Probabilistic Analysis of Cold Expanded Holes

SOUTHWEST RESEARCH INSTITUTE®

David Wieland
Southwest Research Institute
United States of America
dwieland@swri.org

Outline

- Acknowledgments
- Abstract
- Background
- ERSI Round Robin Data
- Damage Tolerance Analysis of cold expanded hole
- Random variables
- Baseline Probabilistic Analysis
- Effects of tracking variables in a digital twin
- Conclusion

Acknowledgments

- Engineered Residual Stress Implementation (ERSI) Working Group
- Air Force Research Laboratory (AFRL)
  - This research used resources generated by the Air Force Research Laboratory (AFRL) as part of the Enhanced Lifing Management for Engineered Residual Stress (ELMERS) program in collaboration with the Materials Solutions Network at CHESS (AFRL Contract No. FA8650-19-2-5220) and the Advanced Photon Source (APS). APS is a U.S. Department of Energy (DOE) Office of Science user facility operated for the DOE Office of Science by Argonne National Laboratory (Contract No. DE-AC02-06CH11357).

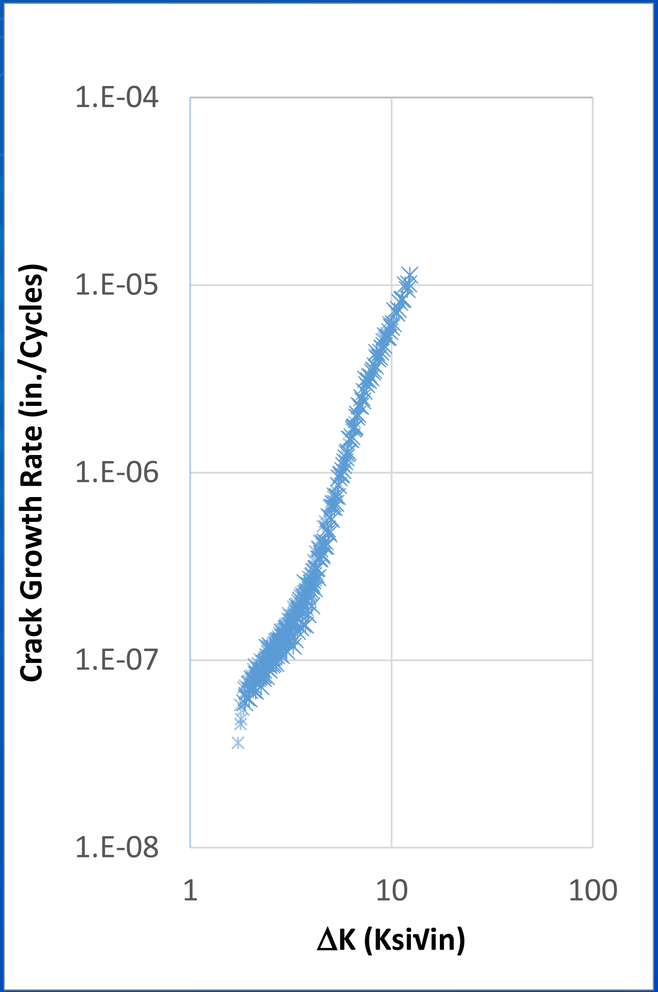
ABSTRACT

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 can reduce the overall uncertainties in the crack growth prediction of a digital twin.

Overview of Linear Elastic Fracture Mechanics (LEFM)

- Fracture mechanics is used to predict how a crack will grow in a structure from an initial state to failure.
- LEFM assumes there is a crack like defect present at a structural critical location or detail
- Cracks cause a stress intensity factor
  - Function of geometry, crack length, loading residual stresses
- Cyclic loading causes a change in the stress intensity factor (ΔK)
- Crack growth rates are determined from material testing
- ΔK is used to determine how much a crack grows for each cyclic load applied to the structure
- Parts fails at a critical stress intensity
- Spectrum loading can cause crack growth retardation



Cold Expansion (Cx)

- Cold expansion can increase crack growth life at fastener holes by imparting the compressive residual stress field around the hole.
- The effectiveness of the process is a complex interaction between geometry, amount of applied expansion, material and applied loading
- When applied properly it can increase crack growth life by orders of magnitude
- Often used in commercial and military aerospace applications.

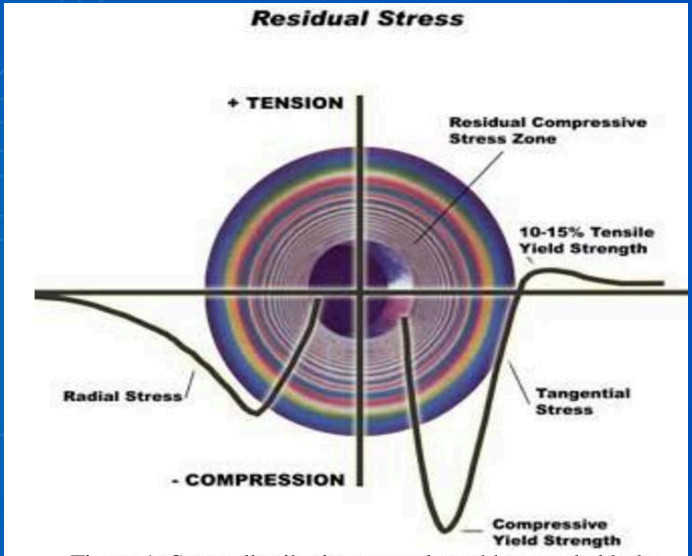
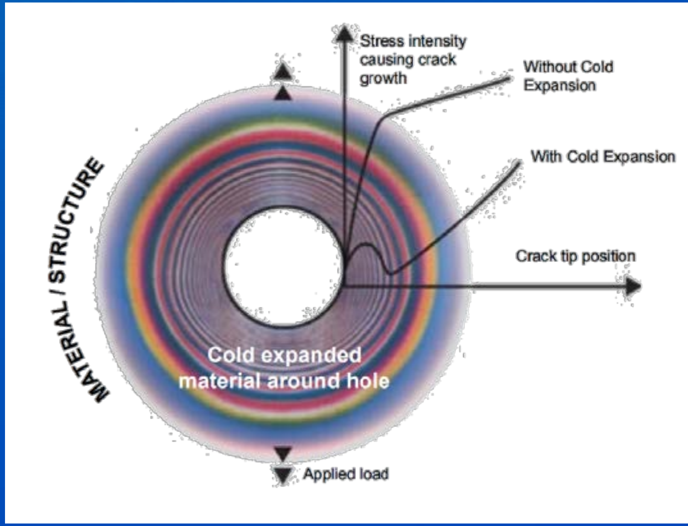


Figure 1: Stress distribution around a cold expanded hole



Cx Process

- Drill starting hole
- Ream to starting diameter
- Verify starting diameter
- Check mandrel
- Slide sleeve onto mandrel
- Insert mandrel into hole
- Perform Cx
- Remove sleeve
- Verify expansion after Cx
- Ream to final diameter if necessary
- Variability in residual stress from Cx process

Video © FTI

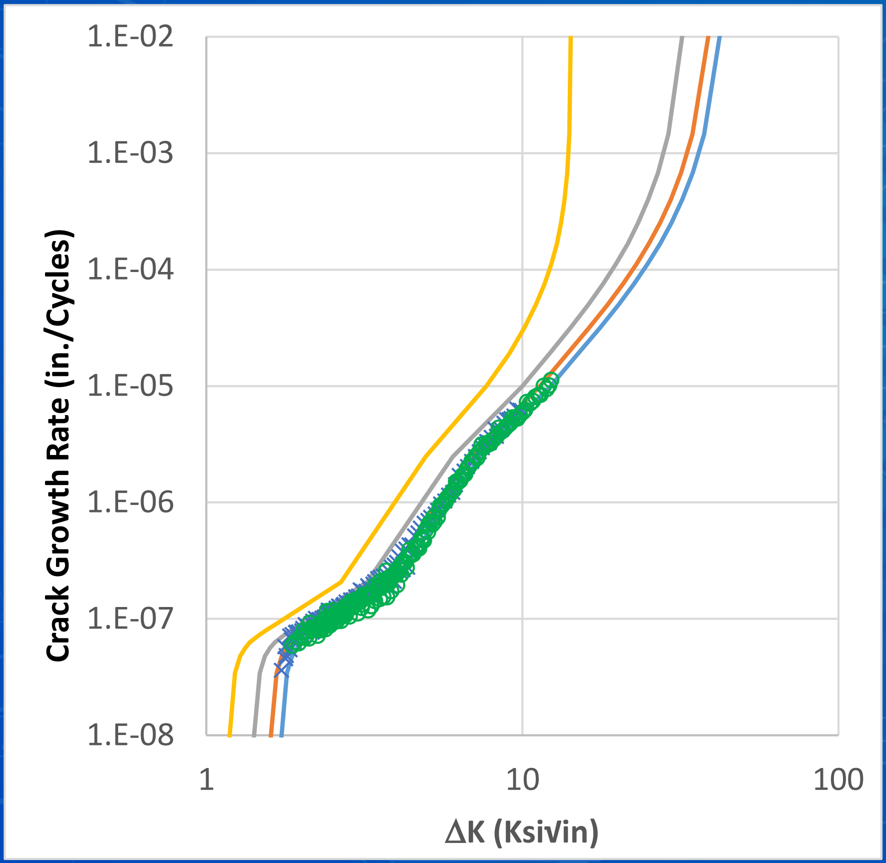
ERSI Round Robin

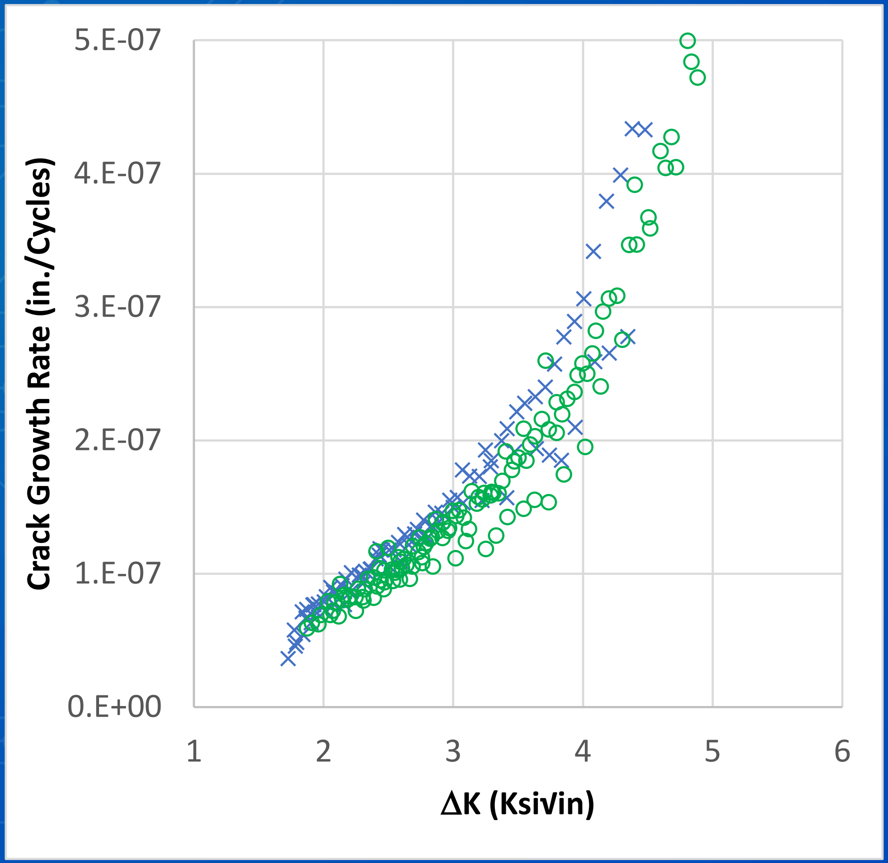
- Engineered Residual Stress Implementation group held a round robin analysis challenge.
  - Predicting life of cold expanded holes with variability
- Provide some test data on material and cold expanded hole residual stress field variability
- Blind predictions submitted before coupon testing for variable amplitude spectrum loading was performed
- Used as a demonstration case for this presentation

ERSI Material Data

- Two lots of 7050-T7451 Plate
- Poisson Ratio = 0.33
- Ultimate Strength (Ksi; L; two replicates)
  - Lot A: 79.8 & 80.2
  - Lot B: 75.8 & 76.3
- Yield Strength (Ksi; L; two replicates)
  - Lot A: 71.4 & 72.2
  - Lot B: 66.6 & 67.2
- KQ (Ksi-√in; L-T) Lot A: 34.1
- KIC (Ksi-√in; L-T) Lot B: 40.4
- Recommended KC (Ksi-√in) 80
- Recommended KIC (Ksi-√in) 40

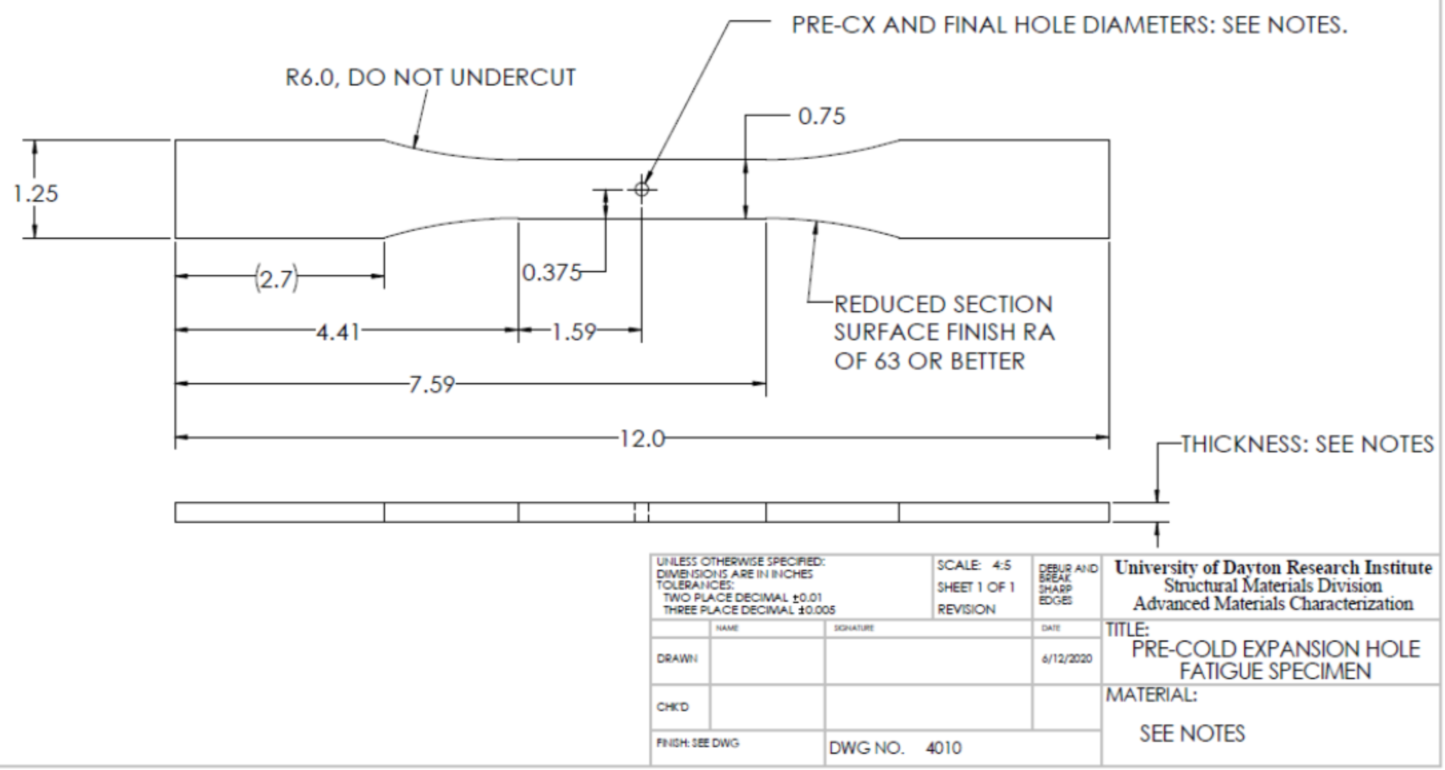
ERSI Crack Grow Rate Data & Fit





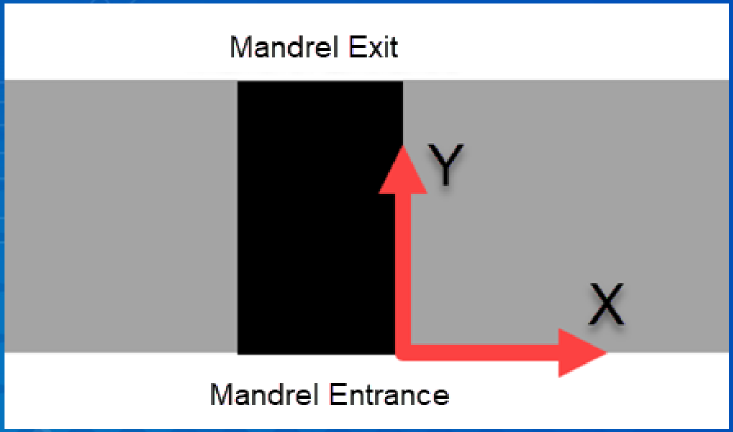
ERSI Test Coupon Geometry

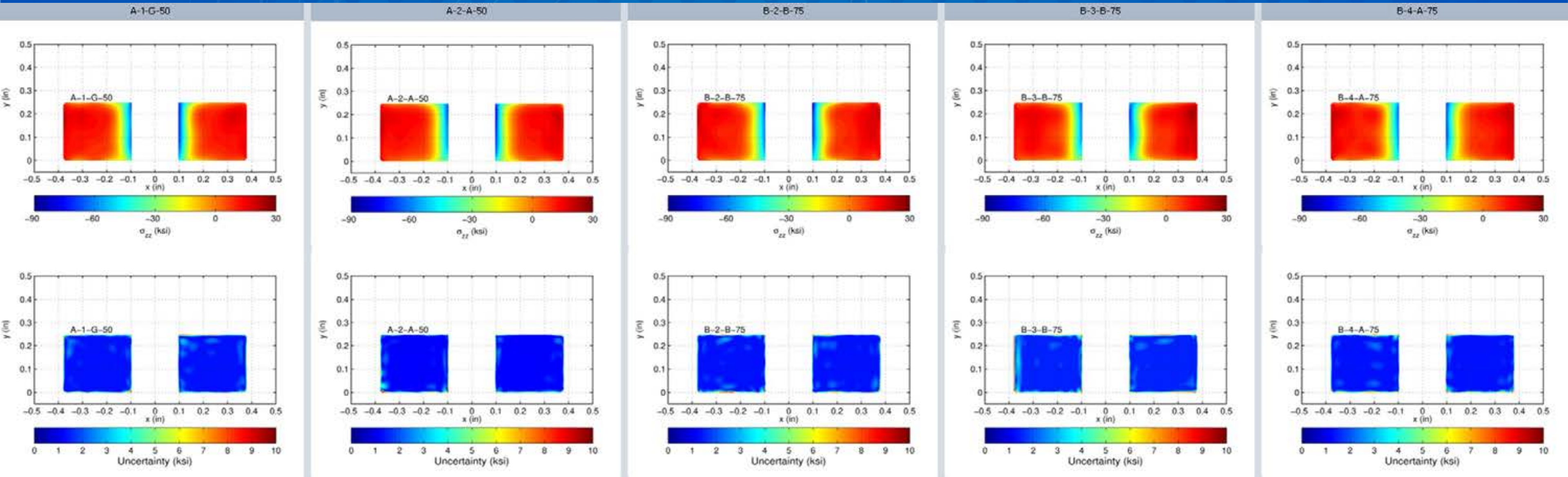
Thickness	Material	Pre-CX Diameter	Final Diameter
0.25	Aluminum 7050	0.170" +/-0.001"	0.1875" +/-0.001"



ERSI Residual Stress Field

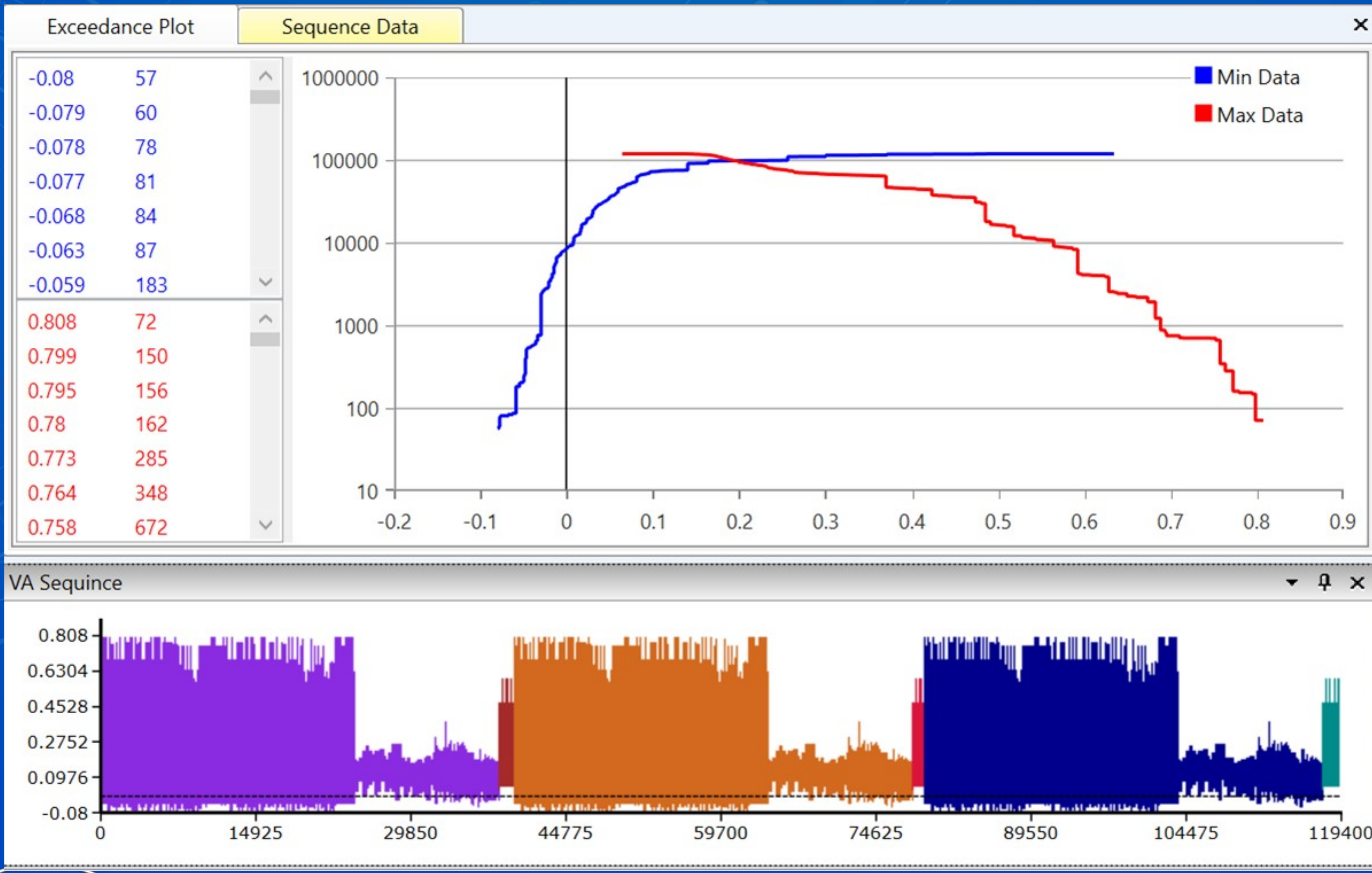
- Provided full 2D residual stress field for 17 Cx holes
  - From 2 materials
  - 3 levels of Cx, "nominal" Cx, low Cx and 3 high cx





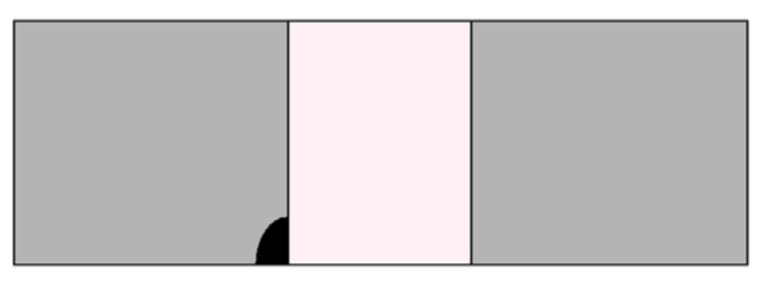
ERSI Variable amplitude (VA) Spectrum

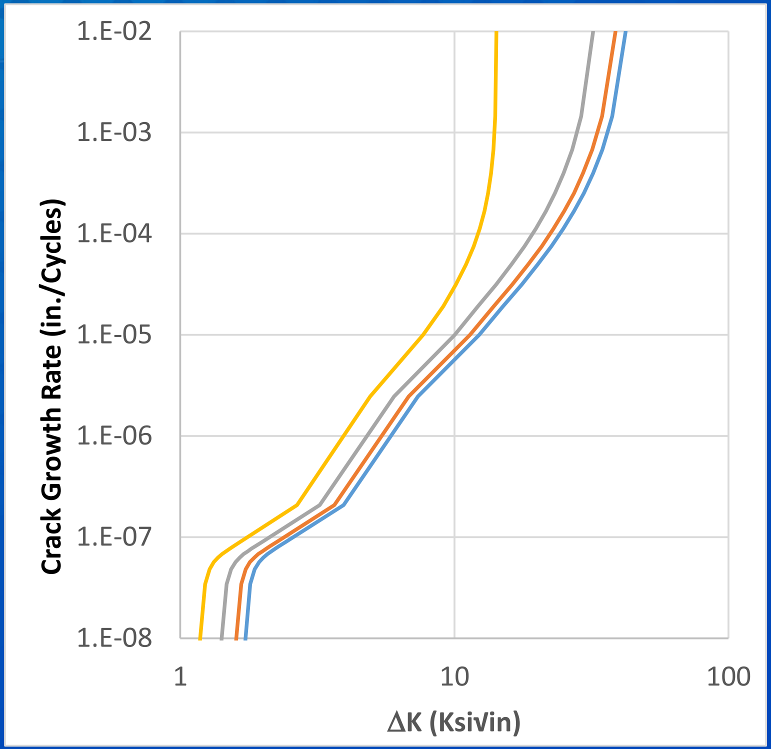
- 119400 Cycles



Damage Tolerance Analysis (DTA) of cold expanded hole

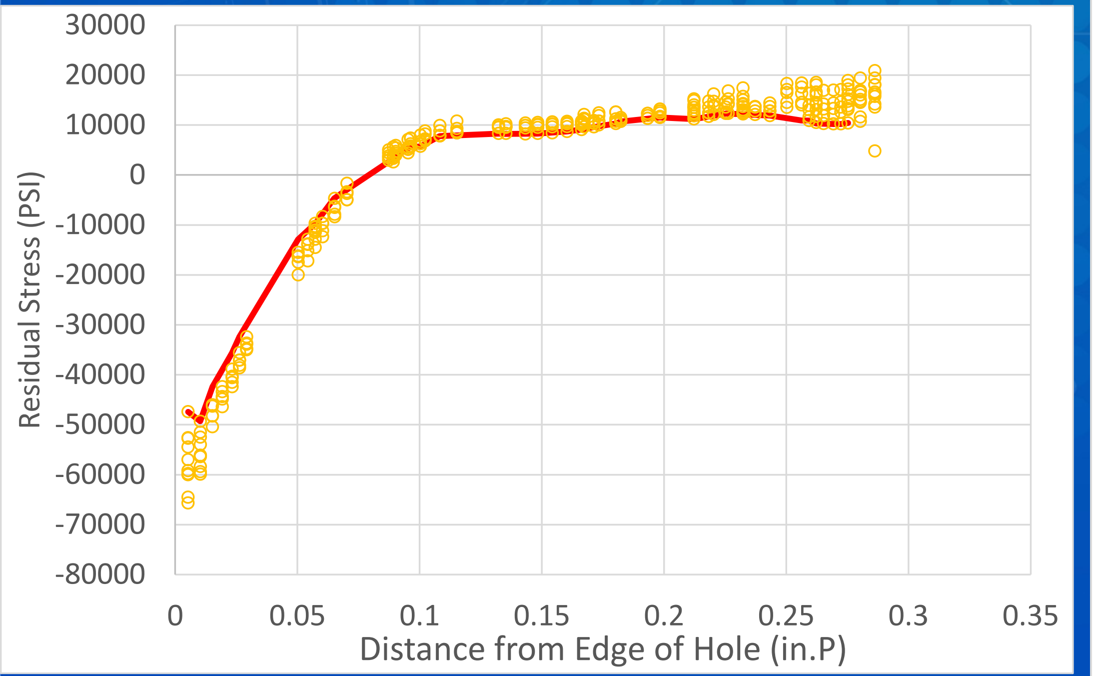
- DTA performed with AFGROW
- Advanced corner crack at a hole model used
- Geometry
  - Width = 0.75, thickness = 0.25, diameter = 0.1875, c crack length = 0.034, a crack length = 0.050
- Material
  - 7050-T7451
- Spectrum scale factor = 50.3
- Spectrum Loading Retardation, SOLR = 2.75

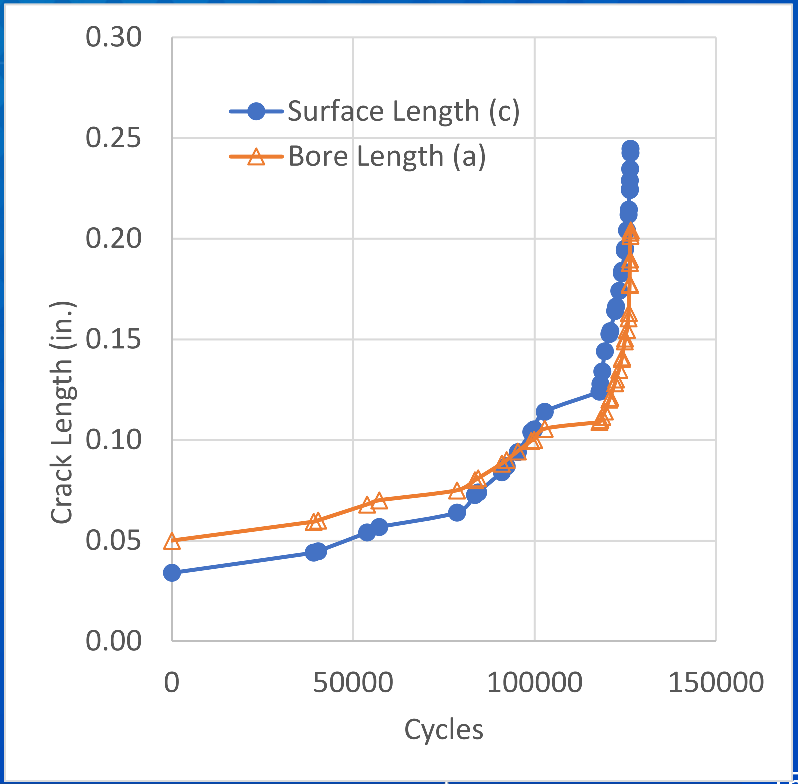




DTA Results for nominal Cx condition

- Analyzed nominal geometry with AFGROWs two-point residual stress field capability
- Used lower bound of nominal measured residual stresses
- Predicted 126434 cycles to failure





NESSUS® Probabilistic Analysis Software

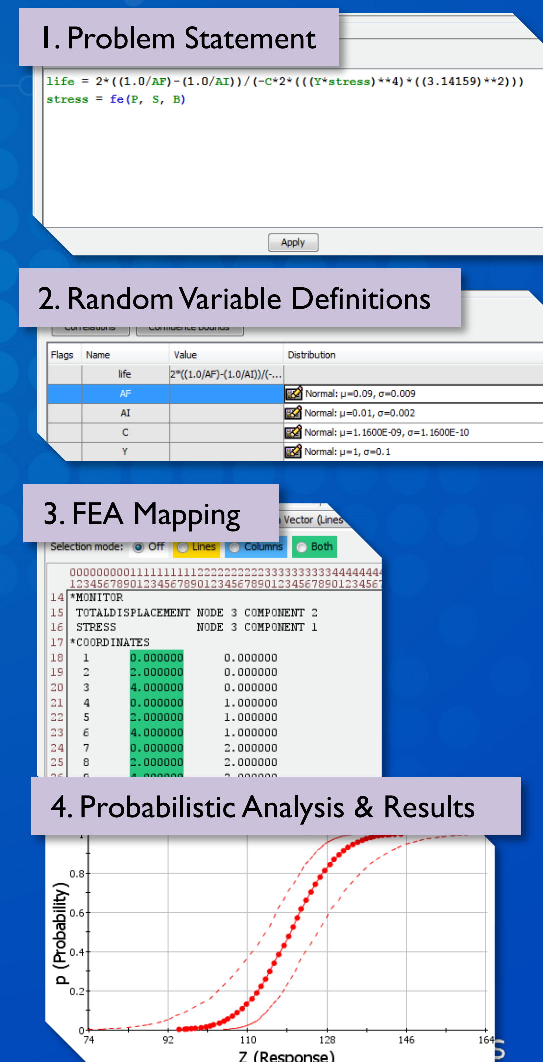
NESSUS® is a **general purpose** software tool for probabilistic analysis

Problem Statement and Model Interfaces

- Problem statement allows mixture of analytical equations and external models
- Flexible definitions of input random variables and uncertainties
- Powerful capabilities for mapping variables into input files
- Custom interfaces for most popular FEA packages

Analysis Algorithms

- 16 probabilistic analysis and reliability methods
- Separation of natural variability and uncertainty as needed
- Advanced response surface models
- Design of computer experiments



swri.org

Probabilistic Analysis

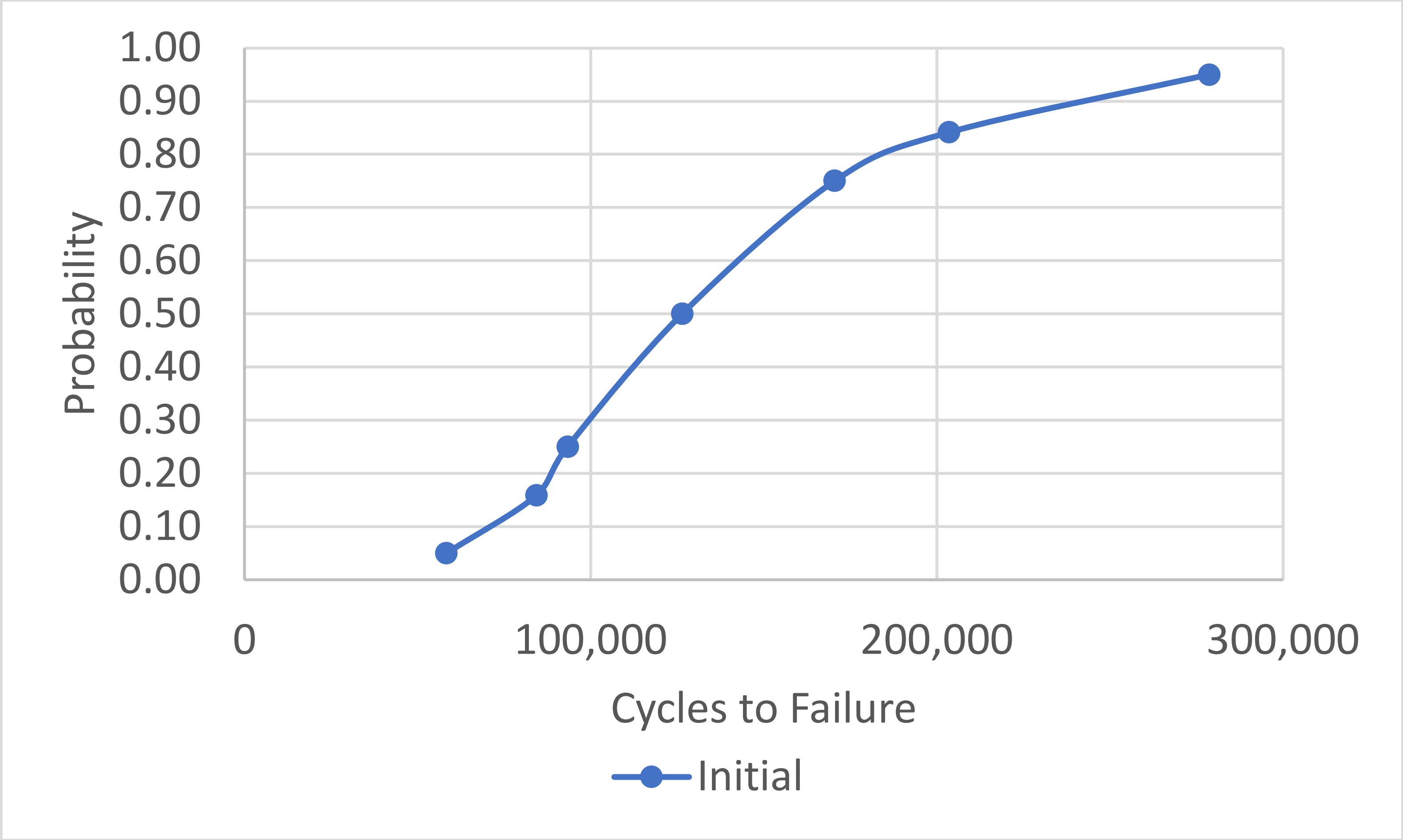
- Linked AFGROW to Nessus with a Python script
- Random variables

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 (da/dN) scale factor	DADN	Normal	Table	0.2
Residual stress field scale factor due to Cx	CX	Normal	Table	0.2
Crack growth retardation	SOLR	Normal	2.75	0.5

- Solved with Advanced Mean Value Plus (AMV+)

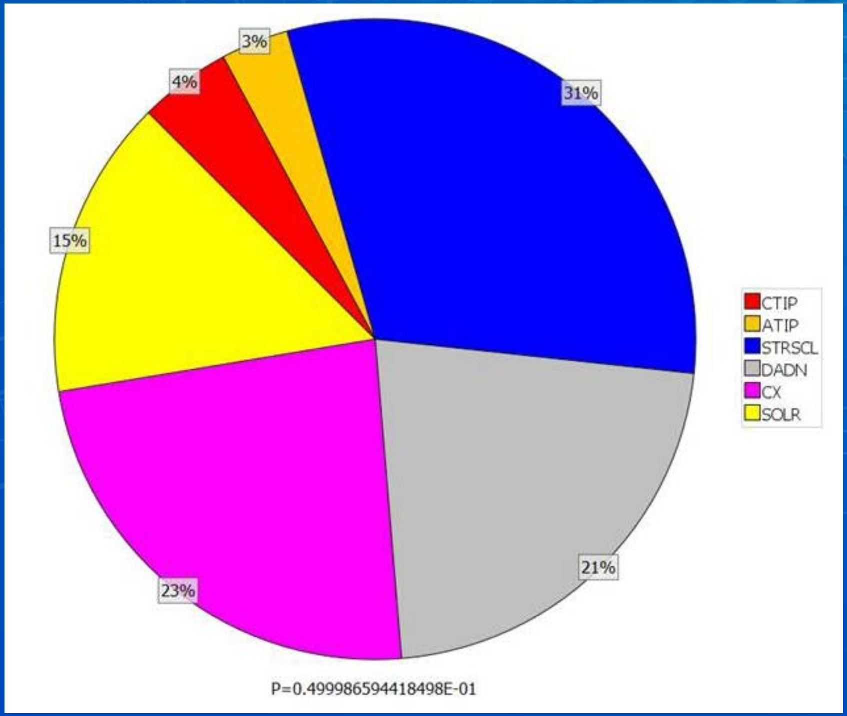
Initial Probabilistic Analysis Results

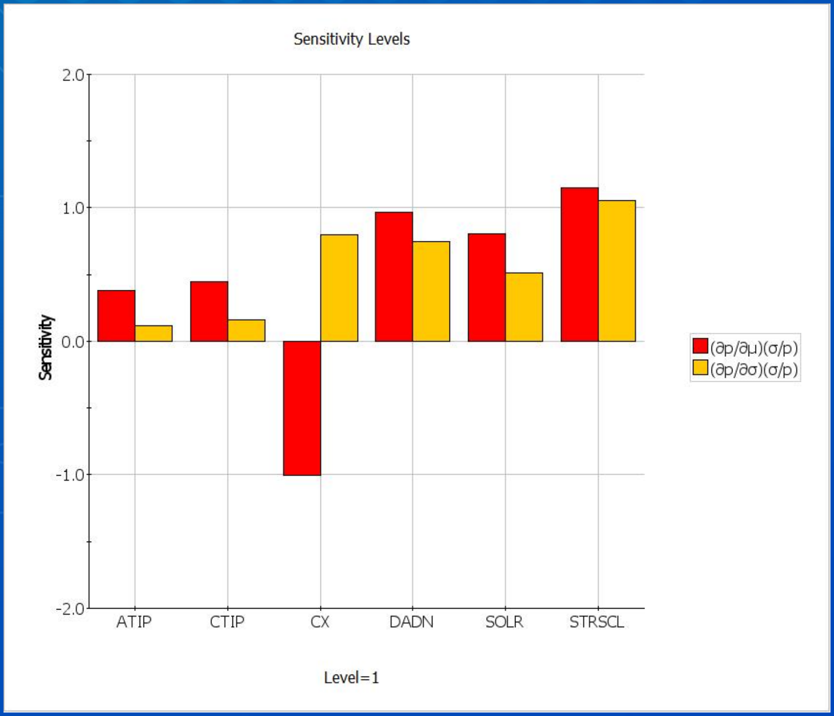
- Large Variability in Life Results



Reduce variability in results

- Ideally tracking more information with a digital twin will reduce the variability and give a more individual aircraft result
- Importance factors and sensitivities can help determine what the digital twin should track



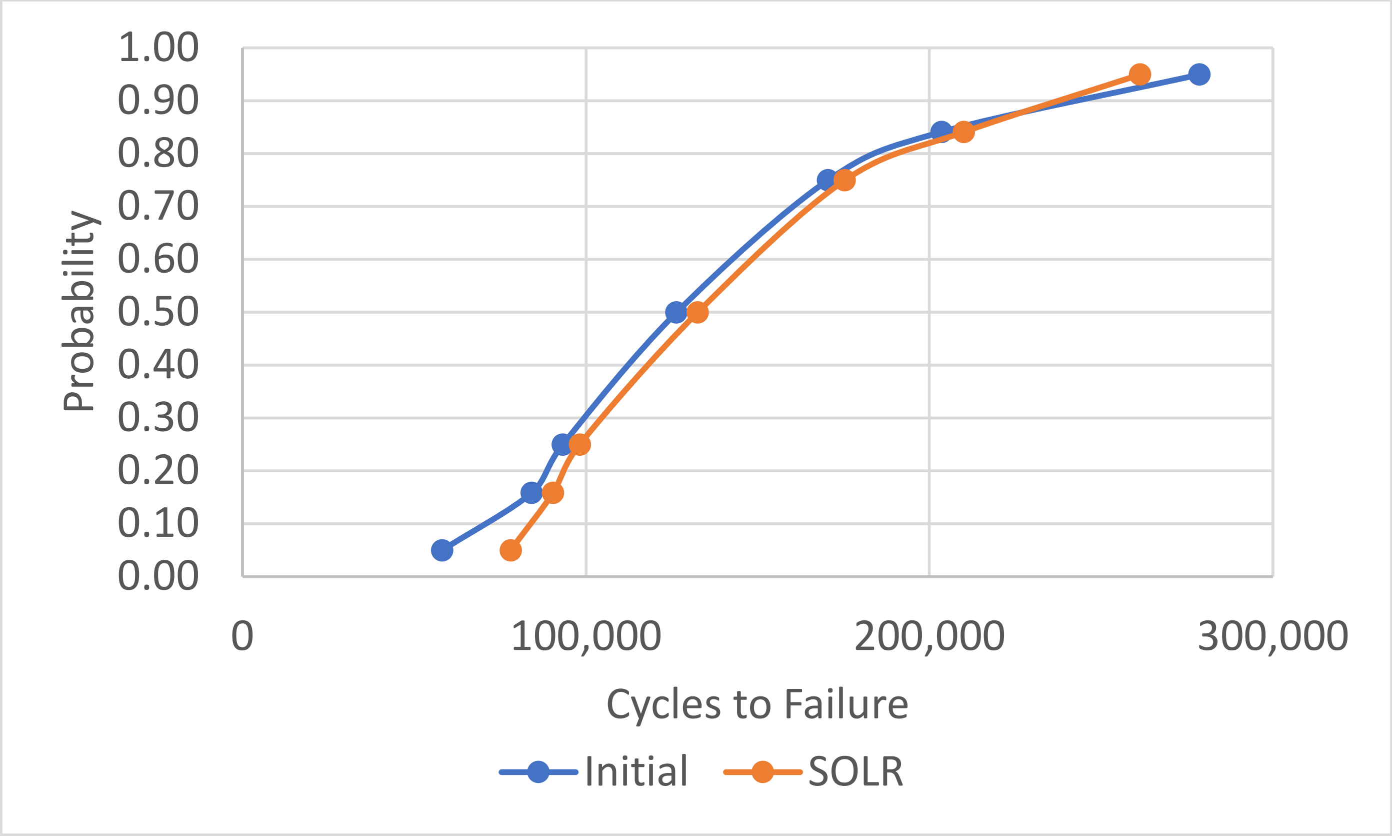


Effects of updating SOLR

- Blind prediction had a large variation in SOLR based on history with aluminum for a wide variety of spectrums
- Determining SOLR for actual spectrum can reduce variability in the results.
- SOLR determined by correlating to nominal test results
- SOLR of 2.6 results in the deterministic analysis matching the test life of a Cx hole with average amount of cold working
- Determining retardation effects is typical done during development and sustainment.
- Could easily be added to digital twin
- Probabilistic Analysis updated with SOLR = 2.6 and standard deviation of 0.05

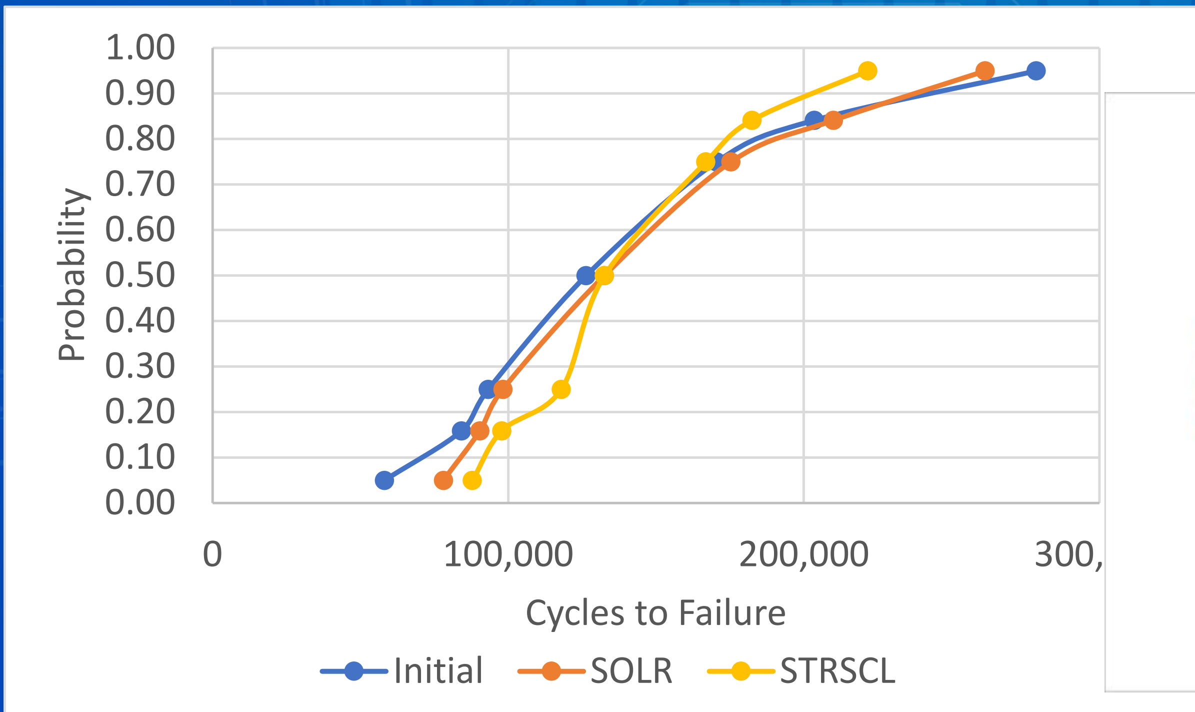
Effects of SOLR

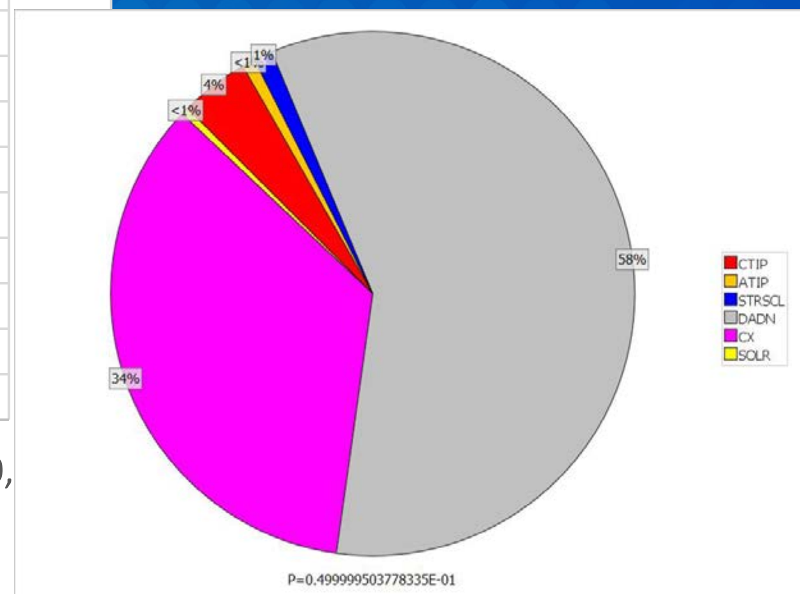
- Tracking SOLR with the digital twin decreases the distribution for cycles to failure slightly
- But it is still not accounting for individual aircraft affects



Adding individual aircraft tracking (IAT) to digital twin

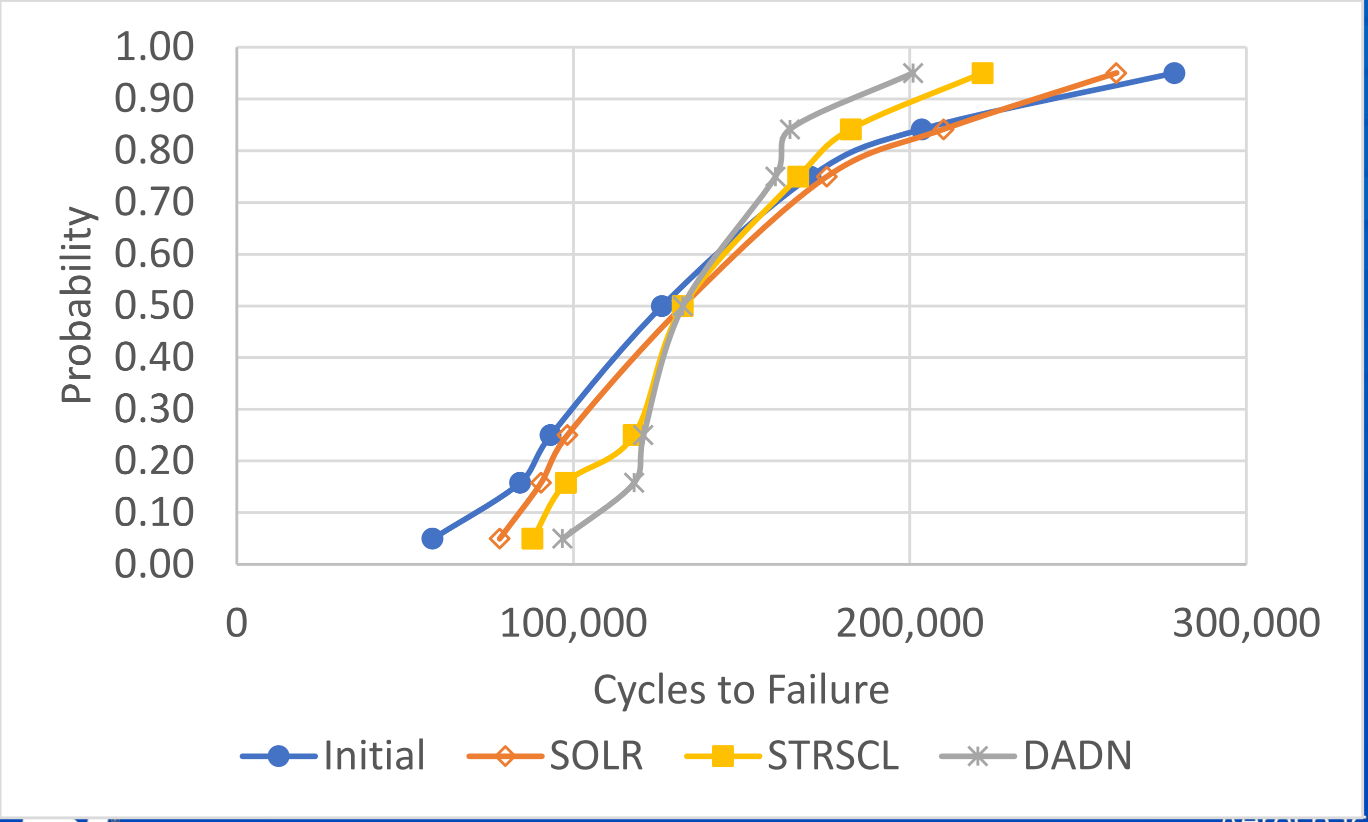
- Adding IAT to digital twin substantially reduces uncertainty in the load sequence.
- There is still some uncertainty in loads due to measurement error and missing flight data.
- Assumed standard deviation reduce to 0.1





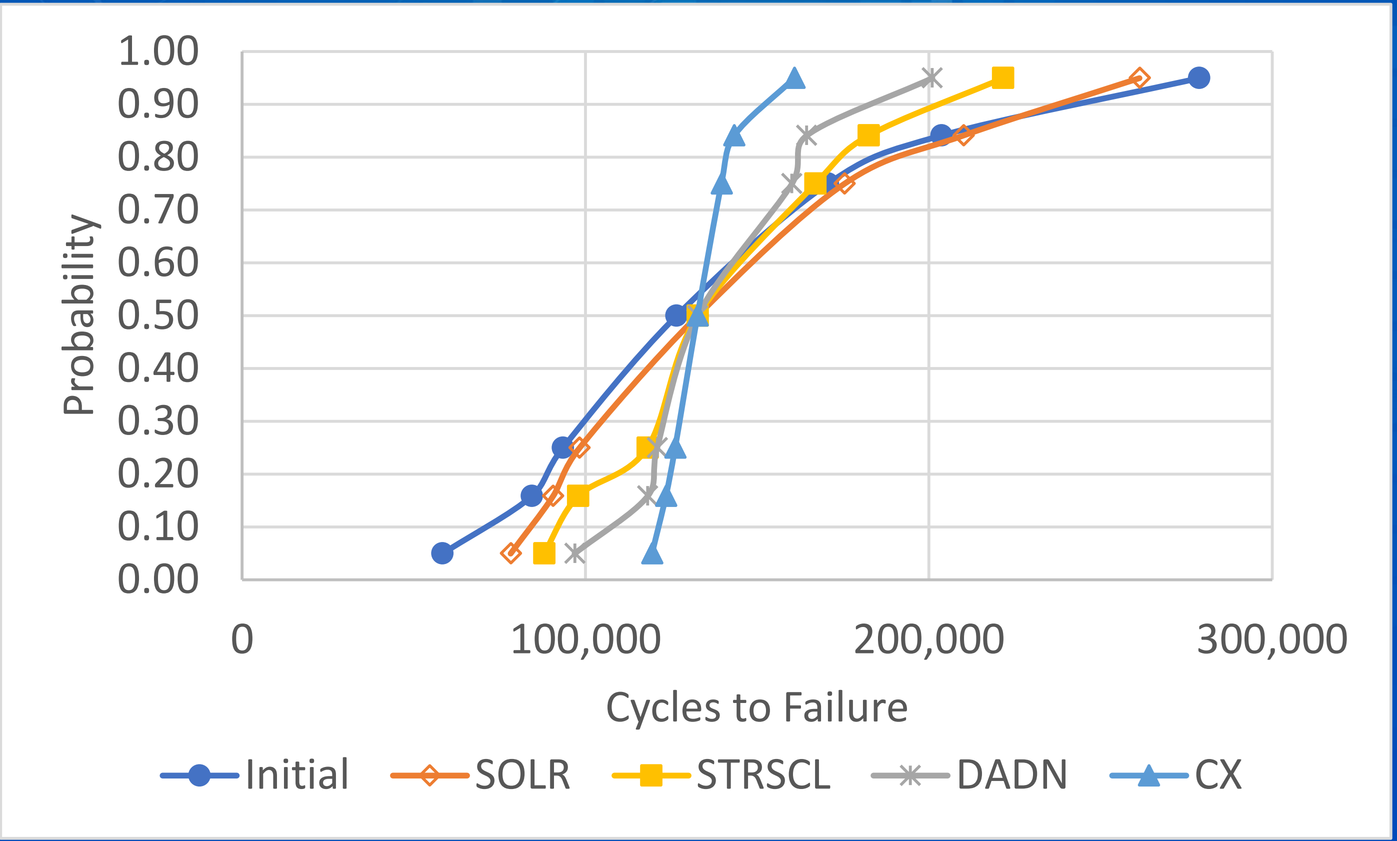
Tracking crack growth rate for material batch in digital twin

- By also tracking crack growth rate in the digital twin analytical life variation is reduced further.
- Assume standard deviation reduced to 0.05



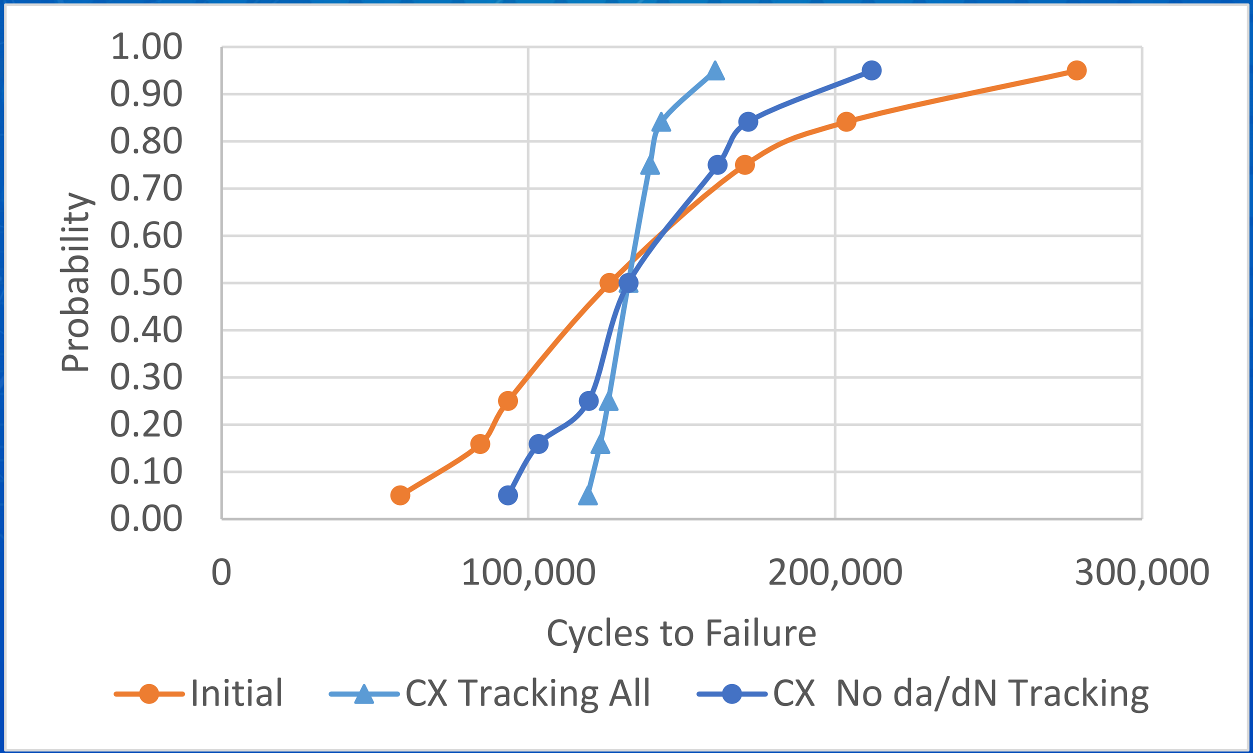
Tracking Cx Residual Stress Field

- Adding the tracking of the Cx residual stress field can greatly reduce the variability in the crack growth life



What if studies

- Can use probabilistic to perform what if evaluations
- For example, if it was decided it is not possible or it is too expensive to track da/dN. What would happen?



Summary

- Performing a crack growth analysis requires lots of inputs.
- The inputs can have a lot of variability.
- If inputs not tracked in a digital twin, there can be a large variation in crack growth life.
- Demonstrated how using probability analysis the variability in crack growth life can be analyzed.
- Demonstrated how tracking additional variables in a digital twin can reduce the variability in crack growth life.
- Probabilistic importance factors and sensitivities can be used to decide what should be tracked in a digital twin.