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Risk & Uncertainty Quantification

-- for implementing engineering residual stress into damage tolerance analysis

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ERSI

Engineered Residual Stress Implementation (ERSI) Workshop, September 15th, 2016

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- **Discussion**
  - TTCP Roadmap

Brief Review of Some Current Practices Considering ERS

- RCAF CF-18 Improvement Process Guideline (2010)
  - Coupon tests and literatures based guidelines, eng. judgments
- ASIWG/P-3 CW Coupon Tests (2014)
  - Coupon test based LIF, reduced from lab tests
- RCAF CP-140/IMP (2014, 2015)
  - Coupon tests and modeling needs, FCG from 0.005" under review
- RCAF/LM CC-130J (2010)
  - Initial & continuing crack size assumptions, analytical benefit
- USAF/SwRI/APES, CW and RS Database (2014, 2015)
  - RS measuring and database; NDI for Quality Assurance; Using RS in crack growth analysis to calculate a LIF
- NRC/DTAES Validation and Transfer of CW Modeling Technology (2015-2016)
  - RS modeling and database; Using RS in crack growth analysis to calculate a LIF, test validation

M. Liao, G. Renaud, G. Li, and Y. Bombardier, Update on NRC Hole Cold Expansion Modeling and Validation, HOLSIP2016

Brief Review of Some Current Practices Considering ERS -- summary

- ERS induced LIF (life improvement factor) varies with lifing policy (Safe-Life vs. Damage Tolerance, CI vs.CG)
- Taking ERS benefits by coupon test based LIF -- based on extensive lab tests, limited to specific conditions (material, e/D, spectra, a/c…), along with engineering judgement
- Taking ERS benefits by reducing initial crack size in DTA (ex. 0.005" current USAF approach)
- Using ERS in FCGR – some methods
  - Effective K approach, K=Kapp+Krs
    - RS model by Rich-Impellizzeri, Ball, Chang…
    - RS database (USAF)
  - Beta correction based on test (Boeing, FTI)
  - QF based da/dN (EU ADMIRE project)…

M. Liao, G. Renaud, G. Li, and Y. Bombardier, Update on NRC Hole Cold Expansion Modeling and Validation, HOLSIP2016

Uncertainty Qualification (UQ) in ASME V&V 10-2006

ASME V&V 10-2006: Verification and Validation Computation Solid Mechanics

Uncertainty Qualification (UQ): *"the process of characterizing all uncertainties in the model or experiment and of quantifying their effect on the simulation or experimental outcomes".*

- *Characterize "inputs"*
- *Quantify "outputs"*

Validation Metrics: to compare the simulation outcomes with the experimental outcomes, ex. relative error

Accuracy Adequacy: ex. partially accuracy met (10% vs. 15%), confidence level (90% vs. 95%)

Validation Documentation: document the process, conclude if the model/experiment are successfully validated for the intended use

Uncertainty Qualification (UQ) in ASME V&V 10-2006

ASME V&V 10-2006: Verification and Validation Computation Solid Mechanics

UQ in Experiment: to *quantify* the effects of measurement error, design tolerances, construction uncertainty, and other uncertainties on the experimental outcomes.

Two types of errors in experiment:

1) **Random error** (precision, inherent/irreducible, ex. dimensional tolerances on test parts or measurement locations, variability of material properties, and mechanical equipment variances due to friction...)
2) **Systematic error** (bias, maybe difficult to estimate, ex. transducer calibration error, data acquisition error, data reduction error, and test technique error)

Uncertainty Qualification (UQ) in ASME V&V 10-2006

ASME V&V 10-2006: Verification and Validation Computation Solid Mechanics

UQ for Simulation: the process of characterizing all uncertainties in the model, and of quantifying their effect on both simulation and experimental outcomes

Two types of uncertainties for UQ in Model:

1) **Irreducible/Inherent/Aleatory** (ex. geometry/material property/load/environment/assembly...)
   - Characterizing methods: component-level tests + prior experience/engineering judgment
   - Quantifying methods: statistical distribution, probabilistic methods (Monte Carlo/sensitivity study/FORM/SORM…)
2) **Reducible/Epistemic** (ex. lack of data, prior knowledge)
   - Statistical uncertainty – limited samples/data/info.
   - Model uncertainty – model form, assumptions, errors.

UQ for Engineering Residual Stress (ERS)

- UQ for FEM on ERS
  - Characterize inputs ?
  - Quantify outputs ?
- UQ for experimental measurement on ERS
  - Characterize inputs ?
  - Quantify outputs ?
- Validation Metrics: mean vs. mean, variance vs variance, distribution vs distribution?
- Accuracy Adequacy: acceptable errors? confidence level?

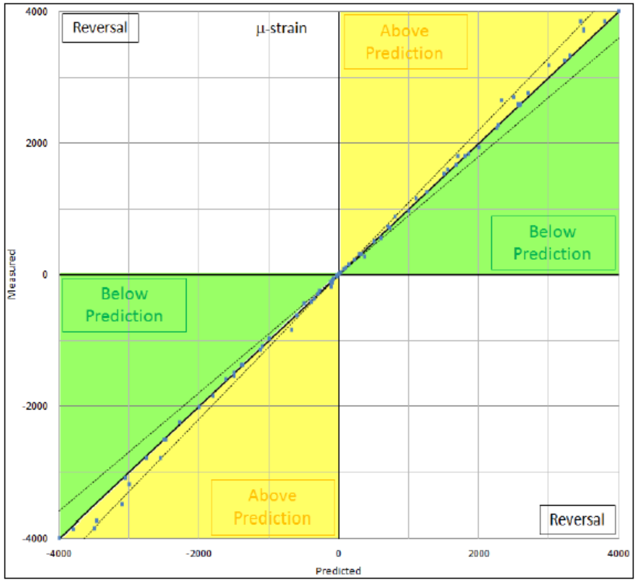


Figure 1 – Sample Correlation Plot with Error Bands

Example: USAF EN-SB-11-001, Guidance on Correlating Finite Element Models to Measurements from Structural Ground Tests. ***How about "Guidance on Correlating FEM to ERS Measurements" ?***

Risk Analysis Considering ERS
-- Safe-Life based

1) Fatigue origin/nucleation mechanisms due to surface finish and ERS (ex. sub-surface cracking, fretting..)

2) Stress-Life Analysis: S-N curve shift

3) Strain-Life Analysis (ε-N curve), ex. affecting mean stress/strain,

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f - \sigma_m}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c$$

4) Risk analysis based on Lognormal or Weibull analysis – *how will ERS affect fatigue life scatter factor (or stdev for Lognormal, shape factor for Weibull)?*

-- CF-18 example (next slide)

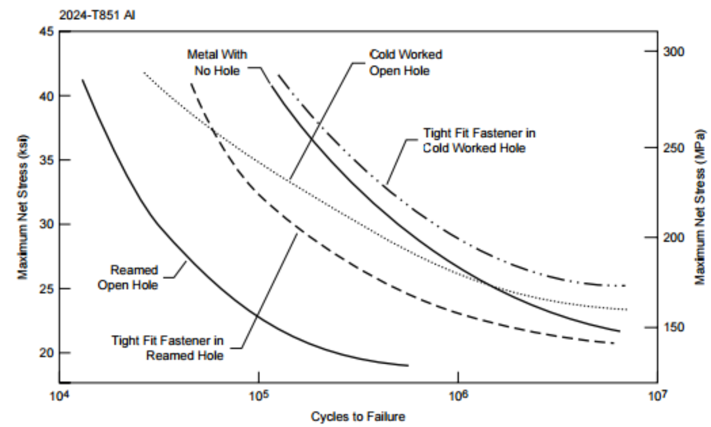


Fig. 14.27 Fatigue life improvement with cold working. Source: Ref 13

ASM Chapter 14

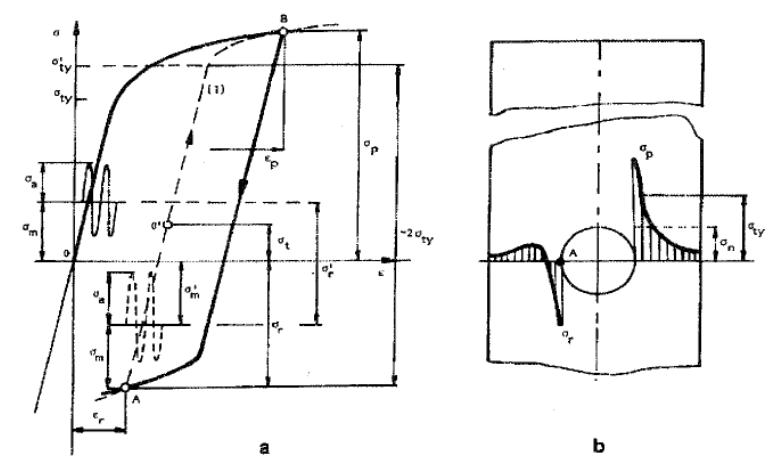


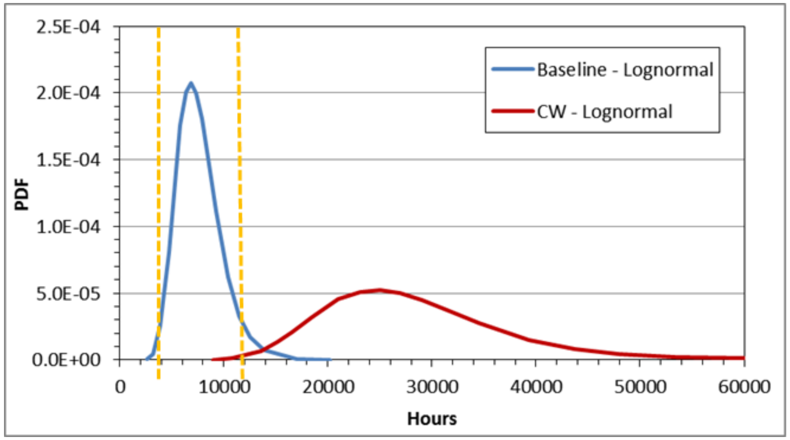
Fig. 1 Loading and unloading of the material volume inside the hole: (a) stress–strain curve and cyclic loading parameters; (b) stresses during loading (expansion) at the peak stress level σ_p and unloading reaching σ_r in the hole root

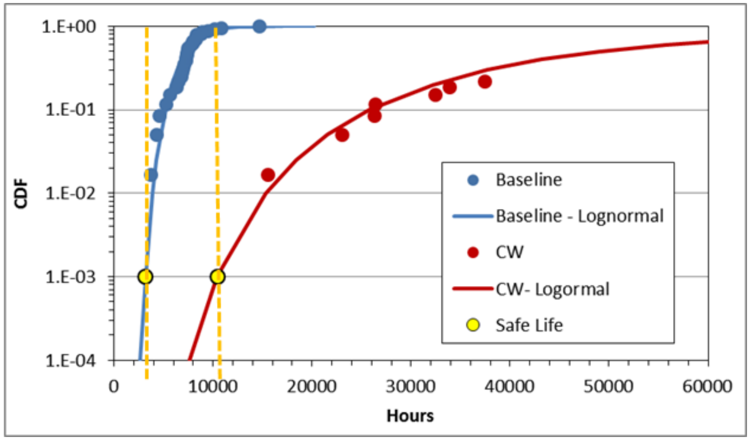
Int. J. Fatigue, 15. No. 2 (1993), pp 93-100

Risk Analysis Considering ERS
-- Safe-Life based

- **CF-18 LIF calculation for “CI” (crack to 0.01” depth)**
  - LIF is calculated based on the ratio of the life at a CPOF of 1/1000 between the baseline and improved holes. The 1/1000 life is obtained by dividing the log-average life by a scatter factor
  - The scatter factor utilized for the current test data is derived from the same equation currently used in the CF-18 lifing policy,
    - Lognormal, μ–unknown, σ–known, Bullen Case (III) $SF = 10^{Z\sigma\sqrt{\frac{n+1}{n}}}$
    - In case σ–unknown (new process), Bullen Case (I) $SF = 10^{T\sigma\sqrt{\frac{n+1}{n}}}$

    Should this case be included in the lifing policy?





Risk Analysis Considering ERS – DaDTA based

Current ASIP DaDTA and Risk Analysis for a cold-worked hole,

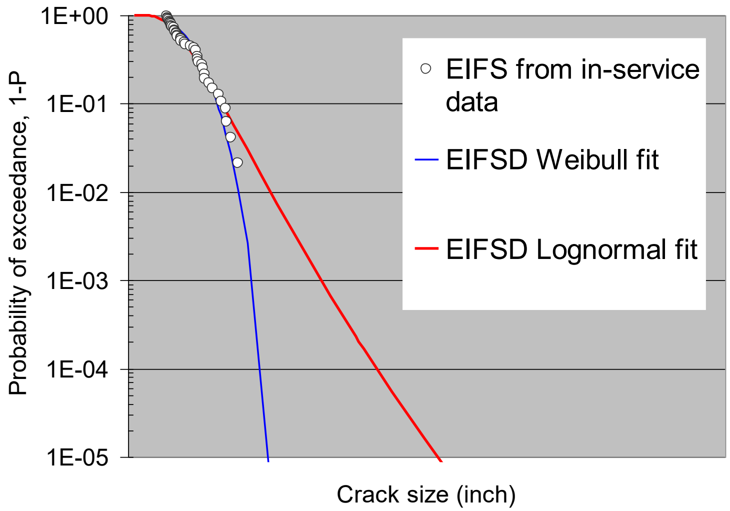
1) DaDTA
   - Durability Analysis (ex. a0=0.01”→0.005”)
   - Damage Tolerance Analysis (ex. a0=0.05”→ 0.03”, no continue damage)
     - Determine initial inspection interval by DTA
     - Determine repeat inspection intervals with a_{NDI}
2) Risk Analysis using,
   - In-service damage based EIFSD
   - Durability analysis a-t curve (even lower, ex. a0=0.002”)
   - POD for Taper-Lok, High-Tigue hole, cold-worked hole
   - Calculate SFPOF to determine service life limit (with MSD/WFD)

No direct/physical ERS consideration? Worst case scenario? Conservative or not ?

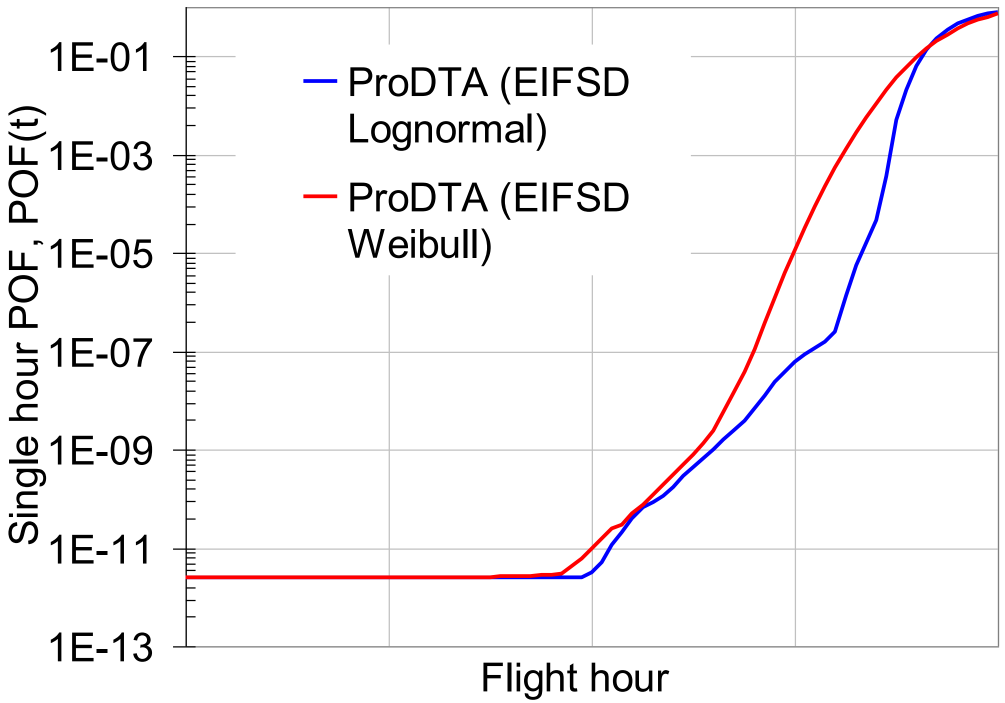
Risk Analysis Considering ERS – DaDTA based (working table)

RA Inputs	ERS Impact	Significance / Confidence	How to quantify uncertainty and variability
Initial crack size distribution (ICSD/IDS/EIFSD): related to material, geometry, manufacturing, usage/load, plus analytical method for EIFSD	Nucleation mechanism (sub-surface cracking, fretting etc.), EIFSD changed if DaDTA method changed too	High / ?	Discussion -- below
Crack growth a-t curve: material/geometry/loads fracture mechanics (LEFM) modeling	Short crack growth, near threshold growth, high quality data. New a-t with ERS	High / ?	Discussion -- below
Maximum stress distribution: stress exceedance, loads/usage	Nominally no effect	None / None	Discussion ?
Fracture toughness (Kc) distribution or residual strength: material, geometry/thickness, analytical method	Bulk ERS may affect Kc or σ_{RS} (integral panel with ERS), self-equilibrating RS effect? conservative assumption?	Low-Med / High?	Discussion ?
POD data: over 20 factors including human factor	Lower POD, higher a90/95	High / ?	Discussion
Repaired crack size distribution: repair & modification (drilling/grind-out/cold-work/peening/bonding…)	Different RCSD (CW) from ICSD (non-CW), EIFSD also depending on DaDTA method/curve. New a-t curve, new POD	High / ?	combine EIFSD and POD discussion

Significance of ICSD (EIFSD/IDS) on PoF



Probability of exceedance (1-CDF) for ICSD



Single hour PoF(t), using different ICSD curves

- ICSD tail fits showed that a Lognormal distribution resulted in higher PoF results than a Weibull distribution.

Risk Analysis Considering ERS – DaDTA based (ICSD)

RA Inputs	ERS Impact	Significance / Confidence	How to quantify uncertainty and variability
Initial crack size distribution (ICSD/IDS/EIFSD): related to material, geometry, manufacturing, usage/load, plus analytical method for EIFSD	Nucleation mechanism (sub-surface, fretting etc.), EIFSD changed if DaDTA method changed	High / ?	• In-service damage based EIFSD, including ERS effect already? • New ICSD/EIFSD from new a-t curve • Statistical analysis/Lognormal/Weibull/censored/non-censored data

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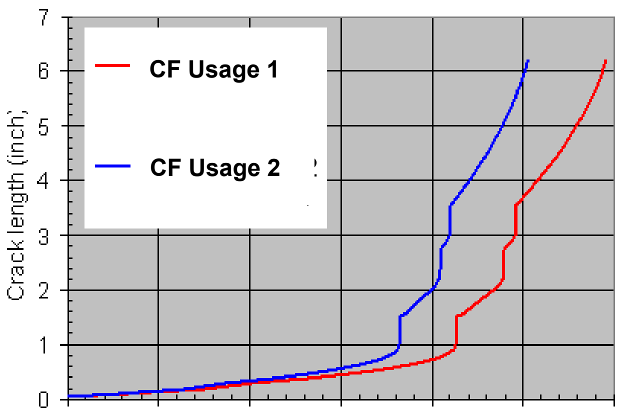
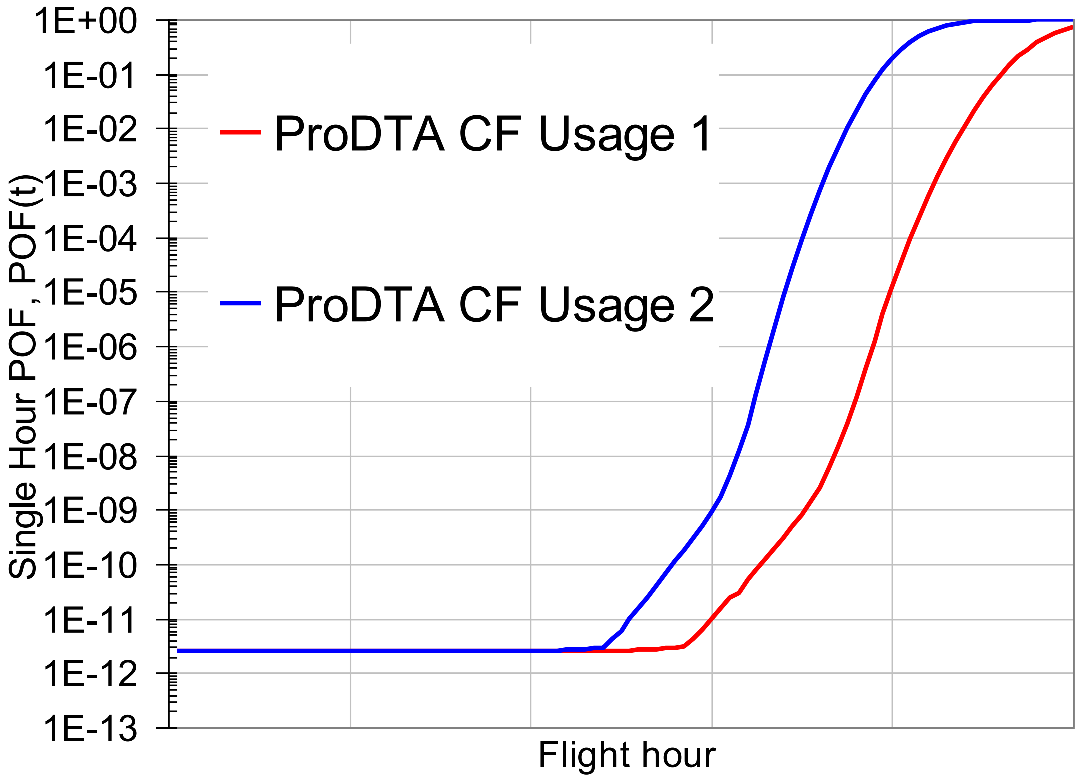
Significance of crack growth (a-t curve) on PoF



Crack growth (a-t) curve



Single hour POF(a), using different crack growth curves

Risk Analysis Considering ERS – DaDTA based (CG)

RA Inputs	ERS Impact	Significance / Confidence	How to quantify uncertainty and variability
Crack growth a-t curve: material/geometry /loads fracture mechanics (LEFM) modeling	Short crack growth, near threshold growth, high quality data. New a-t with ERS	High / ?	• Using a0=0.005" a-t curve, upper bound? • Using ERS based a-t curve, upper bound/1Stdev? • Using ERS distribution to determine a-t distribution by Monte Carlo simulation, i.e., ***one more random variable ERS?*** • Using QF based FCGR?

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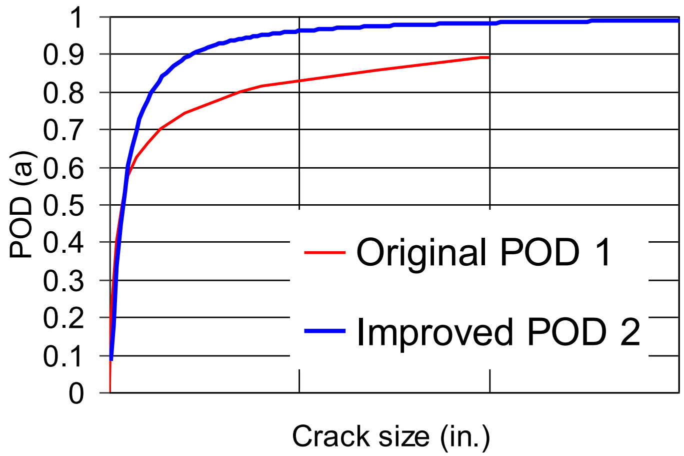
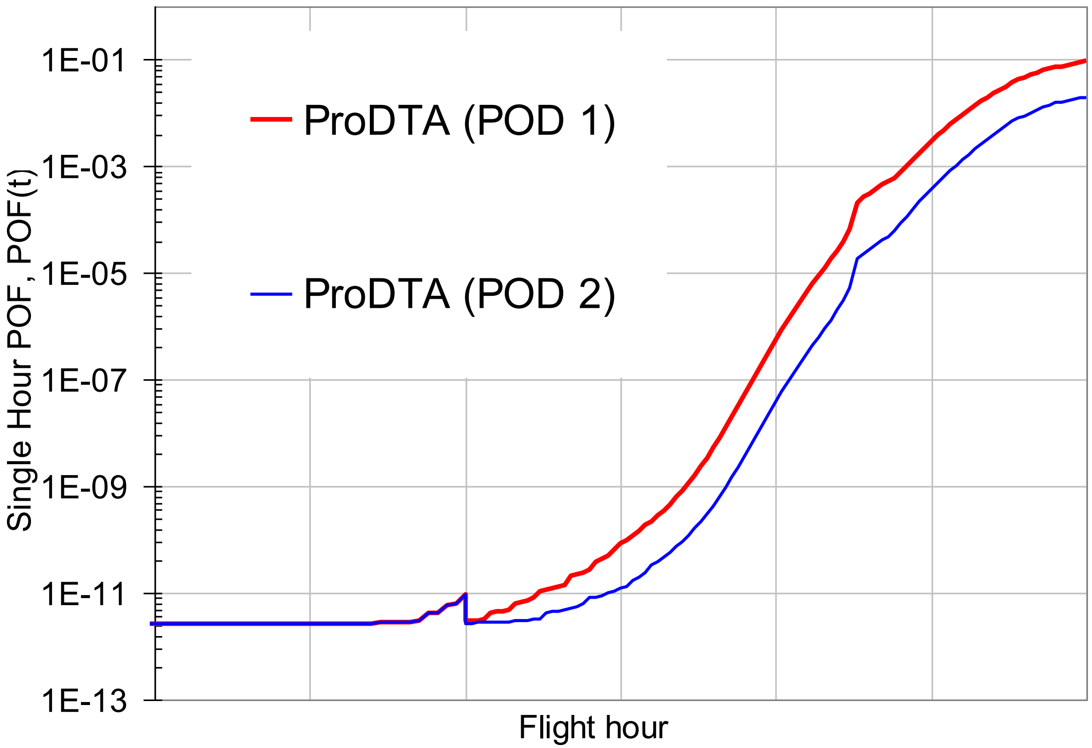
Significance of POD (a) on PoF



Bolt hole EC POD (a)

Red – original POD(a) 1

Blue – improved POD(a) 2, std dev reduced by 50%



Single hour POF(a), using different BHEC POD(a) curves

Also POD can affect in-service damage based EIFSD when censored scenarios are considered

Risk Analysis Considering ERS – DaDTA based (POD)

RA Inputs	ERS Impact	Significance / Confidence	How to quantify uncertainty and variability
POD data: over 20 factors including human factor	Lower POD, higher a90/95	High / ?	• Full POD study? • Model-assisted POD study?

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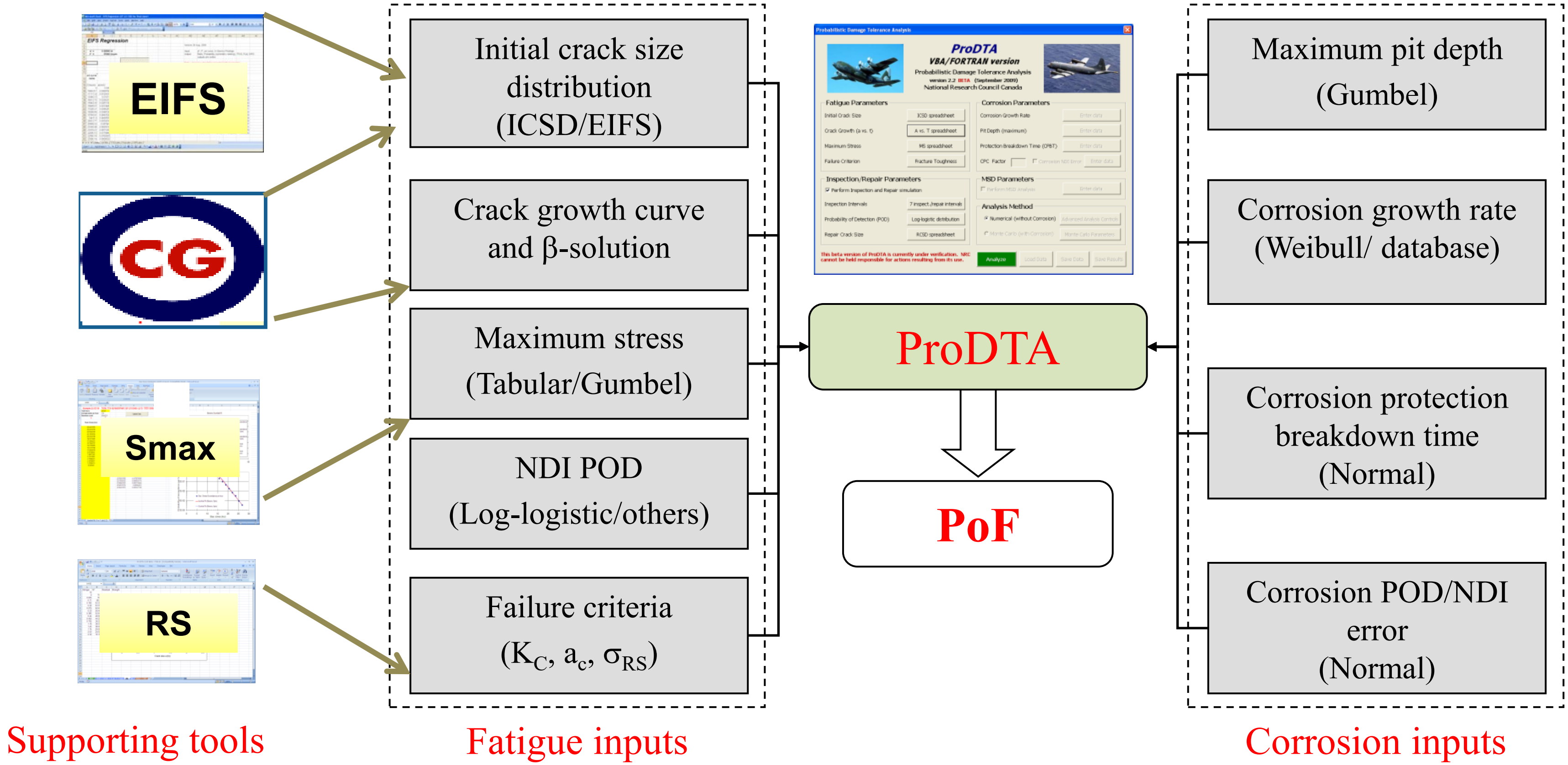
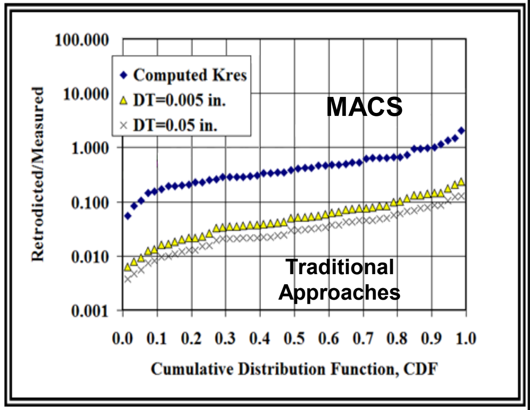
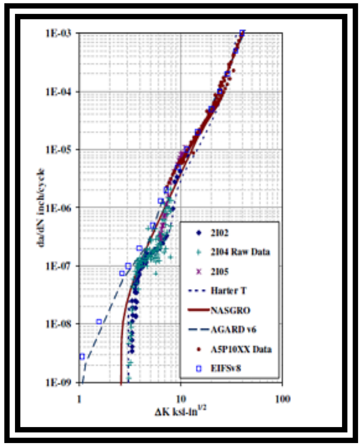
Needs on Risk Analysis Tool
-- Flexibility, Accessibility, for example

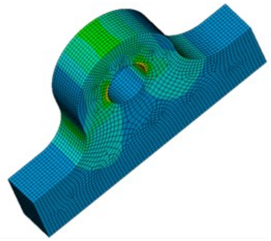


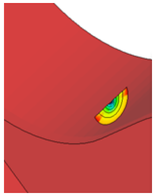
- NRC tools use either Lincoln, Berens, or Freudenthal SFPOF calculations
- NRC tools have gone through some verification and validation
- NRC tools do both probabilistic integration and Monte Carlo simulation

TTCP Activity









AER TP 4 Work Unit: **CP 4A.2 (Closing)**

Improved Fatigue Models for Engineered Residual Stresses

Problem Statement: Improved fatigue models are needed by airworthiness authorities to allow certification of structure containing engineered residual stresses, with a lesser requirement on costly physical testing.

Outcomes: Improved fatigue models and methodologies to support certification of structures with reduced amount of testing needed, e.g. AU AP-3C, C-130 fleets.

Exploitation Route: Improved life prediction models will be assessed experimentally.

S&T Challenges: Computational simulation of fatigue crack growth and non linear residual stress fields.

Outputs: Preliminary fatigue models and modelling techniques, documented in reports.

Measures of Success: Experimental validation of improved life prediction models.

Timeline: (2013 – 2015)

2013
- CP initiated as a follow on from CP4A.8
- Refinement of Stress Models

2014
- Development of model enhancement
- Comparison of new models to test data
- Refinement models

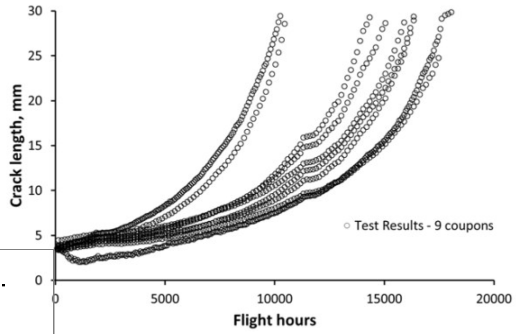
2015
- Incorporation of new models into existing tools
- Certification aspects pushed forward to SA4A.12

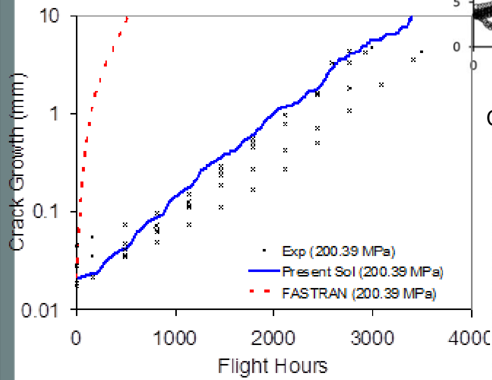
Milestones:
- Re-design cold rolling tool using FEA that resulted in a 40% life improvement.
- First-ever method to link desired fatigue response to Laser Shot Peening parameters.
- Simulation technique reduces computational time by factor of 10.
- Submodeling technique developed for large scale problems
- Tests carried out to remove residual effect on crack growth

CP 4A.2 Achievements/Outcomes

- Improved life prediction models that reliably account for the effects of residual stresses are the critical first step toward achieving certification of ERS-enhanced structure with reduced reliance on physical testing*.
- Under this CP, various fatigue models were augmented to include residual stresses, with varying levels of experimental support. The planned benchmarking of these models for certification and acceptance was pushed to SA 4A.12 to allow for more in-depth development.
- Enhancements accomplished under this CP include:
  - Re-design of an cold rolling tool using finite element analysis that improves fatigue life by 40%
  - Preliminary development of a two-level damage tolerance assessment method (initial screening followed by detailed analysis)
  - Development of closed-form equations for estimating the laser peening parameters required to achieve a specified fatigue response
  - Development of analysis method for removing residual stress effects from fatigue crack growth data
  - Enhanced computational techniques for accelerating laser peening simulation time by a factor of 10
- Reports/papers done by New Zealand, Australia on 3D FEM on hole cold expansion, and weight function to calculate stress intensity factors of fastener hole with residual stress

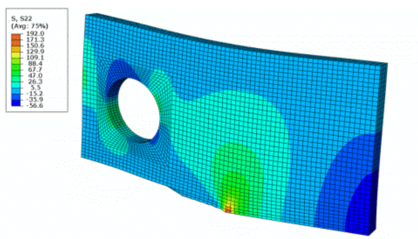
** ERS: Engineered residual stress, such as resulting from laser peening, burnishing, cold- working, etc.*





Fatigue crack growth predictions (open hole subject to spectrum loading

Crack growth variability under representative spectrum loading



AER TP 4 Work Unit: **SA 4A.12 (Extension Requested)**

Roadmap Towards Maintenance Credit for Engineered Residual Stresses (ERS)

Problem Statement: To increase service lives and reduce maintenance requirements, military fleet managers would like to exploit ERS. Current regulations to extend fleet lives based on ERS favor extensive physical testing. Operators have a need for analytical tools to reduce the testing burden.

Outcomes: Stakeholders will have a clear path identifying the R&D activities required to support routine acceptance and certification of ERS-enhanced aircraft structures with minimal physical testing

Exploitation Route: Technology development plans will be assessed by regulators; CP results will be provided to OEMs and aircraft structural integrity managers.

S&T Challenges: Coordinate all relevant activities being carried out in the TTCP nations to establish barriers to routinely incorporating lifing credit for beneficial residual stresses in metallic airframe components. Creation and acceptance of a combined technology development roadmap

Outputs: A detailed technological roadmap which can be used as a basis for developing an R&D programme leading to the certification of life extension based on ERS.

Measures of Success: Acceptance of the roadmap by regulators, operators, OEM's and maintainers. Development of a R&D strategy to optimise the physical testing and analysis requirements for certifying residual stress effects

SA Timeline:

Task	July-15	Apr-16	Oct-16
Collect requirements for incorporating lifing credit			
Develop combined roadmap & proposed path forward			
Obtain national buy-in and concurrence for roadmap			
Report Deliverable			

Milestones:

- Develop combined roadmap & proposed path forward
- Obtain national buy-in and concurrence for roadmap
- Report Deliverable

TTCP TP4 Panel Discussion on SA 4A.12

- SA 4A.12 is aiming for a technical roadmap for various ERS techniques (cold expansion, shot peening, laser peening, low plasticity burnishing), and for wide range of aircraft fleet application
- SA 4A.12 is being extended for incorporating with the USAF sponsored ERSI workshop on roadmap development
  - NRC participation
  - DSTG participation
  - AFRL/USAF participation
  - US Army (Nate Bordick) request: laser peening and tool path optimization to achieve desired residual stresses. One concern is residual stress relaxation, “will the same residual stresses that are present on day 1 still be there on day 10,000. If not, how do you analytically predict relaxation and still take advantage of any benefits in certification / maintenance”

Summary

- **Brief Review of Some Practices Considering ERS**
  - LIF varies with lifing policy (CI vs CG), based on extensive lab tests, strictly limited to specific conditions (material, e/D, spectra, a/c…), no analytical LIF adopted yet.
- **UQ for ERS Modeling and Experimental Measuring**
  - ASME UQ Process
  - UQ for ERS: a new EN-SB similar to EN-SB-11-001 (FEM and Test)?
- **Risk Analysis Considering ERS**
  - Safe-Life based risk analysis
  - DaDTA based risk analysis
    - ICSD – impact of ERS
    - Master a-t curve – impact of ERS
    - POD/NDI – impact of ERS
- **Discussion**
    - TTCP Roadmap on ERS

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Thank you

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