Chapter 15 – EXFOLIATION CORROSION AND FATIGUE MODELING

Min Liao
Institute for Aerospace Research
National Research Council Canada
Ottawa, Ontario
CANADA

Thomas Mills
Analytical Processes / Engineered Solutions, Inc.
Saint Louis, Missouri
USA

15.1 INTRODUCTION

Corrosion is a persistent threat to aircraft structural integrity, yet existing structural integrity methodologies tend to treat corrosion in a questionable manner. The safety factors employed in the safe life approach prove to be unreliable. The practice in the damage tolerance approach that large assumed crack sizes 'cover' the influence of corrosion might be valid in some cases, but there are many cases where that assumption is invalid or just unaffordable.

Thus, the aviation community needs methods that properly account for the physical effects of corrosion on a structure. Part of this need is driven by the desire to reduce maintenance costs and increase aircraft availability, and part of it is driven by emerging regulatory requirements, such as the recent US Federal Aviation Administration proposed rulemaking on Widespread Fatigue Damage (WFD) [1] and the recent notices for proposed rulemaking issued regarding damage tolerance for rotorcraft [2] and engine life-limited parts [3].

This chapter specifically studies the latest advances in the modeling of exfoliation/fatigue interactions using Finite Element Analysis (FEA) and fracture mechanics methods.

Exfoliation corrosion, defined as a severe Intergranular Corrosion (IGC) (ASTM G15-97a), is one of the most common corrosion forms found in aircraft structures [4],[5]; however, its significance has long been undermined as merely a warning of other insidious failure modes such as Stress Corrosion Cracking (SCC) or as only a threat to static strength or stability. To illustrate this perception, even the ASM Handbook on Corrosion [6] explains that exfoliation itself is not of concern because it is a surface phenomenon that is "easily detectable", that "proceeds to only a limited depth", and that "does not result in sudden failures" as does SCC. This view is unsatisfactory for a number of reasons:

- Aircraft structural members have been completely consumed by exfoliation corrosion thus nullifying the limited depth argument.
- Many aircraft structural components that suffer from exfoliation corrosion (such as stringers and internal surfaces of wing skins) are hidden from view and are, as a consequence, not readily inspectable.
- Exfoliation damage has been shown to cause sufficient stress concentrations to nucleate multiple fatigue cracks [7]-[9].
- Studies have shown that fatigue crack growth rates through exfoliated material can be higher than in uncorroded material [10]-[13].

The studies referenced above did much to explain the degree by which exfoliation affected the fatigue performance of aircraft structural aluminum alloys, but they did not delve into the modeling of exfoliation and fatigue interactions other than to account for increases in crack growth rate due to thickness loss.

In general, exfoliation effects on static properties, such as buckling, yielding, and bearing strength, can be conservatively modeled by simply considering exfoliation corrosion as a thickness loss. However, as illustrated by the following factors, the modeling of the exfoliation effect on the fatigue response is much more complicated:

1) Multiple cracking mechanisms – fractography has shown that fatigues cracks could start from:
   a) Pits on the bottom of the exfoliated surface;
   b) Tip of intergranular corrosion; and
   c) A particle or grain denuded by IGC/exfoliation [14],[15].
2) Complex exfoliation morphology – particularly, when exfoliation occurs in a complicated geometry, like near or under a countersunk hole in a lap joint.
3) Loading spectrum – some tests showed that exfoliation had a benign effect on the fatigue life when the structure is under a compression-dominated spectrum loading, like a representative loading for upper wing skin [14]-[16]. Other tests showed that, under the severest constant amplitude loading, i.e., R = -1, the exfoliation dramatically reduced the fatigue life [17].

In addition, the difference between artificial and natural exfoliation is not completely understood. These differences, where they exist, may also affect the applicability of some models developed using the artificial corrosion data to a natural exfoliation situation.

This chapter introduces two types of exfoliation and fatigue models:

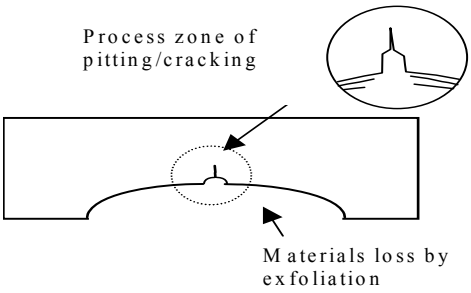
1) The Defence Science and Technology Organisation (DSTO) process zone model; and
2) The National Research Council Canada (NRC) exfoliation model.

15.2 DSTO PROCESS ZONE MODEL

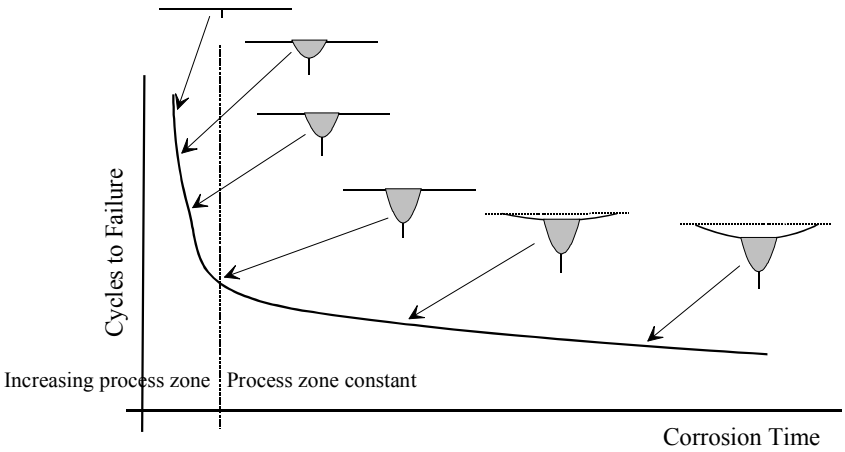
15.2.1 Original DSTO Research

Clark, et al. [18] conceptualized the process zone model in 1998. Their hypotheses supported the view of Mills [8] that the discontinuities, which violate the surface integrity, are key fatigue-related concerns with exfoliation. Mills joined Clark and Sharp in 2000 – 2001 to further develop data to support the original process zone model presented in various publications [19]-[20].

The process zone in exfoliation and fatigue seeks to explain the rapid drop in fatigue life exhibited in the early stages of corrosion damage. The ‘zone’ was found to be a pit-like intrusion with intergranular cracking at the tip (see Figure 15-1(a). This microscopic pit-plus-crack combination is at the base of the exfoliated region, and it travels with the exfoliation as the damage deepens to a severe level (see Figure 15-1(b). The efforts at DSTO focused on determining how exfoliation attacked 2024-T351 and 7075-T651 alloys subjected to an ASTM EXCO environment (ASTM Standard G34).



(a)



(b)

Figure 15-1: (a) Schematic of the Process Zone Model; and (b) Variation of the Process Zone with Exposure Time to EXCO (after [19]).

The pit-like intrusions were of particular interest because they, more than any other feature, supported the process zone model. Note the convincing image of the 'process zone' shown in Figure 15-2 [19]. This specimen, exposed for 48 hours, shows a classic pit-like fatigue crack origin along with the general thinning associated with advanced exfoliation.

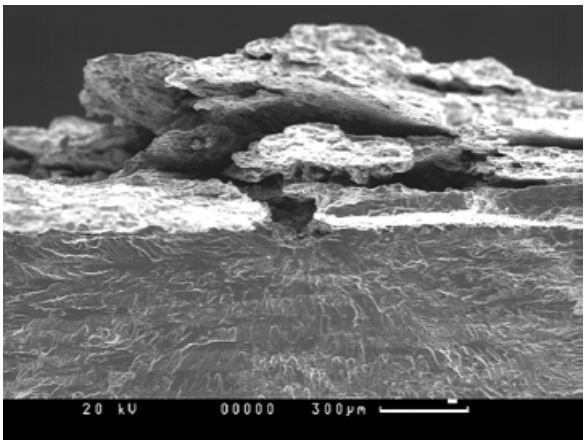


Figure 15-2 : Pitting and Exfoliation at Crack Nucleation Site in Specimen Exposed 48 Hours to EXCO (after [20]).

Pit sizes tended to reach a maximum of 100 microns (0.0039 inch) in the 2024 alloy [21]. Moreover, many of the pits showed small intergranular cracks (0.001 inch or 25 microns) at their bases, which is not at all surprising since exfoliation propagates along intergranular paths.

In the original work, DSTO conducted fatigue modeling of these experimental results using FASTRAN II. In FASTRAN II, the process zone was represented by a notch and crack combination with sizes derived from experimental observations of pit and intergranular crack sizes for various corrosion stages. For modeling the corrosion damage in 7075-T651 dogbone coupons, Clark et al. [19] examined cases where the process zone was represented by a pit ranging in depth from 20 – 100 µm and an intergranular crack ranging in depth from 10 – 30 µm emanating from the base. The corrosion damage was generated using the EXCO solution for 2 to 245 hours. The coupons were then subjected to a constant amplitude loading ($R = 0.1$, $\sigma_{MAX} = 240$ MPa) until failure. Figure 15-3 displays experimental results together with those from the three FASTRAN based process zone models. Model (4a), which forms the upper bound, was based on an initial process zone made up of a notch (representing the pit) with a size between 20 – 100 µm and a 10 µm crack at the tip. Model (4b) varies notch (pit) size with a 20 µm crack, and Model (4c) varies notch (pit) size with a 30 µm crack. As can be seen from Figure 15-3, all models give slightly unconservative results, close to the experimental data.

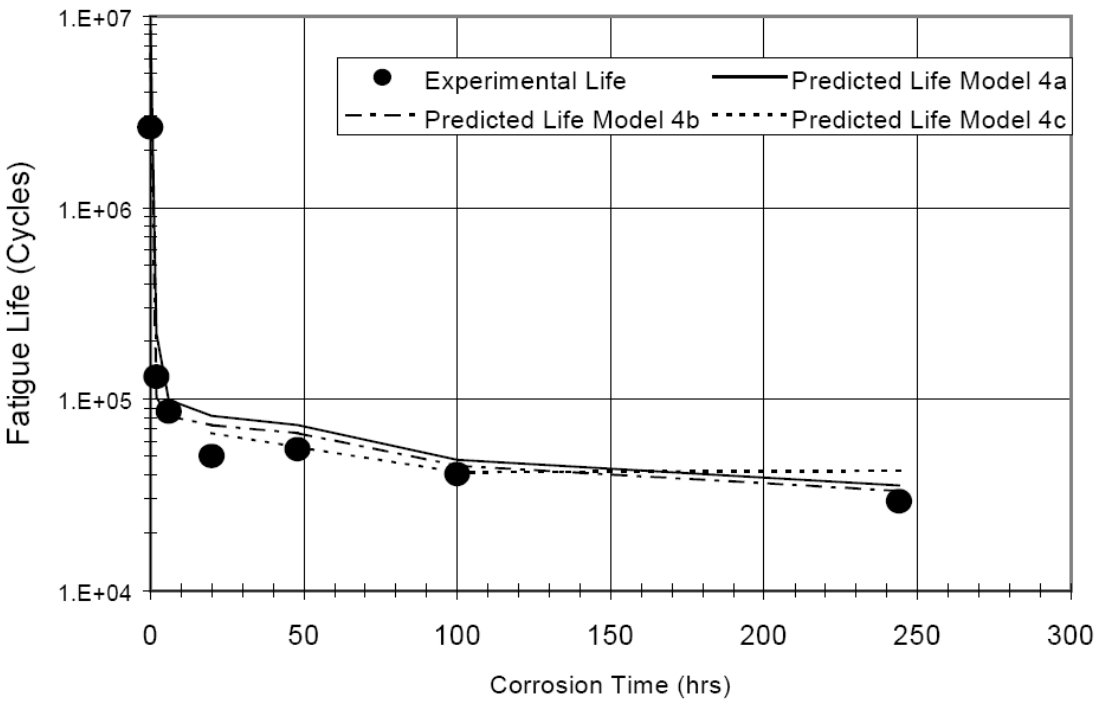


Figure 15-3: Predicted 7075-T6 Fatigue Life vs. ASTM EXCO Corrosion Time Using the 'Process Zone' Model and FASTRAN [19].

As part of these same studies [20], the authors also investigated other models for estimating the influence of exfoliation on fatigue response. These models included:

1) Treating exfoliation as a semi-elliptical crack with the same dimensions as the 2D slice through the corrosion.
2) Treating exfoliation as a semi-circular crack with depth equal to that of the exfoliation.
3) Treating the exfoliated region as a blended region. The model assumed the presence of a typical inclusion-sized starter crack (a = 3 µm and c = 9 µm) at the base of the blended region.

As might be expected, the first two models produced extremely conservative results. The third model produced – as expected – seriously unconservative analytical results.

15.2.2 Studies of the Process Zone Model at APES

In 2003, APES began working with the DSTO Process Zone model, as it fit well within the surface integrity effects models that the company was developing to address corrosion and fatigue interactions. The primary difference between the activities at DSTO and APES was that DSTO attributed the crack-like discontinuities necessary for a fracture-mechanics based analysis to intergranular cracking at the tip of the exfoliation process zone, whereas APES modeled the failure scenario by assuming that the material Initial Discontinuity State (IDS) could be related to the second phase constituent particles present in high-strength aluminum alloys. These particles are often associated with fatigue failure of uncorroded material in the laboratory, and the hypothesis was that the distribution of the particle sizes provided a reasonable starting crack size distribution for crack growth analyses.

Also, where DSTO used a notch model in FASTRAN II, APES used beta correction capabilities in the crack growth code, AFGROW, to simulate the effect of a pit on the IDS (this now becomes the process zone).

So, for the APES analyses (conducted by Mills et al. [22]-[23]) the growth of the IDS was influenced by surface integrity effects models for pitting (solutions based on both 2D-FEA and 3D-FEA models of pits were used) and by the general thinning associated with gross exfoliation. This revised analytical approach was applied to the same data sets as the original DSTO work discussed previously.

For fatigue life post-dictions of the 2024-T351 data from DSTO ($R = 0.1$, $\sigma_{MAX} = 240$ MPa), the ninety percentile (90%) IDS from the size distribution was used (Note: derivation of the IDS distribution is beyond the scope of this chapter, but it has been presented in the literature in the past [22]-[23]). The 90% IDS value for 2024-T351 was found to be 25.4 microns (0.001 inch) and was selected because that value produced a life post-diction that correlated to one pristine fatigue life (2,268,668 cycles) data point within 10%.

This IDS size was then coupled with various models and levels of corrosion damage for each test specimen to produce post-dictions of the experimental fatigue lives. The corrosion damage for the specimens was modeled as a combination of a corrosion pit 60 microns (0.0027 inch) deep, which represented a typical size of the process zone from the DSTO fractography work discussed previously, and the corresponding thickness loss for that specimen. Three pitting models were selected for post-diction:

- None: Only thickness loss was taken into account (net section stress increase);
- 2D-FEA: Where (in addition to thickness loss) a process zone pit is treated as a sharp crack of equivalent depth and influences an adjoining IDS with an aspect ratio of 1.0; and
- 3D-FEA: Where (in addition to thickness loss) a hemispherical pit influences the stress intensity factors of an adjoining IDS.

These various initial states were modeled in AFGROW as general surface cracks using FEA-based beta corrections to account for the pits and higher stress multiplication factors and reduced thicknesses to account for the thickness loss to produce the fatigue life estimates.

The results are summarized in Figure 15-4 and show that by assuming only thickness loss, fatigue life is over-estimated by a factor of four. This clearly reinforces the DSTO conclusions that it is necessary to include the effects of surface integrity to capture the appropriate degradation in life. Figure 15-4 shows that the experimental results are bounded by the 3D-FEA estimates, which treat the pits as hemispherical notches, and the more severe 2D-FEA estimates, which treat the pits as sharp cracks. On average, the 3D-FEA estimates produce a ratio of computed life to experimental life of 1.08, and the 2D-FEA estimates

produce a computed to experimental life ratio of 0.69. Although the 3D-FEA produced the best results based on the average, only the 2D-FEA results captured the most aggressive cracking behavior.

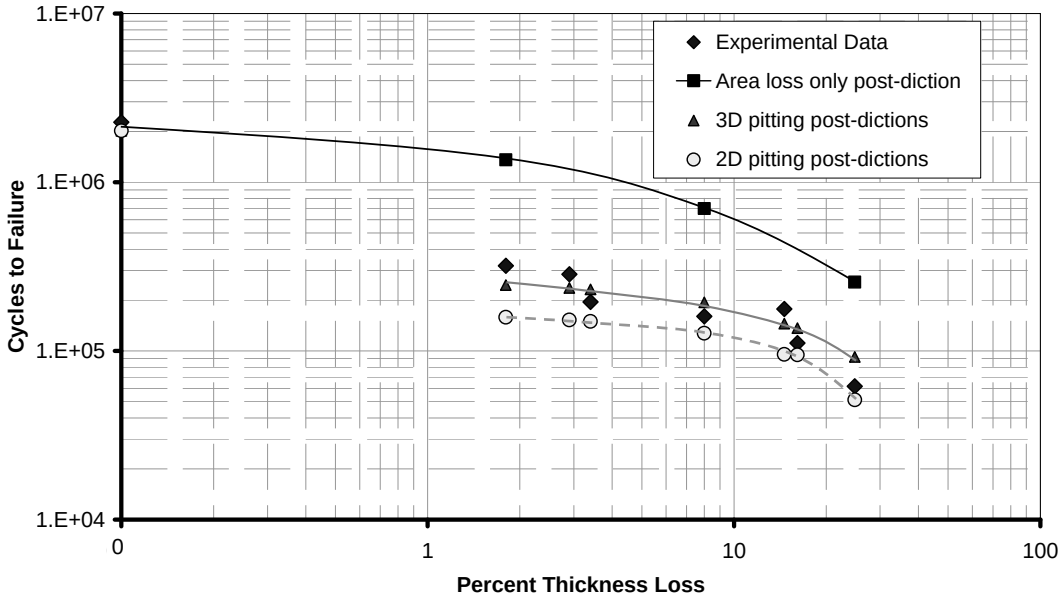
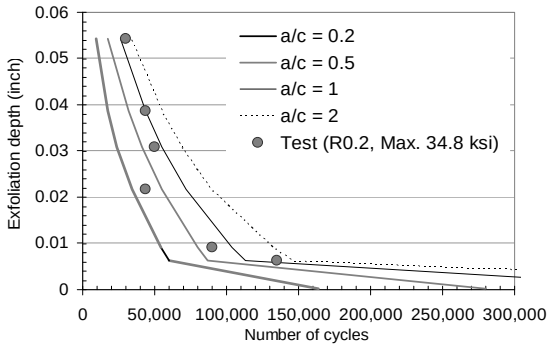


Figure 15-4: Cycles to Failure vs. Percent Thickness Loss for Exfoliated Coupons (Note that only by incorporating pitting into the models do the post-dicted fatigue lives approximate those of the coupons. Assuming area loss only is extremely unconservative (factor of 4)).

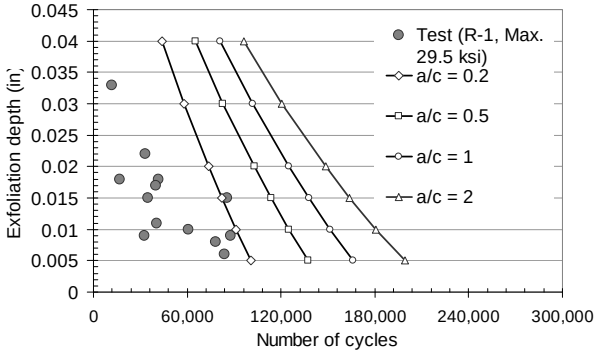
The most important message that can be derived from this effort is that if exfoliation is treated as simply a general thinning of material for analytical purposes, then expect the assessments to be dangerously unconservative. Exfoliation is closely related to corrosion pitting, and this fact should be exploited in modeling considerations. It was obvious from the laboratory experiments that even small levels of exfoliation damage, with barely any perceptible thickness loss, have profound effects on fatigue life in laboratory experiments. Therefore, susceptibility to exfoliation is not the same as structural vulnerability. 'Mild' exfoliation can be almost as damaging to structural fatigue performance as 'severe' exfoliation.

15.2.3 Studies of the Process Zone Model at NRC

Liao et al. also examined the 'process zone' concept using AFGROW [17]. Since AFGROW does not have a starter notch model, the 'process zone' was simplified as a semi-elliptical crack with a depth of 120 μm on the substrate material (i.e., similar to DSTO Model 4(b)), in which the exfoliation layer was removed and the net stress was increased correspondingly. Because the real aspect ratio of the corrosion pit was unknown, different crack aspect ratios were used in the analysis. The analytical results are presented in Figure 15-5(a), along with the DSTO test results. It is shown that the 'process zone' concept can be implemented using AFGROW to provide similar life estimations for the DSTO specimens, especially with aspect ratio of 1.0 to 2.0.



(a) DSTO artificially exfoliated 7075-T6 specimens.



(b) NRC naturally exfoliated 7075-T6 specimens.

Figure 15-5: Predicted 7075-T6 Fatigue Life vs. Exfoliation Depth Using the 'Process Zone' Model and AFGROW [17].

However, in an example in [17], the 'process zone' model largely over-estimated the life of the naturally exfoliated 7075-T6511 coupons under a fully reversed cyclic load (R = -1) (test details are described in Section 3.3, Example 2), even with the upper limit of pit depth of 100 μm, plus remote stress increased based on the maximum depth of exfoliation (determined by ultrasonic Non-Destructive Inspection (NDI)), the model still over-estimated the lives, Figure 15-5(b). The over-estimation might be caused by the following factors:

- Differences between natural and artificial corrosion such as:
  - a) The exfoliation area or volume in the naturally exfoliated NRC specimens were mostly larger than those in the DSTO EXCO specimens♣; and
  - b) Natural and artificial corrosion may have produced different hydrogen embrittlement effects in the material, which could affect the crack nucleation and small crack growth.
- High compression loads may cause local buckling or delamination in the natural exfoliation damage, which in turn may affect the fatigue life. It is also difficult to model the fatigue crack growth behavior under the stress ratio R = -1 due to crack closure effects.

In general, the major limitation of the 'Process zone' model is that detailed fractography is needed to determine how the depth of exfoliation changes with time, and to determine when the growth of the 'process zone' stabilizes. For these reasons, DSTO abandoned the 'Process Zone' model around 2001. However, the disconnect between current NDI capabilities and the physical material features that are critical to fatigue response under corrosion conditions is not a new issue. The same argument could be made for trying to detect and assess pitting corrosion.

A large research program in the USAF from 2003 – 2006 (the Corrosion Effect on Structural Integrity) encountered this same difficulty. The proposed action at that time was to build a "library of damage", wherein the subtle damage details could be inferred from the macro "indications" derived from NDI and derived from the construction of an alloy's microstructure and grain orientation. This approach was

♣ The ASTM EXCO solution was found too corrosive for 7000 series aluminum alloys, which during the first 24 hours of the test, the EXCO solution is highly acidic, starting at pH 0.4 and gradually stabilizing at pH 3.2 [24]. This explains why the EXCO often produce extensive corrosion pits at the beginning, and then takes a long time to produce less IGC than natural exfoliation. An aluminum chloride modified EXCO solution, i.e., ANCIT [24], starts the corrosion test at pH 3.2 and creates more aggressive attack along grain boundaries. The ANCIT has been found to repeatedly produce more representative exfoliation to aluminum alloys [24],[25].

reasonable, and it is unfortunate that this work was not pursued in earnest. Regardless, it is still needed to develop high-fidelity corrosion structural effects models to understand the important aspects of the failure mechanisms. It is impossible to evolve towards more holistic assessment mechanisms without understanding the physics of failure.

Another apparent limitation is that for exfoliation corrosion around fastener/rivet holes. As originally presented in the literature, it is difficult to use the 'Process Zone' model where cracks nucleate from the countersink or bore surface. However, exfoliation at fastener holes often has attendant with it pitting down the bore of the holes. In these cases, it may be possible to analyze failure progression through a pitting analysis (at the bore of the hole) coupled with an increase in net section stress due to exfoliation.

15.3 NRC EXFOLIATION MODEL

15.3.1 Finite Element Model

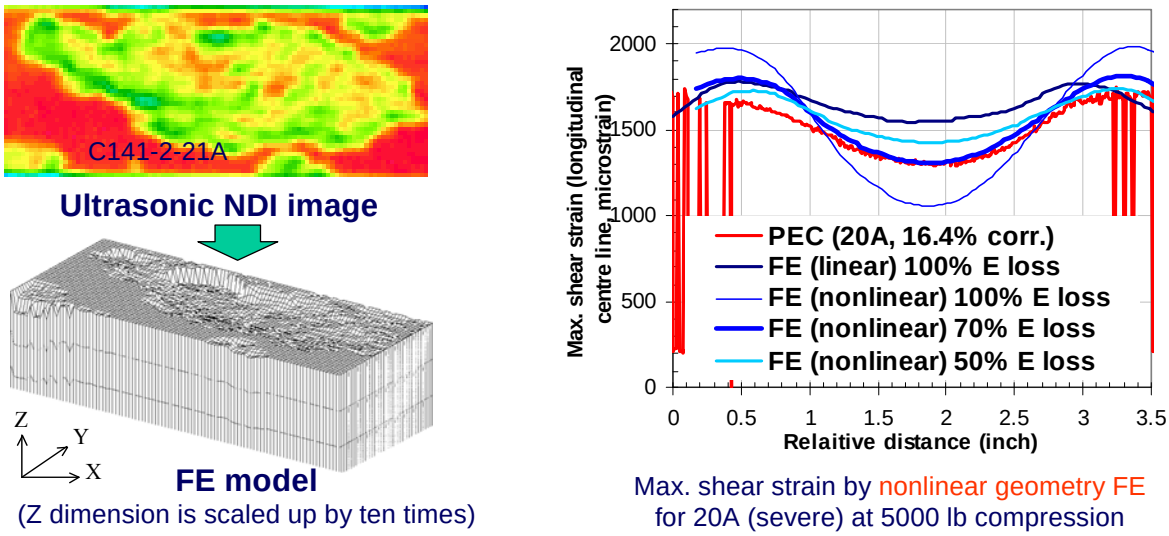
A three dimensional (3D) Finite Element (FE) model was developed to determine the local stress/strain distribution of fastener specimens. In the model, a "soft inclusion" technique, which was previously developed and verified at NRC to simulate Compression After Impact (CAI) in composite structures [26] was applied to simulate the exfoliation present in the specimen. The basic assumptions associated with the soft inclusion are:

- Exfoliated area, simulated by a soft inclusion with reduced stiffness, has some load carrying capability;
- Soft inclusion is an isotropic material; and
- Soft inclusion can have uniform depth or irregular geometry as corrosion.

A calibration and validation for the 'soft inclusion' model was carried out using smooth coupon specimens and Photoelastic Correlation (PEC) measurements [27]. A technique to automatically generate the 3D geometry of the 'soft inclusion' (damage zone) from the NDI input was developed using the PATRAN Command Language (Figure 15-6(a)). Non-linear FE analysis was then performed to analyze the non-linear bending effect due to exfoliation [27]. The calibrated results, as shown in Figure 15-6(b), indicated that:

1) Different Young modulus (E) reduction should be used for different exfoliated area to match FE with the PEC; and
2) 70% E reduction led to numerical results that matched the test results.

After the calibration, the 'soft inclusion' based FE model was used to provide the local stress distribution for fatigue modeling. In addition, the 'soft-inclusion' model has been successfully applied for quantifying the effects of the exfoliation on the residual strength (yielding strength and buckling) [27].



(a) FE model based on NDI inputs. **(b) Calibration of soft-inclusion stiffness.**

Figure 15-6: FE Modeling Process Using NDI Inputs and Modeling Results (Note: Young's modulus E loss was calibrated in between 50 – 70 % by non-linear FE analyses. The PEC measurements were performed on the back (non-corroded) surface of the coupon).

Figure 15-7 presents a 3D FE model generated for a corroded specimen with exfoliation damage. The exfoliation was simulated using a number of 3D elements with the calibrated Young's modulus (E). The thickness of the soft inclusion was set by the maximum depth of the exfoliation that was measured by ultrasonic inspection. The FE analyses were carried out using the commercial code MSC/MARC including contact analysis between the fastener to plate, plate to flange, and flange to fastener.

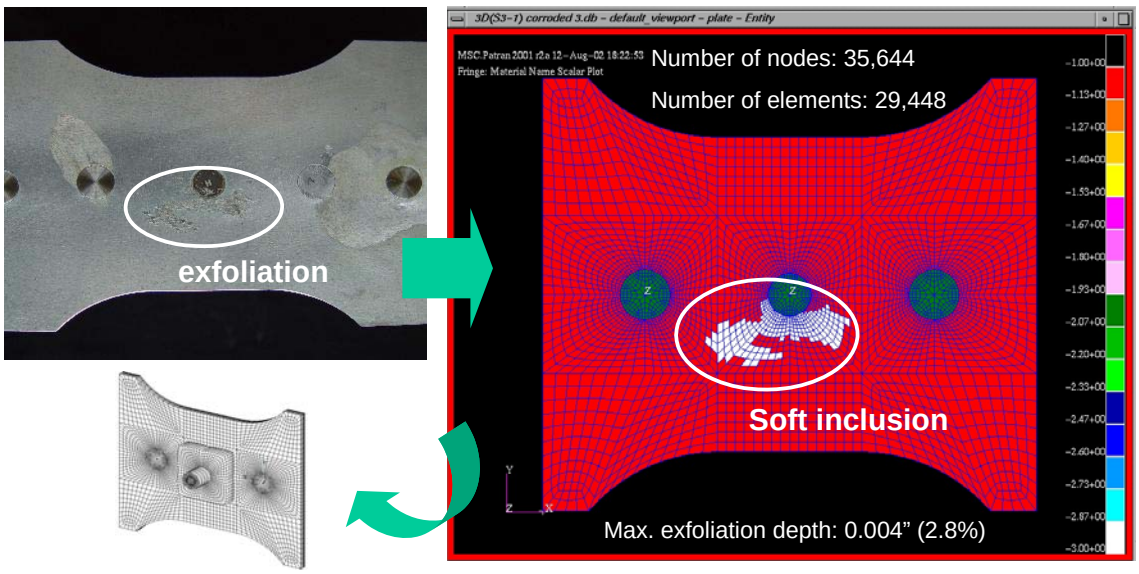


Figure 15-7: 3D FE Mesh with Soft Inclusion for Specimen 1 (362-A-S3-1).

A comparison between the crack nucleation sites in an exfoliated specimen with the location of the maximum principal stress ($\sigma_{1,\ max}$) determined from the FE analysis for tension loading is shown in

Figure 15-8. The crack nucleation sites are located near the 1 o'clock and 5 o'clock positions. The FE analyses were carried out under both tension and compression loading in order to obtain the local stress results for fatigue analysis.

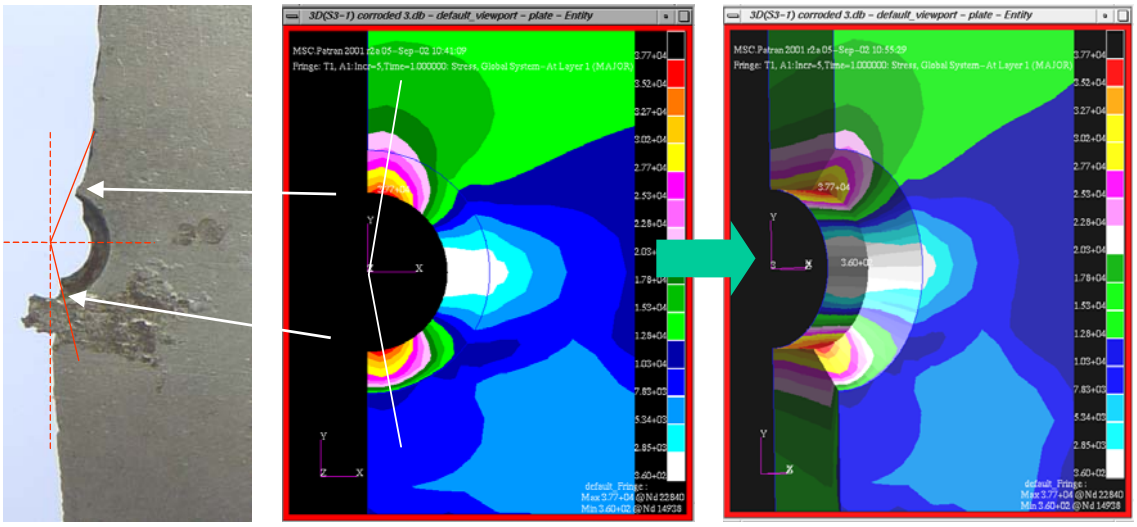
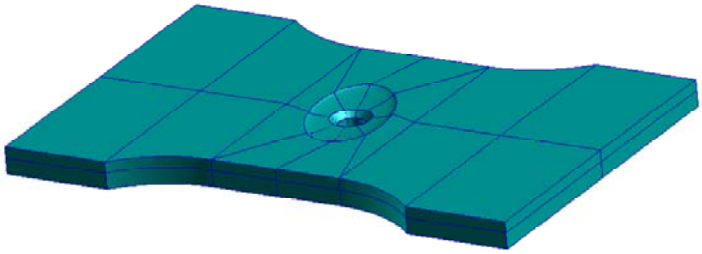


Figure 15-8: Crack Nucleation Site and 3D FE Analysis Results.

Recently, the MSC PCL based automation technique was further improved at NRC to quickly generate a soft-inclusion based FE model for different degrees of exfoliation corrosion found at aircraft rivet holes [28]. Figure 15-9 presents the modeling variables that can be changed for different rivet hole models.



User-defined geometric variables

Damage zone: ellipsoid short and long axes, max depth, angle, position
Rivet hole: radius, countersink depth, countersink angle
Plate: grip length, width, radius, grip length, tapered thickness

Figure 15-9: An Example FE Model Generated by NRC Automation Technique (the soft inclusion and rivet have been removed for clarity) [28].

15.3.2 Fatigue Model for Rivet Specimens

From the existing studies on exfoliation kinetics, the crack-nucleating pits, IGC, and particles or grain boundaries denuded by IGC are created by the local electrochemical cells of precipitates at grain boundaries [29]. From a mechanical point of view, the corrosion pit and denuded particle or grain could easily serve as local stress concentrations. The tip of IGC could also become a high stress site when the IGC dissolves precipitates or turns into the next layer of grains. Since upper layers of exfoliated materials would be pushed and flaked away, the pit/IGC discontinuities on the exfoliation sub-surface would remain of limited depth depending on the microstructure.

Due to the multiple cracking mechanisms in the exfoliation region [16],[17], it is difficult to use a single model to cover all of them. Also due to the complexity of the pit/IGC geometries, plus the chemical

effects on material properties, it is very difficult to accurately determine the local stress distribution for pit/IGC tips, and the stress intensity factors. Simplifications and assumptions are needed for developing an engineering model. A common simplification is to consider the pit/IGC as a pre-crack, then use a fracture mechanics model to estimate the remaining fatigue life with the prior corrosion. Two examples are presented as follows.

Example 1: Fatigue Life Analysis for Riveted Specimens

Fatigue tests were carried out on naturally exfoliated 7178-T6 coupons, using a constant amplitude loading (R = -1.67, σ_{max} = 12 ksi). The fractography found that a primary crack formed from a corrosion pit-like discontinuity on the countersunk surface of one coupon. This coupon was cut from a B707 wing panel, with 5.4% exfoliation (i.e., max. exfoliation depth/nominal thickness) at the fastener hole, Figure 15-10.

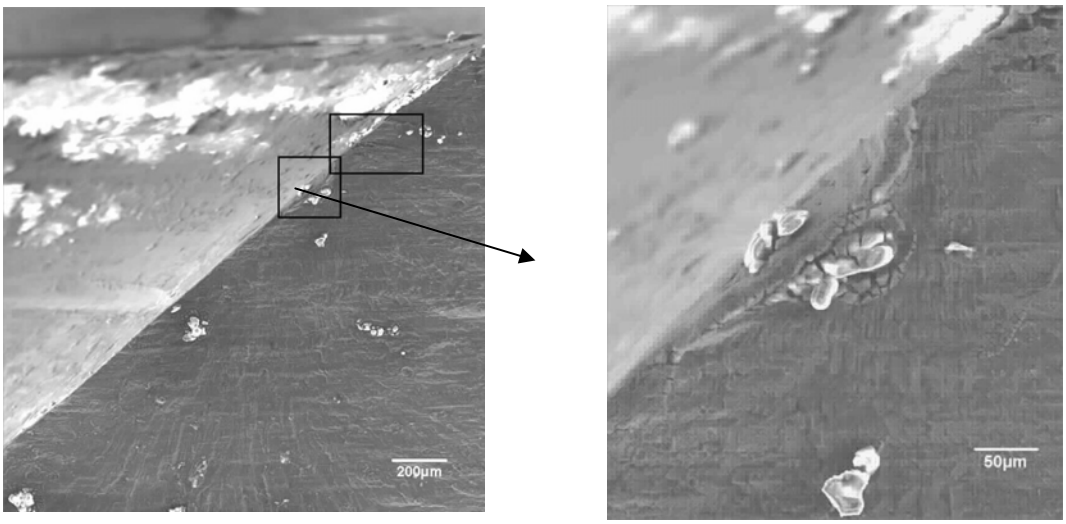
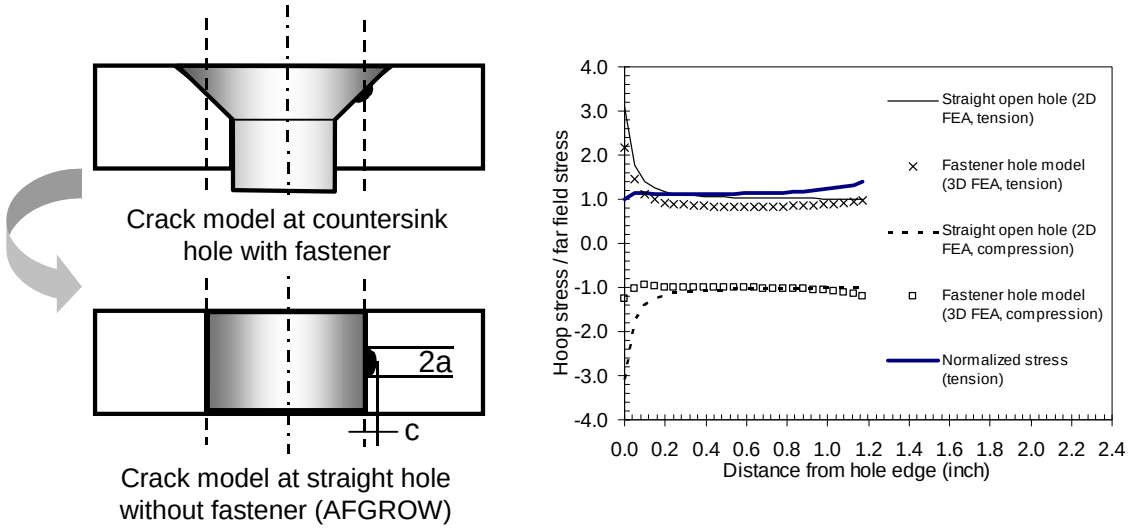


Figure 15-10: Crack Nucleation Site at a Colony of Corrosion Pits on Countersunk Surface.

A crack growth analysis starting from the pit-like discontinuity to final failure was first carried out using 3D FE analysis results and AFGROW [16]. The pit-like discontinuity was assumed to be a half-elliptical crack with dimensions of 262 x 98 µm, measured from the SEM image (Figure 15-10). Since the current version of AFGROW does not have a crack model for a countersink hole filled with a rivet, a straight open hole crack model was used for the crack growth analysis along with corrected beta factors from FE, see Figure 15-11(a). Based on a point load stress intensity solution, the beta correction factors were calculated by AFGROW using the normalized stress distribution. This stress distribution was determined by the following procedure. First, a 2D FE analysis was carried out on the straight open hole model and the stress distribution along the assumed crack path was obtained. For the countersink hole model (with fastener), the stress distribution along the assumed crack path was obtained from the 3D FE analysis previously described. Then the ratio of the stress distribution from the countersink hole to that of the straight hole model at various crack length intervals was determined. Finally, the normalized stress values along the assumed crack path were calculated by dividing each ratio by the ratio at the crack origin. The normalized stress values along the assumed crack path are presented in Figure 15-11(b).



(a) Crack model for AFGROW. **(b) Normalized stress distribution along crack path.**

Figure 15-11: Crack Model for Crack Growth Analysis.

Using the NASGRO material model (i.e., 7178-T6 and T651 Al, [Plate and sheet; L-T; LA, HHA]), AFGROW calculated the crack growth life from the pit-like discontinuity to final failure as 179,217 cycles, which is about 33% less than the test results. This conservative prediction can be attributed to:

1) The pit to crack nucleation life was not included in the analysis; and
2) The fatigue life scatter including possible analytical errors due to the complex geometry and beta solutions.

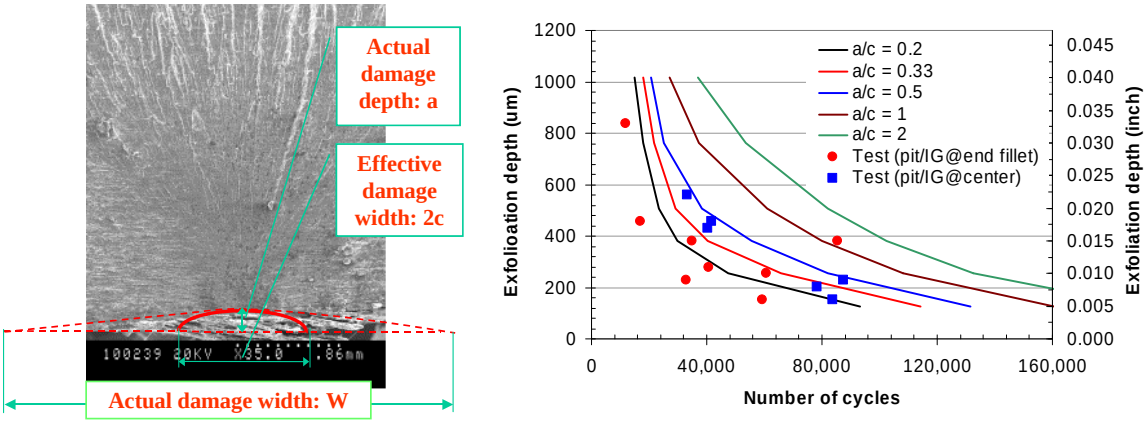
Overall this example showed that assuming a pit to be a pre-crack could result in a reasonable, conservative fatigue life prediction.

Example 2: Fatigue Life Analysis for Smooth Specimens

In a previous NRC project, dog bone specimens were manufactured from the 7075-T6511 upper wing panels of C141 aircraft containing natural exfoliation. The maximum depth of the exfoliation damage was determined by ultrasonic NDI. A number of fatigue tests were carried out under fully reversed constant amplitude loading (R = -1.0), and fractographic analyses were performed to examine the cracking mechanisms in the exfoliation region.

As described in Section 15.2, the DSTO ‘process zone’ model was first used but largely overestimated the fatigue lives. A simplified fatigue model was proposed at NRC to estimate the remaining fatigue life of the corroded specimens [17]. In this model, the exfoliation damage was assumed as a surface crack with a depth that was presumably available from an NDI or grind-out database. The initial idea of the model was to treat the exfoliation damage as a semi-elliptical surface crack with a profile that would approximate the projection of the exfoliation zone onto the plane vertical to the tensile loading direction. Later a modified profile with reduced crack length (exfoliation width) was found to have almost the same stress intensity factor as the original profile. The model actually used a modified profile and was calibrated using different crack aspect ratios (i.e., same depth but varying length) with the intention to seek an ‘effective crack’ for providing a good life estimation. The calibrating process essentially made the model more ‘effective’, so the simplified model is also called the ‘effective crack’ model. A schematic of the model is shown in Figure 15-12(a). It should be noted that the remote stress is not increased by the material loss in the

'effective crack' model. In this way, the pristine/design stress can be used directly in this mode to predict the remaining life.



(a) 'Effective crack' model

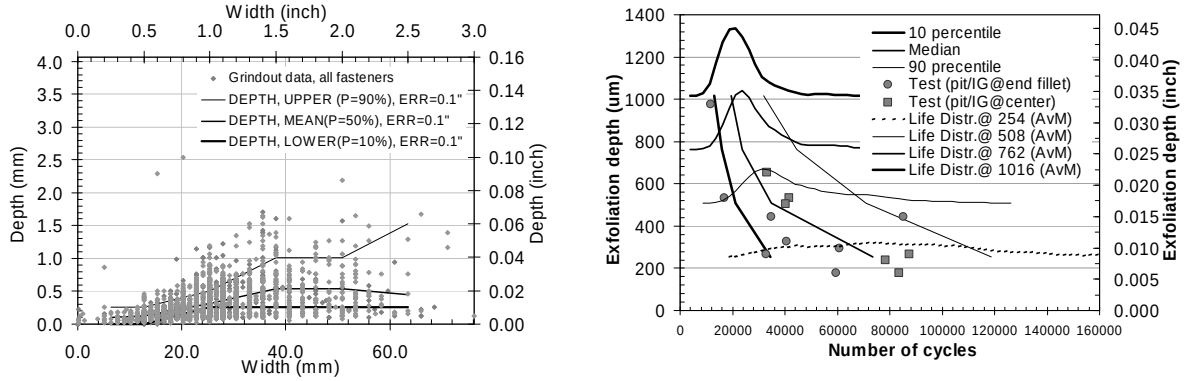
(b) Remaining life estimation

Figure 15-12: Cracking Model and Life Estimation Using Simplified Fatigue Model [17].

Along with the test results, the fatigue lives estimated by the 'effective crack' model are presented in Figure 15-12(b). This figure indicates that with crack aspect ratios (crack depth / half crack length, a/c) ranging from 0.2 – 2.0, the model gave good estimation of the range of the fatigue lives. Particularly, the aspect ratio a/c = 0.33 was found to give the best representation of the average test results. Therefore, the ratio a/c = 0.33 was considered as an 'effective' aspect ratio for the model to give good results on the average life. To apply the model to other structure applications, the 'effective' crack aspect ratio has to be calibrated using coupon tests, the representative spectrum loading, and the approach developed in this chapter.

Example 3: Probabilistic Fatigue Modeling

In practice, conventional NDI techniques still have difficulty in determining the exfoliation depth on the wing skin without disassembling the structures. Advanced NDI, such as angled ultrasonic, may be able to do so but it is still very time-consuming and needs further development. A grin-out database provides a practical option to estimate the exfoliation depth without disassembly. In this estimation, the grind-out area (width and depth) is assumed to be equal to the corrosion damage (width and depth). As an example, a grind-out database based on exfoliation repair records for some large transport aircraft is shown in Figure 15-13(a). This figure shows that a large scatter is associated with the depth or width data. To address this scatter, the simplified model was enhanced with probabilistic techniques in order to handle the exfoliation depth as a random variable.



(a) Grind-out database example. **(b) Fatigue life distribution vs. exfoliation depth.**

Figure 15-13: Probabilistic Fatigue Modeling Based on a Grind-Out Database.

For demonstration purposes, the exfoliation depth estimated from the grind out database (Figure 15-13(a)) was assumed as a lognormal distribution with a Coefficient Of Variation (COV) of 54%. A MS Excel Visual Basic for Applications (VBA) program was developed to execute the Component Object Model (COM) version of AFGROW in a Monte Carlo simulation. For the naturally exfoliated specimens, the fatigue life distributions were obtained by the Monte Carlo AFGROW analysis using the random exfoliation depth and the 'effective' aspect ratio of 0.33 for the surface crack. The life distributions for different exfoliation depth and the life curves for the 10, 50, and 90 percentiles are presented in Figure 15-13(b). The Monte Carlo simulation used 1000 trials for determining each life distribution. If required, safety factor or risk analysis could be carried out using the life distributions, which are not available from the traditional fatigue or damage tolerance analysis without corrosion considerations.

15.4 SUMMARY

As the fractographic analysis revealed multiple cracking mechanisms from exfoliation, it also revealed the difficulties to develop an 'accurate' fatigue model. Simplifications and assumptions are needed for developing an engineering fatigue model.

The DSTO modeling showed that the 'process zone' model gave a good estimation on the fatigue life of artificially exfoliated specimens, but its applicability for fleet problems was limited to simple geometry and by lack of detailed fractography data in the field. A simplified 'effective crack' model was proposed at NRC with the motivation to estimate the fatigue life using the exfoliation depth available from either an NDI or grind-out database. It was shown that this model could give good life estimation for the naturally exfoliated specimens, under the severest constant amplitude loading (R = -1).

The NRC soft-inclusion model was originally developed to simulate the stiffness reduction and quantify the residual strength of exfoliated material, but it can also provide a better local stress distribution for fatigue modeling purpose. In particular, for complex geometry, such as fastener holes where the majority of exfoliation was found, the soft-inclusion based FE and fracture mechanics model provided reasonably well life estimation.

Overall, fracture mechanics based models could provide reasonable prediction of the remaining fatigue life of prior-exfoliated aluminum alloys. More fundamental work including characterization of exfoliation sub-surface topography could build-up a database for the topography of exfoliation corrosion. With such a database, a local pit/IGC model may be developed and integrated with the 'Process Zone' or 'soft-inclusion' model to provide better and practical life prediction for corroded structures.

15.5 REFERENCES

[1] "Notice of Proposed Rulemaking", Federal Register: April 18, 2006 (Vol. 71, No. 74), 14 CFR Parts 25, 121, and 129 (Docket No. FAA-2006-24281; Notice No. 06-04).

[2] http://www.faa.gov/regulations_policies/rulemaking/committees/arac/media/r/R_MRS_T1.pdf.

[3] Notice of Proposed Rulemaking, Federal Register: February 2, 2006 (Vol. 71, No. 22), 14 CFR Part 33, (Docket No. FAA-2006-23732; Notice No. 06-03).

[4] Liao, M. and Komorowski, J.P., "Effect of Prior Exfoliation Corrosion on Fatigue and Fracture Behavior of Aging Aircraft Structures and Materials", Technical Report, IAR-LTR-SMPL-2002-0136, National Research Council Canada, Ottawa, Ontario, Canada, 2002.

[5] Wallace, W. and Hoeppner, D.W., "Aircraft Corrosion: Causes and Case Histories", AGARD Corrosion Handbook, Vol. 1, AGARD-AG-278, p. 93, Neuilly-sur-Seine, France, 1985.

[6] "Metals Handbook", 9th Ed., Vol. 13, Corrosion, American Society for Metals, Metals Park, Ohio, USA, pp. 584-609, 1985.

[7] Shaffer, I.S., Sebastian, J.C., Rosenfeld, M.S. and Ketcham, S.J., "Corrosion and Fatigue Studies of Extruded 7075-T6 Spar Caps", Journal of Materials 3 (2), pp. 400-424, June 1968.

[8] Mills, T.B., **"**The Effects of Exfoliation Corrosion on the Fatigue Response of 7075-T651 Aluminum Plate", Ph.D. thesis, University of Utah, USA, June 1995.

[9] Hubble, M.J. and Chubb, J.P., "The Effect of Corrosion on Fatigue Crack Initiation in 2024-T3 and 7075-T6 Aluminum Alloys", Proceedings of 5th International Conference on Structural Airworthiness of New and Aging Aircraft, Hamburg, Germany, pp. 231-232, 1993.

[10] Chubb, J.P., Morad, T.A., Hockenhull, B.S and Bristow, J.W., "The Effect of Exfoliation Corrosion on the Fatigue Behavior of Structural Aluminum Alloys", Structural Integrity of Aging Airplanes, pp. 87-97, 1991.

[11] Chubb, J.P., Morad, T.A., Hockenhull, B.S. and Bristow, J.W., **"**The Effect of Exfoliation Corrosion on the Fracture and Fatigue Behavior of 7178-T6 Aluminum", International Journal of Fatigue 17, (1), pp. 49-54, 1995.

[12] Koch, G.H., Hagerdorn, E.L. and Berens, A.P., "Effect of Pre-existing Corrosion on Fatigue Cracking of Aluminum Alloys 2024-T3 and 7075-T6", Final Report to Flight Dynamics Directorate, WPAFB, Dayton, OH, USA, August 1995.

[13] Mills, T.B. and Paul, C.A., "Constant Stress Intensity Determination of Fatigue Crack Growth Rates in Exfoliated Panels of 7075-T651 Aluminum", AFOSR Summer Research Program Report, USA, September 1996.

[14] Bellinger, N.C., Komorowski, J.P., Liao, M., Carmody, D., Foland, T. and Peeler, D., "Preliminary Study into the Effect of Exfoliation Corrosion on Aircraft Structural Integrity", Proceedings of 6th Joint FAA/DoD/NASA Conference on Aging Aircraft, San Francisco, CA, USA, 16-19 September 2002.

[15] Bellinger, N.C., Foland, T. and Carmody, D., "Structural Integrity Impacts of Aircraft Upper Wing Exfoliation Corrosion and Repair Configurations", Proceedings of the 7th Joint DoD/FAA/NASA Conference on Aging Aircraft, New Orleans, LA, USA, September 2003.

[16] Liao, M., Bellinger, N.C. and Komorowski, J.P., "Modeling the Effects of Prior Exfoliation Corrosion on Fatigue Life of Aircraft Wing Skins", International Journal of Fatigue, 2003:25 (9-11), pp. 1059-1067, 2003.

[17] Liao, M., Renaud, G. and Bellinger, N.C., "Fatigue Modeling for Aircraft Structures Containing Natural Exfoliation Corrosion", International Journal of Fatigue, 29/4, pp. 677-686, 2007.

[18] Sharp, P.K., Cole, G., Clark, G. and Russo, S.G., "The Influence of Corrosion on Aircraft Structural Integrity", Proceedings, 21st Congress of the International Council Aeronautical Sciences, Melbourne, Victoria, Australia, 13-18 September 1998.

[19] Sharp, P.K., Mills, T. and Clark, G., "Modeling of Fatigue Crack Growth from Pitting and Exfoliation Corrosion", Proceedings, 21st Symposium of the International Committee on Aeronautical Fatigue, Toulouse, France, pp. 485-498, 27-29 June 2001.

[20] Sharp, P.K., Mills, T. and Clark, G., "Aircraft Structural Integrity: The Impact of Corrosion", Proceedings, 10th International Congress of Fracture (ICF 10), Honolulu, HI, USA, Elsevier Science, 3-7 December 2001.

[21] Sharp, P.K., Mills, T., Russo, S., Clark, G. and Qianchu, L., "Effects of Exfoliation Corrosion on the Fatigue Life of Two High-Strength Aluminum Alloys", Proceedings, 4th Joint DoD/FAA/NASA Conference on Aging Aircraft, St. Louis, MO, USA, Universal Technology Corporation, 15-18 May 2000.

[22] Mills, T.B., Honeycutt, K.T. and Brooks, C.L., "Demonstration of an Holistic Structural Integrity Process Using Corrosion/Fatigue Interactions from Laboratory Experiments and Field Experience", Proceedings, 6th International Aircraft Corrosion Workshop, Solomons, MD, USA, August 2004.

[23] Mills, T.B., Honeycutt, K.T., Brooks, C.L., Sharp, P.K., Loader, C. and Crawford, B., "Development and Demonstration of an Holistic Structural Integrity Process using the Initial Discontinuity State Concept for 7050-T7451 Aluminum", USAF Aircraft Structural Integrity Program Conference, Memphis, TN, USA, November 2004.

[24] Lee, S. and Lifka, B.W., "Modification of the EXCO Test Method for Exfoliation Corrosion Susceptibility in 7XXX, 2XXX, and Aluminum-Lithium Alloys", ASTM STP 1134, V.S. Agarwala and G.M. Ugiansky, Ed., American Society for Testing and Materials, Philadelphia, PA, USA, pp. 1-19, 1992.

[25] Bellinger, N.C., Overton, J.M., Roe, P.W. and Gould, R.W., "Accelerated Exfoliation Protocol", IAR-LTR-SMPL-2002, 0083, National Research Council Canada, Ottawa, Ontario, Canada, 2002.

[26] Xiong, Y. and Poon, C., "Failure Prediction of Composite Laminates Containing Impact Damage", IAR-LTR-ST-1898, National Research Council Canada, Ottawa, Ontario, Canada, 1992.

[27] Liao, M., Renaud, G., Bellinger, N.C., Backman, D. and Forsyth, D.S., "Effects of Exfoliation Corrosion on Static and Fatigue Behavior of Aircraft Materials and Structures – Testing and Modeling Studies", The 8th Joint NASA/FAA/DoD Conference on Aging Aircraft, Palm Springs, CA, USA, January 2005.

[28] Renaud, G., Liao, M., Uebersax, A. and Huber, C., "Static and Fatigue Analysis of an Upper Wing Skin with Exfoliation Corrosion", Proceeding of the 26th International Congress of the Aeronautical Science (ICAS), Anchorage, AK, USA, 2008.

[29] Speidel, M.O. and Hyatt, M.V., "Stress-Corrosion Cracking of High-Strength Aluminum Alloys", Chapter 3 in "Advances in Corrosion Science and Technology", Vol. 2, Edited by M.G. Fontana and R.W. Staehle, Plenum Press, 1972.