PROBLEM NO. NRC-2

Title: Residual Life Assessment of Corroded Fuselage Lap Joints

Objective:

To illustrate the process for including the effects of corrosion in the residual life assessment of fuselage lap joints.

General Description:

This problem focuses on the methods that can be used to carry out a residual life assessment of corroded fuselage lap joints. The first method is based on the Equivalent Initial Flaw Size approach, which can be used for quick assessments of the impact of corrosion on the structural integrity. The second method based on the holistic life assessment approach can be used to carry out a corrosion damage tolerance analysis on environmentally sensitive components. Finite element techniques will be described to take into account the increased stress caused by the build-up of corrosion products between the different layers of skin, referred to as "corrosion pillowing". This change in stress is required for both methods. The AFGROW crack growth rate program is also used in the first method to calculate the number of cycles to failure.

Topics Covered: life assessment, equivalent corrosion damage, finite element analysis.

Type of Structure: fuselage lap joints

Relevant Sections of Handbook: Section 8

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Overview of Problem Description

This problem focuses on the impact that corrosion has on the residual strength of transport fuselage lap joints, Figure NRC-2.1, as well as the techniques that can be used to determine this impact. This example will concentrate on using the Equivalent Initial Flaw Size (EIFS) approach to predict the fatigue lives of pre-corroded lap joint specimens that were subjected to constant amplitude loading. To differentiate the use of the EIFS approach in a corrosion fatigue situation, the phrase 'Equivalent Corrosion Damage' (ECD) is used. A new procedure, known as the holistic life assessment approach, currently being developed for implementation by the United States Air Force, will also be discussed.

The corrosion products contained in aircraft lap joints fabricated from 2024-T3 clad aluminum were analyzed and found to contain a mix of oxides, primarily aluminum oxide trihydrate. This type of oxide had a molecular volume ratio to the alloy from which it originated of 6.45 (Bellinger et al., 1994). It was this high molecular volume ratio that is responsible for the deformation of the riveted skins in a joint resulting in the appearance commonly referred to as "corrosion pillowing", Figure NRC-2.2.

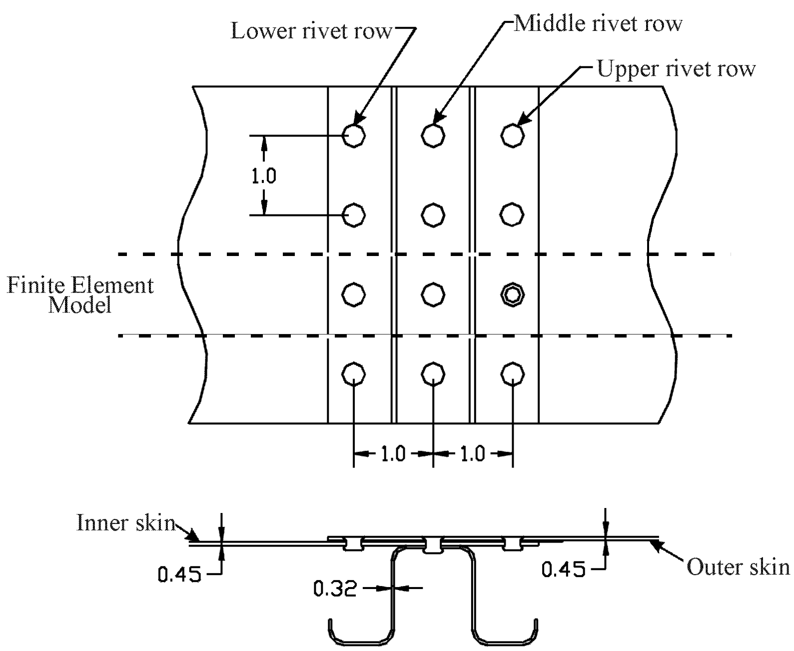

Figure NRC-2.1. Lap joint consisting of two skins and a stringer. All dimensions are in inches (1 inch=25.4 mm)

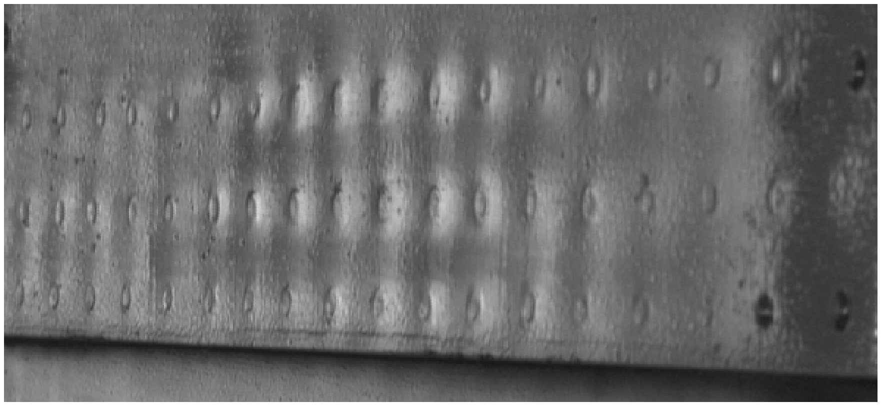

Figure NRC-2.2. D Sight^{TM} Image Showing Pillowing Caused By Corrosion Product Accumulation

Analytical Predictions Using Experimental ECD Values

Experiments have been carried out at NRC Canada on lap joint specimens, Figure NRC-2.3, to determine the effect that corrosion has on the fatigue life. Three levels of corrosion were studied: 0%, 2% and 5% average material loss. The results from these tests, which will be used to verify the capability of the ECD concept to predict the effect that corrosion has on the residual life of corrosion lap joints are present elsewhere (Eastaugh et al., 1998a), (Eastaugh et al., 1998b), (Eastaugh et al., 2000). The majority of the crack nucleation sites for the specimens were located away from the rivet hole along the faying surface. The cracks were semi-elliptical in shape.

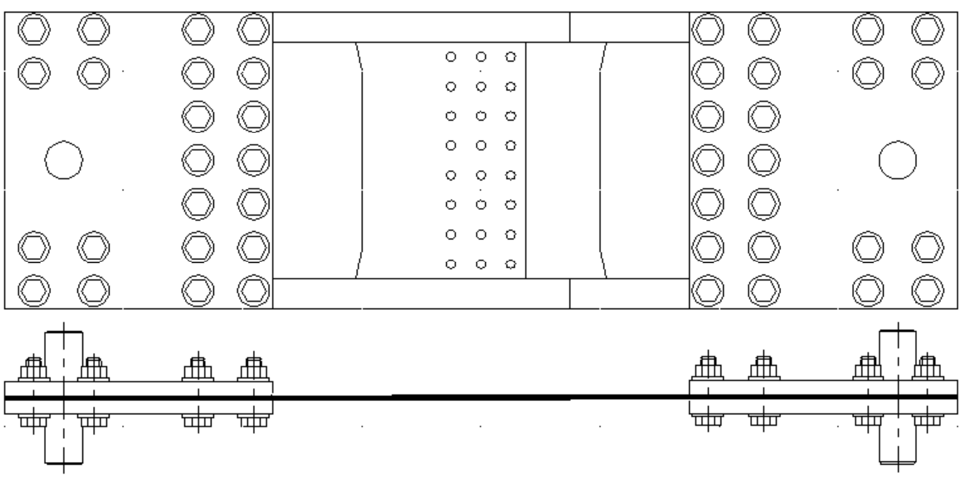

Figure NRC-2.3. Schematic of Lap Joint Specimen

Equivalent Corrosion Damage Values

The procedures to determine the equivalent corrosion damage from corroded (artificial and natural) lap joints are shown in another example problem within this Damage

Tolerance Design Handbook. In this example, coupons were machined from pristine and artificially and naturally corroded lap joints and tested to failure. The corroded lap joints contained different levels of material thinning, 2% and 5% thickness loss. Using scanning electron microscopy and back-calculations, ECD values were determined for the different corrosion levels. All the fatigue nucleation sites were semi-elliptical in shape.

As the cracking scenario that was present in the lap joint specimens (i.e. elliptical crack located away from the hole edge) is not present in crack growth rate programs, it was decided to calculate a semi-circular crack length with an equivalent area to the ECD values. These calculated crack lengths are plotted against the number of cycles to failure in Figure NRC-2.4.

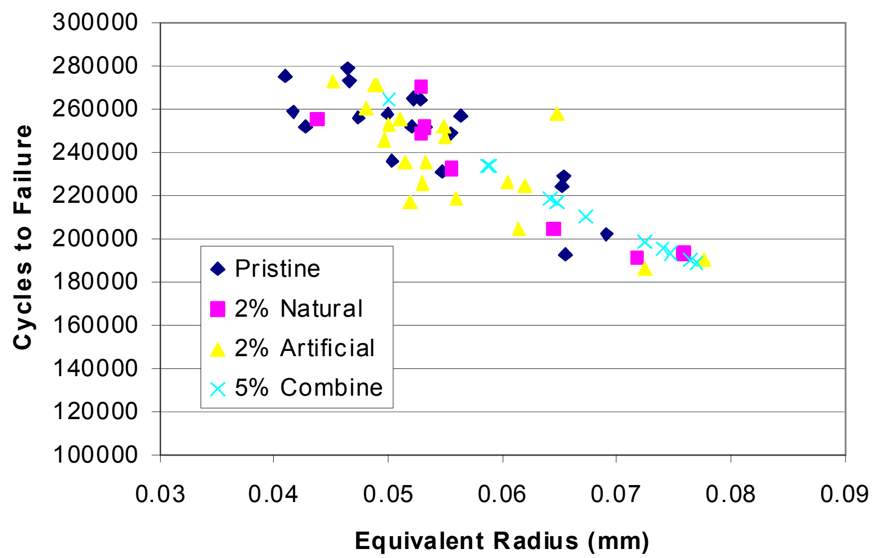

Figure NRC-2.4. Equivalent Circular Radius Versus Number of Cycles to Failure for Pristine, 2% Artificial and Natural and 5% Combined Coupons

Since the version of AFGROW that was used for this example was not capable of predicting a multi-site damage scenario, it was decided to concentrate on predicting the number of cycles to the first observed crack as well as the number of cycles to reach a specified crack length. This length was chosen to be small enough as to not be influenced by other cracks at the other rivets.

Finite Element Analysis

The critical rivet holes in fuselage lap joints are subjected to a complex stress state that is a result of different loading conditions. One load that has a strong influence on the stress state is the secondary bending, which is caused by the eccentric loading in the lap joints. Another one is the pre-stress that results from the rivet installation, which has a significant effect on the crack growth under the rivet head (Liao et al., TBP). Finally, for corroded joints, the out-of-plane displacements, or pillowing, have a very strong influence on the stress state along the faying surface of the lap joint.

Since the AFGROW program could not determine this complex stress state, stress correction curves had to be generated to take into account the different test conditions, 0%, 2% and 5% thickness loss as well as entered into the program. To generate such curves, three finite element models of the lap joint specimens were generated using the commercial finite element package MSC Patran/Nastran (Bellinger et al., 1994; Bellinger et al., 1997). Each model was generated consisting of two 1.02 mm (0.04 inch) skins joined together with three 100^{o} countersink rivets as shown in Figure NRC-2.5.

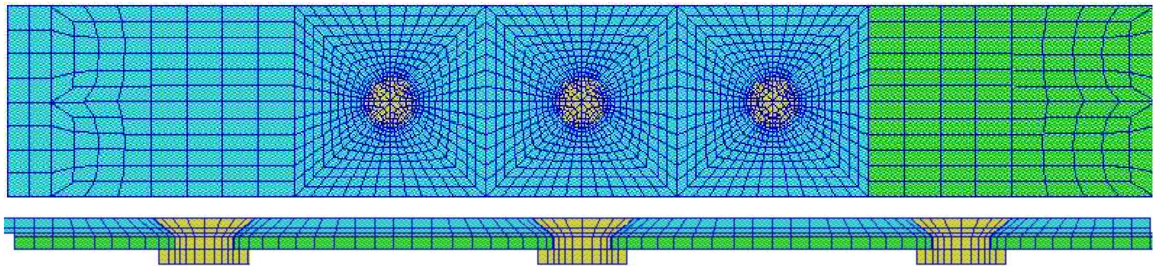

Figure NRC-2.5. Finite Element Mesh of MSD Specimen

All finite element models were generated with first-order brick elements to model the skins and rivets while nonlinear gap elements were used to model the skin/rivet interface. Symmetrical boundary conditions were applied along the edges of the joint and clamped boundary conditions were applied along one or both short edges, depending on the load case being modeled.

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

To simplify the third model (corrosion), it was assumed that the material loss due to corrosion was constant throughout the entire joint (Bellinger et al., 1994). An initial finite element run was carried out in which a pressure of 6.89 kPa (1 psi) was applied to the faying surfaces. The volume under the resulting deformed shape, V_{fem}, was determined using methods available in the Patran software. The actual volume required, V_{req}, to accommodate the corrosion products given a specific material loss was then calculated using:

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

where, V_{mr} is the molecular volume ratio, 6.454 for 2024-T3 clad aluminum, and a and b are the rivet spacing. On the basis of the results from the chemical analysis, the corrosion products were considered to be incompressible (i.e. Young's modulus of the products was significantly higher than that of aluminum). Therefore, a linear relationship was assumed to be present, and thus the pressure-to-volume ratios for the 6.89 kPa and the actual models were set equal:

$$\left(P_{req} / V_{req}\right) = \left(P_{fem} / V_{fem}\right) \qquad (2)$$

From this equation, the pressure necessary to obtain the required volume was determined, which was then reapplied to the faying surfaces in the corrosion model and the corrosion finite element analysis was re-run. D Sight images of fuselage lap joints have shown that only a small amount of pillowing occurs at the free edges compared to the area between the rivets. D Sight is an enhanced visual inspection technique that is very sensitive to out-of-plane displacements (Komorowski et al., 1996). To accommodate this smaller volume, the pressure was progressively decreased from the rivets to the free edges in the finite element model (Bellinger et al., 1997).

To determine the resultant stress that would occur from a combination of the three load cases, the elemental stress values were combined (added together) within the Patran program.

To determine the effect that skin thickness loss has on the stress in a joint, four conditions were studied: 1) no corrosion, 2) corrosion simulated by decreasing skin thickness, 3) corrosion simulated by pillowing and 4) corrosion simulated by pillowing with effective skin thickness reduction. A 10% thickness loss was assumed to be present in all the corrosion models. For the effective thickness loss models, only the outer skin thickness was reduced. The resulting maximum principal stress was non-dimensionalized with respect to the remote stress and plotted in Figure NRC-2.6 for the critical river row (in terms of potential for cracking). As shown in this figure, pillowing has a greater influence on the stress as compared to the effective thickness loss alone and thus needs to be included in a residual life assessment analysis.

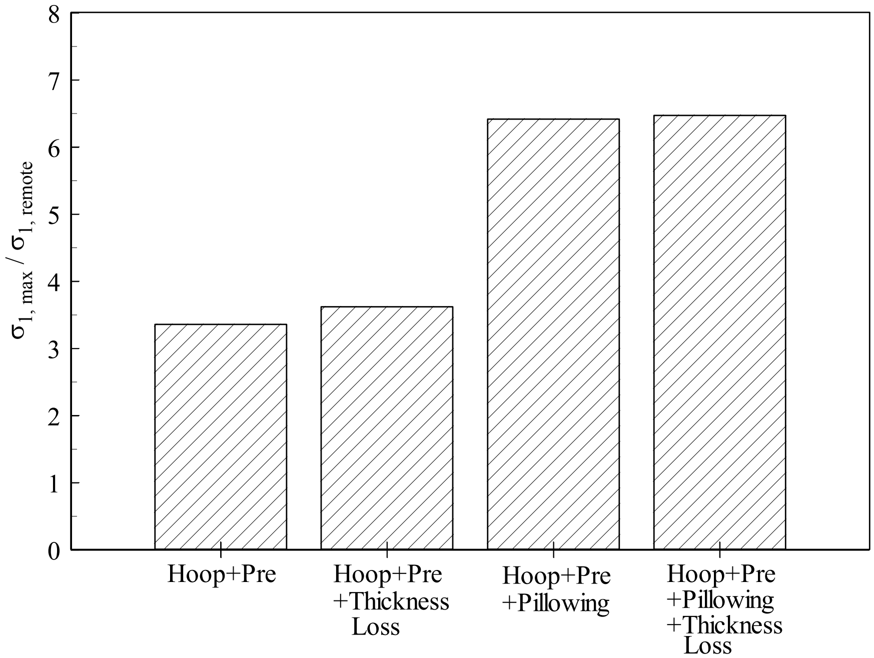

Figure NRC-2.6. Effect On Stress Caused by Reduction of Outer Skin Thickness as Compared to Pillowing (10% Thickness Loss)

The resulting stress plots for the outer faying surface at the critical rivet row area for the 2% thickness loss is shown in Figure NRC-2.7. As can be seen from this figure, the maximum stress in these joints did not occur at the location 90 degrees to the loading direction. To take this change into account, the stress values were determined along the two lines shown in this figure. These values were then non-dimensionalized with respect to the remote stress of 98.5 MPa (14.3 ksi) and the resulting stress correction curves are plotted in Figure NRC-2.8.

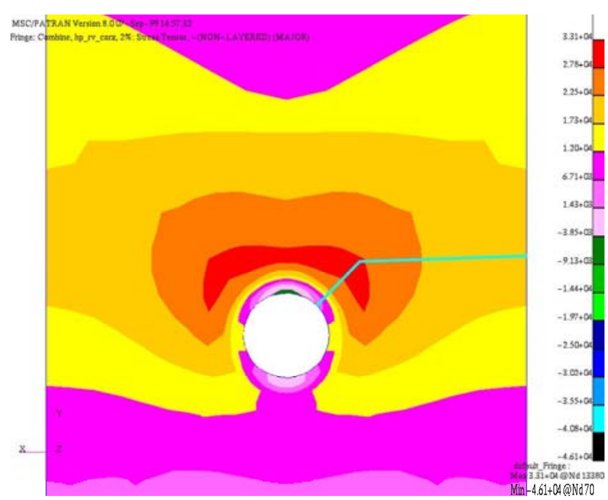

Figure NRC-2.7. Stress plot of maximum principal stress at critical rivet hole in 2% corroded specimen. The blue lines show the location where the stress results were taken to obtain the stress correction factors that were used in the AFGROW program.

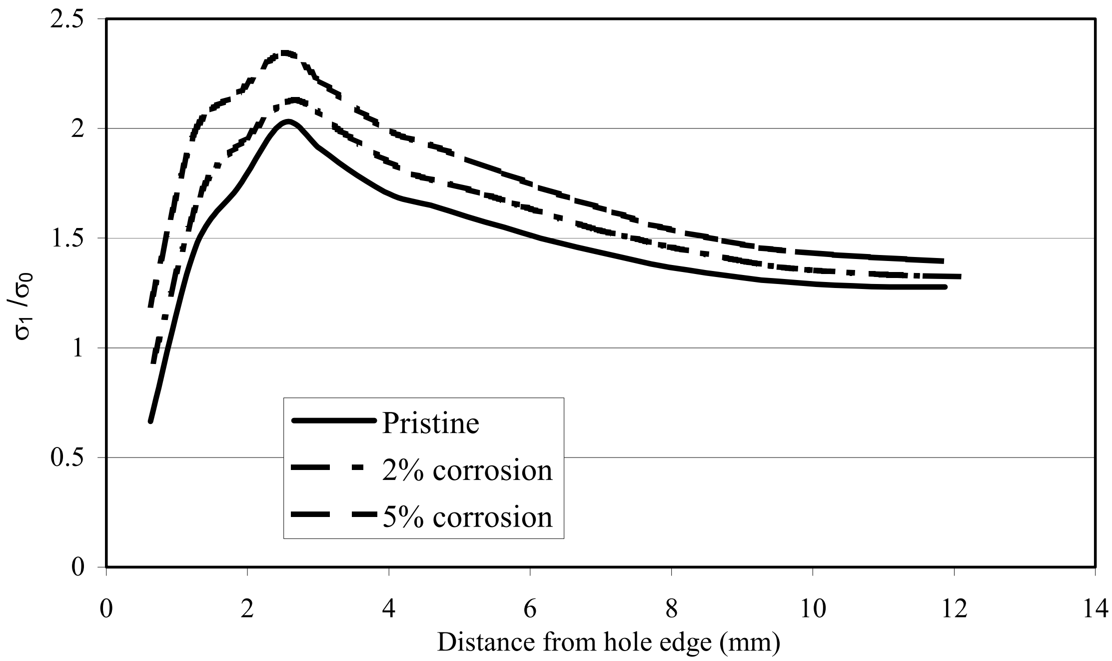

Figure NRC-2.8. Stress Correction Factors Used in AFGROW Program to Correct for Secondary Bending and Corrosion Pillowing Effects

Residual Life Predictions

A single corner crack located at a straight hole was used to predict the lap joint test results in addition to a constant amplitude loading with a load ratio of 0.02 and a maximum stress of 98.5 MPa (14.3 ksi). Short and long crack growth rate curves were used in the AFGROW program to predict the test results. For the 2% and 5% cases, the maximum stress was increased by the appropriate amount to take into account the stress increase caused by material thinning. The appropriate stress correction factors shown in Figure NRC-2.8 for the different test cases were used in the AFGROW program to take into account the secondary bending, rivet pre-load and corrosion pillowing. The results for the different test cases are presented in Table NRC-2.1 along with the average ECD value, the final crack length and the percent difference in the predicted versus observed cycles.

Table NRC-2.1. Predicted versus experimental cycles to failure

% Corrosion	ECD (mm)	Final Crack (mm)	Predicted # of Cycles	Experimental Results	% Diff
Pristine	0.05303	1.422	359600	332800	-8.1
		10.16	395700	375356	-5.4

2% Artificial	0.05512	4.313	172300	160770	-7.2
		10.16	190600	171500	-11.1
5% Combined	0.06736	8.974	104400	104107	-0.3
		12.70	106800	115409	7.5

-ve % differences indicate the predicted values over-estimated the number of cycles.

The final crack length shown in Table NRC-2.1 is the crack length at which the particular analysis was stopped. The smallest number presents the average first observed crack length. The other number gives the specified crack length that was chosen to prevent interaction with other cracks in the lap joint specimens. The experimental results are an average value of all the tests carried out at the specified average thickness loss. As can be seen from Table NRC-2.1, the majority of the predicted values give non-conservative results (over-estimate), which suggests that some of the areas near the critical rivet row had higher levels of corrosion than was first assumed. It should also be noted that the experimental results for the 5% case was based on only one test result. The remainder of the tests had either failed outside of the critical rivet hole at a large corrosion pit or a number of rivets had failed resulting in a stress redistribution that was not included in the finite element results.

Holistic Life Assessment Approach

In the lap joint specimens, corrosion and fatigue acted sequentially and thus were easier to model. Therefore it is no surprising that the calculated results were very close to the experimental ones. What was unexpected was that all the assumptions that were made (constant thickness loss, corner crack, etc.) did not appear to have a significant effect on the predicted results. It must be emphasized, however, that this particular sequence (corrosion then fatigue) would not be expected to occur in aircraft structures. Since in-service corrosion and its associated metrics, which include material thinning, surface topography (such as pits and intergranular attack) and pillowing, evolve, this implies that the ECD value would also change over time. Therefore this ECD approach could be only used to provide a quick assessment of the impact of corrosion on the remaining life of a particular component. Back-calculations could be carried out on failed components, or on samples fabricated from similarly damaged components and fatigue tested to failure, to estimate the ECD value. These calculated values could then be used to calculate the remaining life of the other components to determine if it could remain in-service until the next inspection interval.

The major disadvantage in the ECD approach is that it cannot take into account the fact that corrosion and fatigue act simultaneously in lap joints and also it is very test intensive. Another procedure known as the holistic life assessment approach, which is capable of predicting the progress of a discontinuity state in a material from cradle-to-grave (holistic) could be used to carry out a "corrosion damage tolerance" assessment of critical structural components. This approach allows for an evaluation of a change in state during any time-slice in the holistic model. The terms that have been established to reflect these states include the Initial Discontinuity States (IDS) as well as the Modified Discontinuity States (MDS). IDS is a material characteristic that is related to the intrinsic material discontinuities or the intrinsic manufacturing and joining discontinuities that are present in pristine structures. However, once age degradation is considered then the effect time has on the discontinuity state must be taken into effect. Although IDS itself does not change over time, both cyclic and time domain mechanisms continue to evolve discontinuities.

IDS is used in the analysis to determine the effect that corrosion and cyclic loading has on a structure from the 'As-Built' to 'To-Be' condition. The 'To-Be' condition is the predicted state of the strucutre after a predetermined amount of time. MDS on the other hand is used in the analysis to determine the effect that corrosion and cyclic loading has from an 'As-Is' to 'To-Be' condition. For this time interval, nondestructive inspection techniques would be used to determine the damage state present in the structure and the results would then be used in the analysis to modify the stress state.

Once IDS data and verified holistic life models become available, this approach will be the preferred method of residual life assessment.

References

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