Probabilistic Analysis of Cold Expanded Holes

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ABSTRACT

One of the many goals of a digital twin is to be able to use the "as manufactured" information to determine the aircraft structural life more accurately. Many aircraft make use of cold expanded (Cx) holes to increase the life of select fastener holes. Currently there is not an accepted method to predict the life at Cx holes accounting for the physics of the process. The Working Group on Engineered Residual Stress Implementation (ERSI) has been actively pursuing methods to accurately predict the fatigue life of Cx holes. Recently the ERSI working group put out a round robin exercise focusing on how uncertainty in fatigue response due to the random variability in residual stresses at Cx fastener holes can be captured in damage tolerance analysis (DTA).

The round robin was conducted in a single blind fashion. While most of the respondents to the round robin provided deterministic analysis, Southwest Research Institute (SwRI) performed a probabilistic analysis to better account for random variables. By performing this probabilistic analysis, SwRI is able to identify the sensitivities in the DTA to the input parameters. Once the sensitivities are known they can be used to determine the parameters that need to be tracked for use in a digital twin. This paper will demonstrate how progressively addressing various parameter uncertainties, the overall uncertainties in the crack growth prediction of a digital twin can be reduced.

1.0 INTRODUCTION

One of the many goals of a digital twin is to be able to use the "as manufactured" information to determine the aircraft structural life more accurately. Many aircraft make use of cold expanded (Cx) holes to increase the life of select fastener holes. Currently there is not an accepted method to predict the life at Cx holes accounting for the physics of the process. The Working Group on Engineered Residual Stress Implementation (ERSI) has been actively pursuing methods to accurately predict the fatigue life of Cx holes.

1.1 Cold Expansion

Cx of fastener holes was developed by Boeing Company in the early 1970s. The Cx process (the term "coldworking" is also used for this process) involves an oversized tapered mandrel being pulled through a hole. During this process, elastic–plastic deformation is created as the mandrel is pulled through (Figure 1). After the mandrel has been pulled through, it leaves a residual stress field around the hole that is compressive nearer the hole surface. This residual stress can reduce the stress concentration at the hole and delay the initiation and propagation of fatigue cracks. It is highly effective in delaying or preventing fatigue crack growth at holes undergoing cyclic loading. The technique has been applied to critical holes in highly loaded structures, such as lower wing skins, bulkheads, longerons and landing gear. The cold expansion technique can be used for new aircraft production, and it can also be applied to problem areas of in-service aircraft.

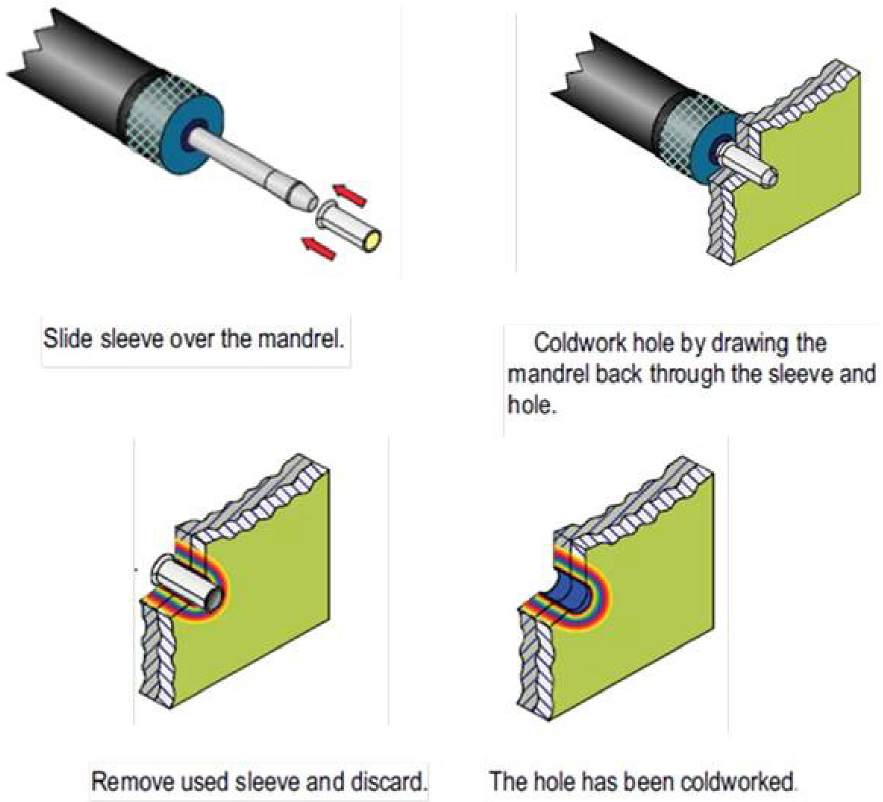

Figure 1: Coldworking process.

Recently the ERSI working group put out a round robin exercise focusing on how uncertainty in fatigue response due to the random variability in residual stresses at Cx fastener holes can be captured in damage tolerance analysis (DTA). The round robin was conducted in a single blind fashion. The round robin provided data on the initial flaw sizes, variation in residual stress fields for Cx holes, crack growth rate data and test coupon geometry. The round robin used Distribution A resources generated by the Air Force Research Laboratory (AFRL) as part of the Enhanced Lifing Management for Engineered Residual Stress (ELMERS) program. The round robin problem will be used to demonstration how having progressively more knowledge of the individual aircraft state can be used in a digital twin to determine the number of cycles to failure.

2.0 PROBABILISTIC ANALYSIS OF COLD EXPANDED HOLES

Damage tolerance analysis (DTA) is widely used in the aerospace industry to determine inspection intervals and safety limits for aircraft primary structure. Preforming DTA of cold expanded holes requires numerous inputs all of which have some variability. They include material crack growth rate, fracture toughness, geometry, initial crack size, Cx residual stress field, retardation affects and usage spectrum. To account for this variability SwRI performed a probabilistic crack growth analysis with the NESSUS® software. NESSUS is a modular computer software program for performing probabilistic analysis of structural/mechanical components and systems. We coupled NESSUS with AFGROW to determine the number of cycles to failure. AFGROW is a Fracture Mechanics and Fatigue Crack Growth Analysis software tool.

2.1 Random Variables

The random variables were material crack growth rate, initial crack surface length, initial crack bore length, spectrum scale factor, amount of Cx and for variable amplitude loading and the amount of crack growth retardation. The test data generated from the ELMERS coupon test was used to develop some of the distributions for the random variables. The ELMERS test defined the coupon geometry, material, spectrum loading and initial crack size. Based on results from previous probabilistic DTA programs the fracture toughness hole diameter and edge distance were dropped from consideration as random variables. The previous programs showed the cycles to failure is not sensitive to these variables if the hole has good edge margin.

2.1.1 Crack Growth Rate

The material used in the round robin was 7050-T7451 Plate. The ELMERS test provided crack growth rate data for two batched of plate at a stress ration of 0.10. They provided an initial tabular fit to the test data and expanded it to additional stress ratios. Figure 2 shows the test data for R = 0.1 and the proved fit. As can be seen there is a fair amount of variability in the test data (note the log-log scale that compresses the scatter visually). The standard deviation for each point in the table was estimated to be 0.2.

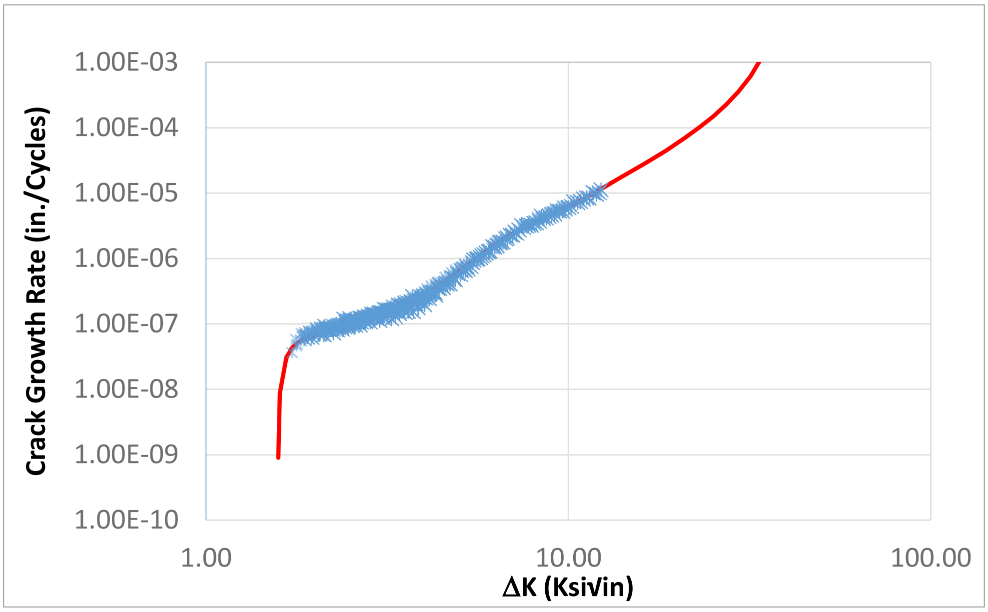

Figure 2: Crack growth rate data for a stress ratio of 0.1 in 7050-T7451 plate.

2.1.2 Residual Stress Field

The cold expansion process causes compressive residual stress near the boar of the fastener hole and is balanced out by residual tension stress farther away from the hole. The residual compressive stresses are highly effective in slowing down or completely arresting crack growth from the fasteners holes without adding weight to the structure. In order to determine the life for a cold expanded hole, knowledge of this residual stress field is critical.

There are various ways to measure the residual stress levels. One of these is the contour method. The contour method uses the principle that a body containing residual stress will deform as a result of sectioning, and that the forces required to restore the sectioned part to its original shape are equal to the residual stress released by sectioning. Through careful sectioning, precision inspection techniques and finite element analysis it is possible to map complex 2D residual stress fields in a wide range of part geometries and materials. Figure 3 shows a typical residual stress field of a cold expanded hole with compression near the boar of the hole and tension away from the hole.

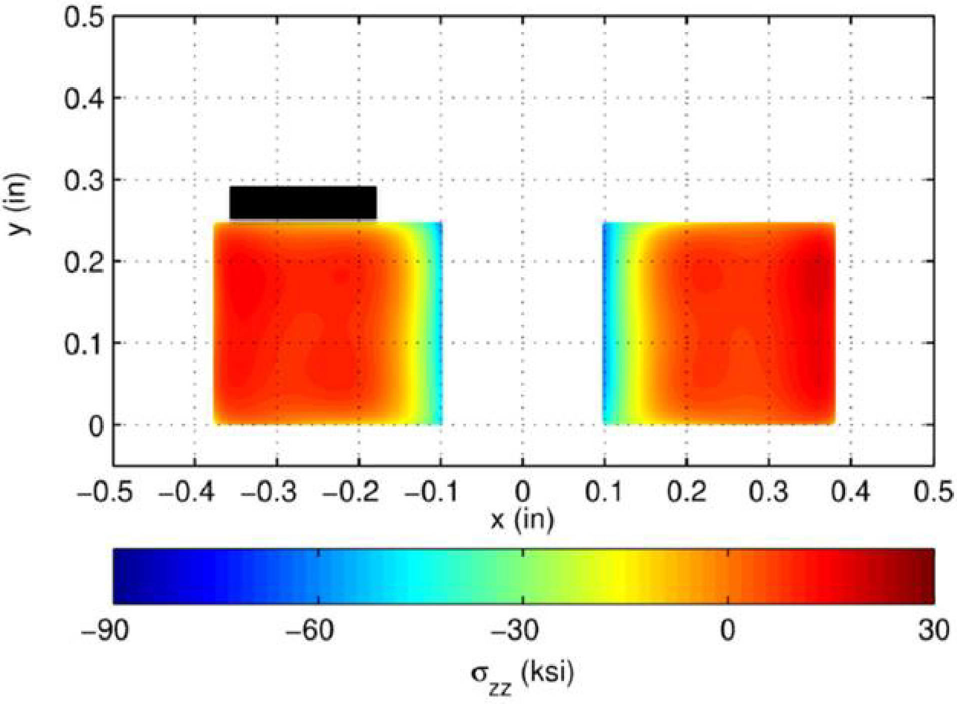

Figure 3: Typical residual stress field of a cold expanded hole.

ELMERS measured multiple residual stress fields for the same nominal hole geometry in two batches of material in order to measure the variability in cold expanded hole residual stress fields. In this analysis SwRI used the two-point residual stress field capability of AFGROW. That basically allows for the input of the residual stress along the surface of the part and the stress field down the boar of the part. Figure 4 shows the measured residual stress near the surface for 10 cold expanded holes. The red line shows the nominal tabular fit to the test data. The standard deviation for each point in the table was estimated to be 0.2.

2.1.3 Additional Random Variables

In addition to the variability measured in ELMERS, there are additional random variables looked at in the analysis. They are the spectrum scale factor, retardation amount and initial flaw size. For the initial crack size there is potentially measurement error for the stating crack size. That was taken to be 0.002 inch for the a and c crack tips.

Under variable amplitude spectrum loading there are often periotic overloads that cause crack growth rate retardation. The amount of retardation is typically determined from coupon testing. For the analysis SwRI used the shut off overload ratio (SOLR) of the Willenborg Retardation Model. Depending on the spectrum SOLR can be anyplace from 1.5 to 4 or greater. For the blind prediction SwRI assumed an SOLR of 2.75 with a standard deviation of 0.5 based on experience with high strength aluminums.

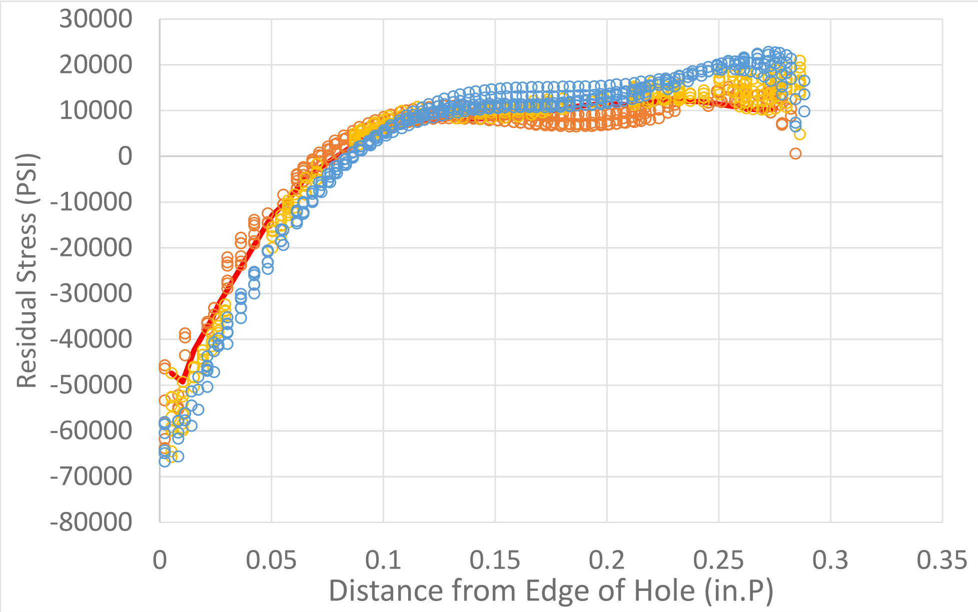

Figure 4: Measured residual stress for 10 cold expanded holes.

For the variable amplitude loading ELMERS provided the normalized test sequence (Figure 5). For the coupon testing the spectrum was scaled by 50.3 ksi. While the test sequence is applicable to the coupon test, in a fleet of aircraft the spectrum would be different for each aircraft. To account for this variation in aircraft usage it was assume the standard deviation of the scale factor was 2.5 ksi.

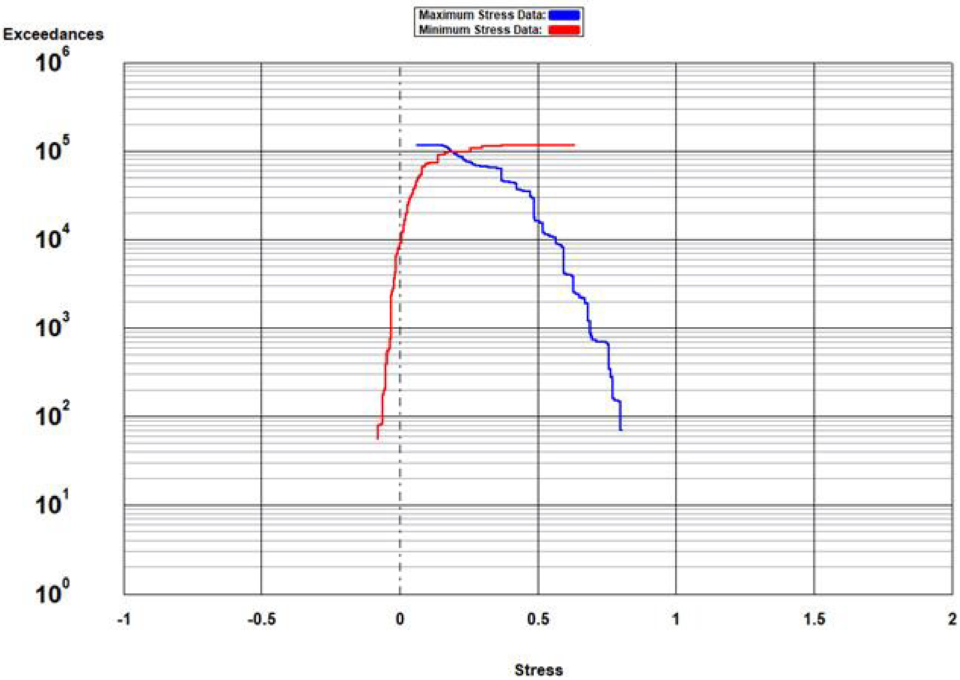

Figure 5: Test sequence exceedance diagram.

3.0 PROBABILISTIC ANALYSIS

An AFGROW crack growth model was set up with the nominal values of the random variables plus other constant inputs based on the coupon geometry. The coupon width is 0.75 in., the thickness is 0.25 in., and the hole diameter is 0.1875 in. The plane strain fracture toughness is 40 ksi root inch, the plain stress fracture toughness is 80 ksi root inch and the yield strength was 68 ksi.

The NESUS software package was used to perform the probabilistic analysis. NESSUS is a modular computer software program for performing probabilistic analysis of structural/mechanical components and systems. NESSUS combines state-of-the-art probabilistic algorithms with general-purpose numerical analysis methods to compute the probabilistic response and reliability of engineered systems. Variations in loading, material properties, geometry, boundary conditions, and initial conditions can be simulated. Many deterministic modelling tools can be used such as finite element, boundary element, hydrocodes, and others. For this case SwRI developed a Python script to interface NESSUS with AFGROW.

A NESSUS analysis was set up with the random variables described above. The AFGROW input file was imported into NESSUS and the random variables were mapped to the correct characters in the input file. NESSUS could then change the input file for each using the random variables distributions. The probabilistic analysis was performed using the advanced mean value method plus (AMV+) method in NESUS. The advanced mean value method plus (AMV+) constructs a first-order Taylor series approximation of the performance function at the mean of the inputs and uses this approximation to estimate the most probable point (MPP). The failure probability is then based on a first-order limit state approximation with additional iterations used when locating the MPP to obtain a more accurate result.

3.1 Initial Analysis

In order to demonstrate how probabilistic analysis can be used in a digital twin effort we start with the problem as describes above. It can be thought of as the initial design of the aircraft where you are doing a generic analysis for any aircraft design. There are still a lot of unknowns in the analysis. For example, there may be a fatigue spectrum used to design the aircraft, but it is not necessarily how the aircraft will actually be flown was fielded.

For the initial analysis, the random variables used are given in Table 1. For item that have table for the mean the entire curve described by the tabular data is scaled by the variable. For example, if the DADN variable is 0.1 for a crack growth analysis, the entire curve is scaled by 1.1. The initial analysis was performed and the probability of failure at various number of cycles in the spectrum was determined along with the probabilistic importance factors and how sensitive the results are to the various random variables.

Table 1: Initial Random Variable Definitions.

Description	Variable	Distribution	Mean	Standard Deviation
C crack tip initial length	CTIP	Normal	0.034	0.002
A crack tip initial length	ATIP	Normal	0.05	0.002
Spectrum Scale Factor	STRSCL	Normal	50.3	2.5
Crack Growth Rate	DADN	Normal	Table	0.2
Residual stress field due to Cx	CX	Normal	Table	0.2
Crack growth retardation	SOLR	Normal	2.75	0.5

Figure 6 shows the cumulative probably of failure for the initial analysis. As can be seen there is a large amount of scatter as would be expected if analysing a fleet of aircraft. Figure 7 shows the importance factors at the 5% failure level that represent early failures. As can be seen all the variables have some affect as expected since the variables that do not have much effect on cycles to failure base d on past programs have already been removed from the random variable list.

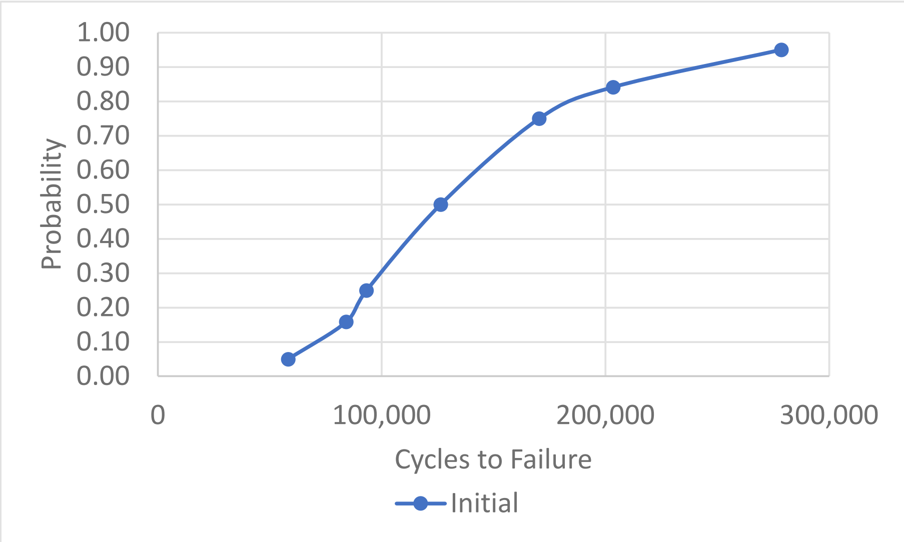

Figure 6: Cumulative probability of failure for the initial case.

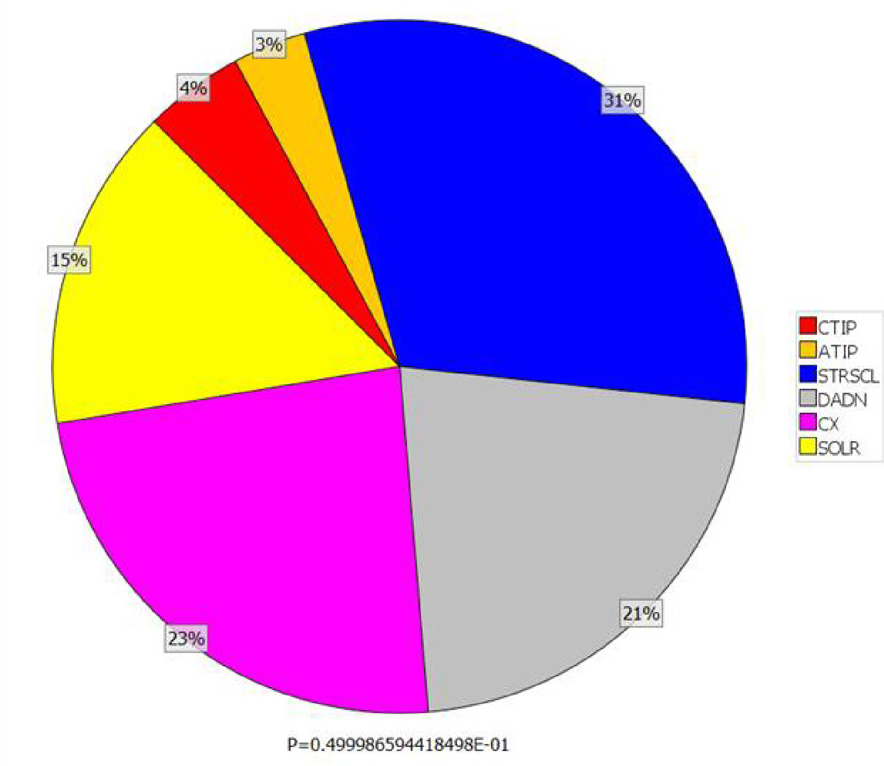

Figure 7: Importance factors for the initial case at the 5% probability level.

3.2 SOLR Analysis

From the importance factors it can be seen that the SOLR variable is an import variable due to the large amount of scatter assumed for the blind prediction. AFTER the blind prediction, test data was provided for the number of cycles to failure for the nominal coupon geometry. This allowed us to tune the SOLR variable so that the nominal deterministic analyse matched the test data. This resulted in a mean SOLR value of 2.6 with a much smaller standard deviation from the test data of 0.05. Testing to determine the amount of retardation in a crack growth analysis is widely performed.

The analysis was performed again with the new inputs for SOLR. The cumulative probability of failure for the updated SOLR value is added to the graph (Figure 8). As can be seen this reduces the scatter a little and the nominal life has increased.

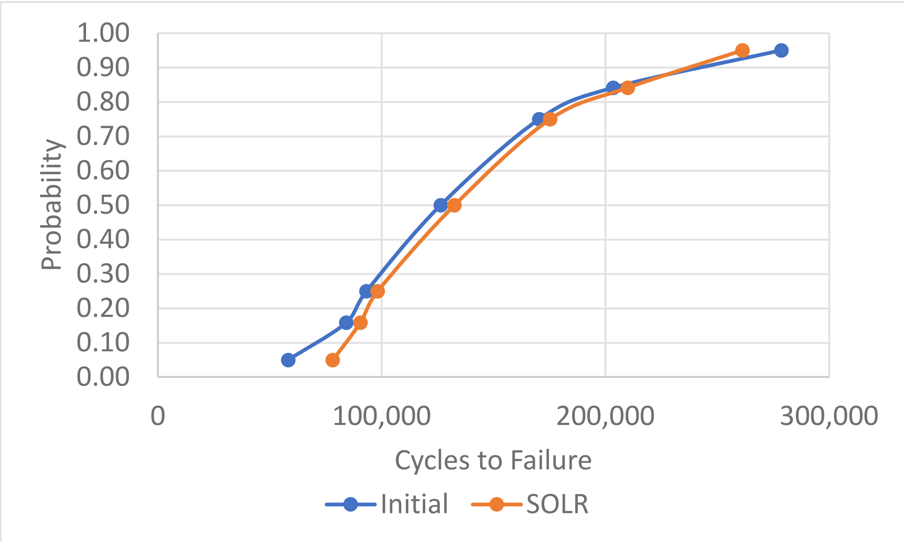

Figure 8: Comparing the cumulative probability of failure between the initial case and the reduced variability in SOLR case.

3.3 Digital Twin Analysis

Reviewing the results of the probabilistic analysis including the sensitivity results and importance factors can be used to guide which items should be tracked in a digital to reduce uncertainty in the analysis. If the actual crack growth rate for each batch of material was tracked as part of the digital twin that would reduce the scatter associated with the crack growth rate. Similar if individual aircraft tracking of the actual flight manoeuvres were recorded the variability in the usage would be reduced. Likewise, if the actual residual stress field could be measure and tracked with a digital twin that would reduce the uncertainty even further.

To demonstrate how this could work, a series of progressive analysis was performed for reducing the standard deviation for each of the remaining items. First it was assumed the digital tween included tracking the actual usage. There is still variability even tracking the actual usage due stress to load equation accuracy, measurement accuracy and using past usage history to project into the future. For the digital twin it was assumed the spectrum scale factor standard deviation was reduce to 0.25. Next for the crack growth rate, the standard deviation was reduced to 0.05. There is still variation in crack growth rate even for a single batch of material, but it is much reduced from the multiple batches of material. Finally, if the actual residual stress field could be measured that would further reduce the uncertainty. Again, there would still be a deviation from the measured stress based on how accurate the stress field could be measure. It was assumed the digital twin could determine the stress field to a standard deviation of 0.05.

Figure 9 shows the results of adding the reduced uncertainty of each variable in a progressive manner. As can be seen in the figure the more data that can be tracked in the digital twin the less scatter there is in the results.

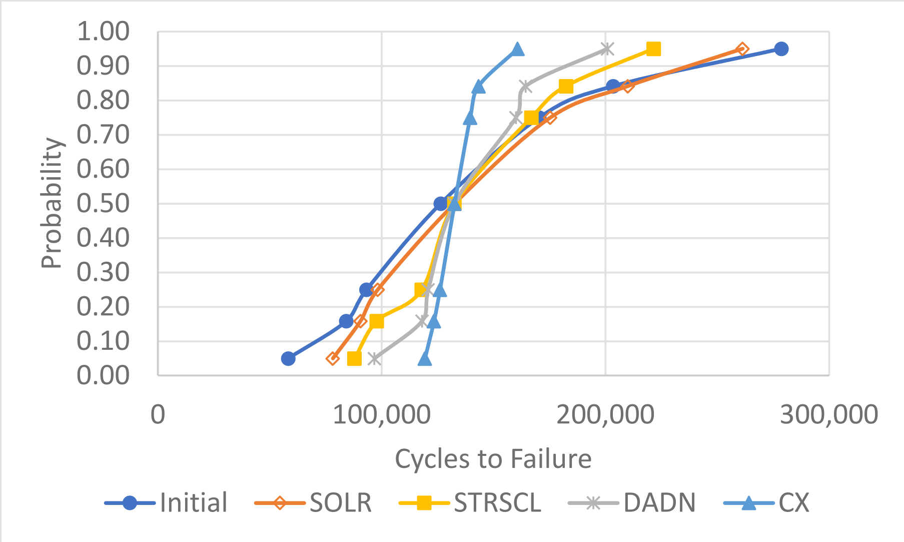

Figure 9: Effects on cumulative probability for sequentially reducing uncertainty in the various random variables.

4.0 CONCLUSION

Preforming DTA of cold expanded holes is a complex problem with multiple random variables. This paper has demonstrated how probabilistic can be used to reduce the uncertainty in the results for a digital twin of a cold worked hole. These same methods could be used for trade off studies. For example, tracking the crack growth rate for every part that is being made by suppliers may be prohibitively expensive. These methods could be used to determine the increased risk of not tracking that variable.

5.0 ACKNOWLEDGEMENTS

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