process.

Figure 17-6 illustrates one block of the loading spectrum, which includes 46,588 cycles that represent 326 SFH.

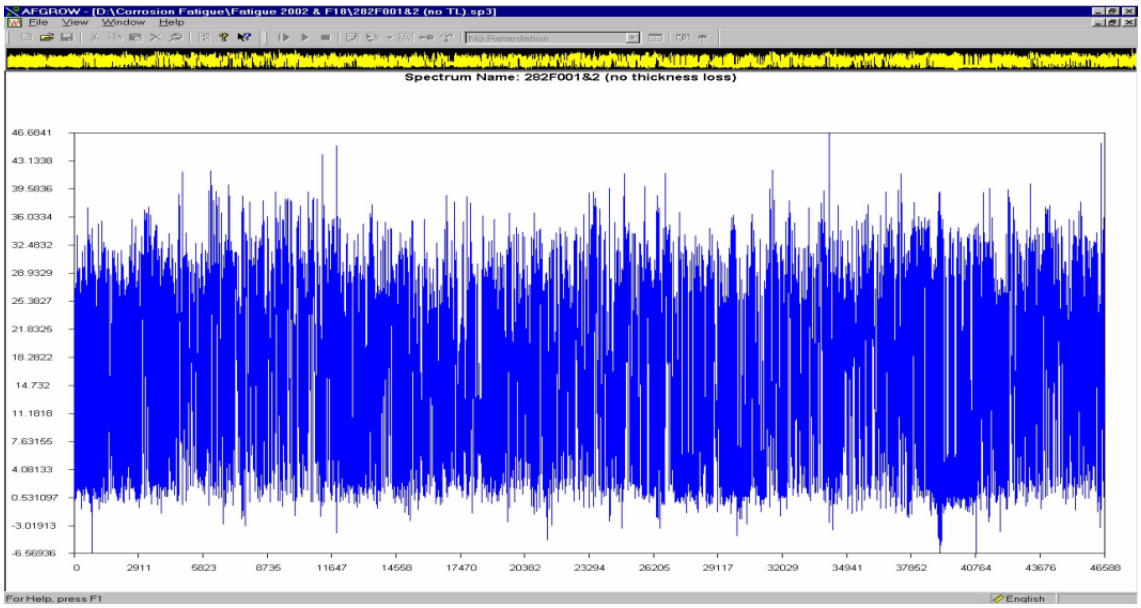

Figure 17-6: Loading Spectrum Obtained from Strain Gauges.

17.4 RESULTS

Using the estimated initial crack size (0.18 mm, 0.0071 inches) and other input parameters (corrosion growth, thickness loss, etc.) discussed in the previous section, the corrosion fatigue analysis was carried out for the corroded UOL using ECLIPSE. This analysis was carried out from the start of service life (1984) to when the crack was found during the wing test. It should be noted that this fuselage had previously accumulated 3,644 flight hours with a recorded FLEI (Fatigue Life Evaluation Index) of 0.309 in the USN, Rutledge et al. [1]. This usage converted to the full scale wing test hours is approximately 1,446 SFH. This reduction is due to more aggressive loading spectrum applied to the wing test. The results, labeled as HOLSIP (corroded), from the corrosion and fatigue analysis are shown in Figure 17-7, along with the test results for the corroded and non-corroded UOL. This figure shows that the analytical results for the corroded UOL are in close agreement with the NRC test results.

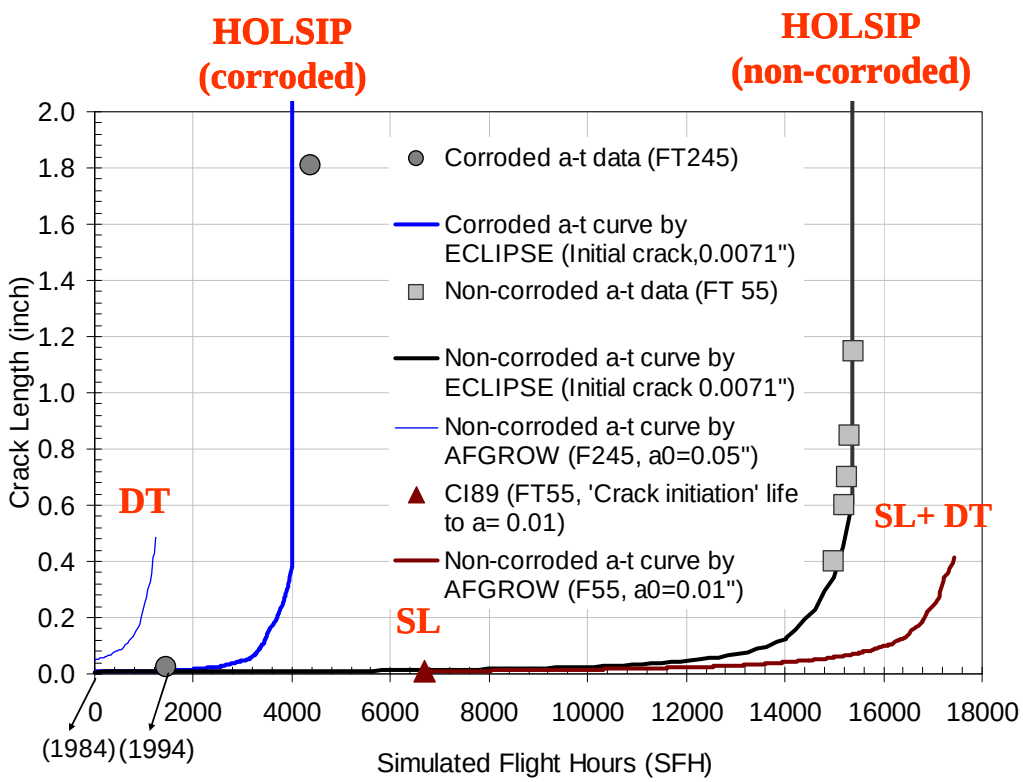

Figure 17-7: Life Comparison Between Corroded and Non-Corroded UOL.

In Figure 17-7, the result of a Damage Tolerance (DT) analysis is also presented. The DT analysis was carried out using AFGROW, and a typical initial crack size of 1.27 mm (0.050 inches). It is shown that the typical DT analysis clearly underestimated the life of the corroded UOL, without including the corrosion effect.

As the F-18 was originally designed based on the Safe Life (SL) approach, a "Crack Initiation" software (CI89) which was specifically calibrated for the CF-18 material and load spectra, was used to estimate the 'crack initiation' life (time to a crack size of 0.25 mm, or 0.010 inches). The CI89 results, labeled as SL, are presented in Figure 17-7. As can be seen, since the SL approach did not consider corrosion effects, its predicted life is longer than that of the corroded UOL, but less than the life of non-corroded UOL. Further analysis was performed to continue a DT analysis (AFGROW) from the 0.010-inch crack to failure, the total life (i.e., sum of CI89 and DT lives) is presented in Figure 17-7, labeled as SL+DT. It is shown that the SL+DT total life approach overestimated the life of the non-corroded UOL, while the HOLSIP approach provided a result close to that of the test.

In summary, both analytical and test results showed that the corrosion pits significantly decreased the life of the UOL. The HOLSIP/ECLIPSE analysis provided most reasonable results for both corroded and non-corroded cases.

17.5 CONCLUSION

A corrosion fatigue analysis using HOLSIP/ECLIPSE was carried out to assess the life of the corroded UOL of an F-18 aircraft, in which the *concurrent* interaction of corrosion and fatigue were quantitatively taken into account. The analytical results were compared to full scale test results. The good agreement

between the analytical and test results indicated that HOLSIP/ECLIPSE is a promising analytical tool for corrosion fatigue analysis of aircraft structures. The HOLSIP framework has potential to augment and enhance the safe life and damage tolerance approaches.

17.6 REFERENCES

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