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International Committee on Aeronautical Fatigue and Structural Integrity

Probabilistic Modelling and Risk Analysis

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Contents

Introduction

- This presentation provides a review of Probabilistic Modeling and Risk Analysis works, as reported in the past ICAF National Reviews from 2017-19, 2019-21, and 2021-23 (part),
  - Keywords used for searching: “Probabilistic” (modeling), “Risk”, “Reliability”, “Statistical” (analysis).
  - Not including Probability of Detection (POD).
- Some works are highlighted in this presentation, with the intention to cover at least one from each Nation who reported the subject works.

This presentation is limited to the details of the National Reviews and the knowledge/understanding of the reviewers

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Introduction

- Probabilistic modeling – using probabilistic and statistical methods to model/simulate the stochastic fatigue and fracture processes
- Risk analysis (aka structural risk analysis) – to evaluate a structural hazard severity and probability of occurrence/failure, mostly caused by the fatigue and fracture process.

where **risk analysis** shall be performed/ used/updated to...

TABLE I. USAF Aircraft Structural Integrity Program Tasks.

TASK I	TASK II	TASK III	TASK IV	TASK V
DESIGN INFORMATION	DESIGN ANALYSES & DEVELOPMENT TESTING	FULL-SCALE TESTING	CERTIFICATION & FORCE MANAGEMENT DEVELOPMENT	FORCE MANAGEMENT EXECUTION
5.1.1 ASIP Master Plan	5.2.1 Material and Structural Allowables	5.3.1 Static Tests	5.4.1 Structural Certification	5.5.1 L/ESS Execution
5.1.2 Design Service Life & Design Usage	5.2.2 Loads Analysis	5.3.2 First Flight Verification Ground Tests	5.4.2 Strength Summary & Operating Restrictions (SSOR)	5.5.2 IAT Execution
5.1.3 Structural Design Criteria	5.2.3 Design Loads/Environment Spectra	5.3.3 Flight Tests	5.4.3 Force Structural Maintenance Plan (FSMP)	5.5.3 DADTA Updates
5.2.1 Durability and Damage Tolerance Control	5.2.4 Stress and Strength Analysis	5.3.4 Durability Tests	5.4.4 Loads/Environment Spectra Survey (L/ESS) System Development	5.5.4 L/ESS and IAT System Updates
5.1.5 Corrosion Prevention & Control (CPC)	5.2.5 Durability Analysis	5.3.5 Damage Tolerance Tests	5.4.5 Individual Aircraft Tracking (IAT) System Development	5.5.5 NDI Updates
5.1.5.3 Nondestructive Inspection (NDI)	5.2.5 Damage Tolerance Analysis	5.3.6 Climatic Tests	5.4.6 Force Management Database Development	5.5.6 Structural Risk Analysis Updates
5.1.5.3 Nondestructive Inspection (NDI)	5.2.5 Damage Tolerance Analysis	5.3.6 Climatic Tests	5.4.6 Force Management Database Development	5.5.6 Structural Risk Analysis Updates
5.1.6 Selection of Materials, Processes, Joining Methods, & Structural Concepts	5.2.7 Corrosion Assessment	5.3.7 Interpretation and Evaluation of Test Findings	5.4.7 Technical Orders	5.5.7 CPC Plan and Corrosion Assessment Updates
	5.2.8 Sonic Fatigue Analysis	5.3.8 Resolution of Test Findings		5.5.8 Analytical Condition Inspection
	5.2.9 Vibration Analysis			5.5.9 FSMP Updates
	5.2.10 Aeroelastic and Aeroservoelastic Analysis			5.5.10 Technical Order Updates
	5.2.11 Mass Properties Analysis			5.5.11 Repairs
	5.2.12 Survivability Analysis			5.5.12 Force Management Database Execution
	5.2.13 Design Development Tests			5.5.13 Structural Certification Updates
	5.2.14 Structural Risk Analysis			5.5.14 Economic Service Life Analysis Updates
	5.2.15 Economic Service Life Analysis			5.5.15 Others as Required

Note: Numbers refer to and are hyperlinked to sections of this document.

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Development of Risk Analysis Tool for Transport Aircraft Structural Risk Analysis (Australia)

- Development of FracRisk – a risk analysis tool, including
  - Improved EIDS estimation with a beta distribution (upper bounded, right tail sensitivity, TTCS based approach etc.).
  - Variability of the master crack growth curve.
- Independent evaluation of FracRisk vs. PROF (USAF).
- Application of the tool for C-130J center wing probabilistic risk analysis with MSD to enhance the ASIP, i.e. maintaining safety while minimizing cost and maximizing availability.

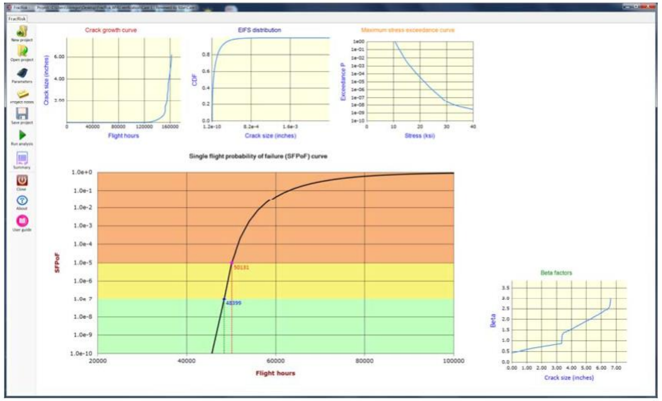
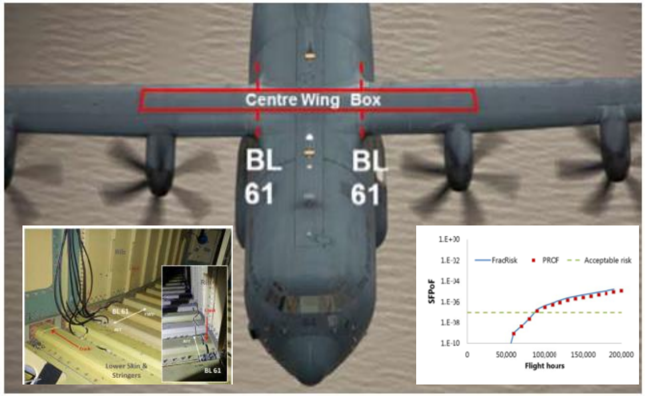


Figure. 3 FracRisk graphical user interface



Probabilistic modeling and Risk Analysis (Brazil)

- Structural risk/reliability analysis to optimize inspection plans considering,
  - Variability of crack growth parameters, and inspection PODs,
  - Monte Carlo crack growth, a Beta distribution of confidence bands for any sample size.
- On the development of statistical knock-down factors for WFD assessment,
  - An in-depth investigation for each of four factors (Testing Factor, Confidence Factor, Reliability Factor, and Scale Factor), presenting an explanation for them based on statistical approaches, together with some examples of application.

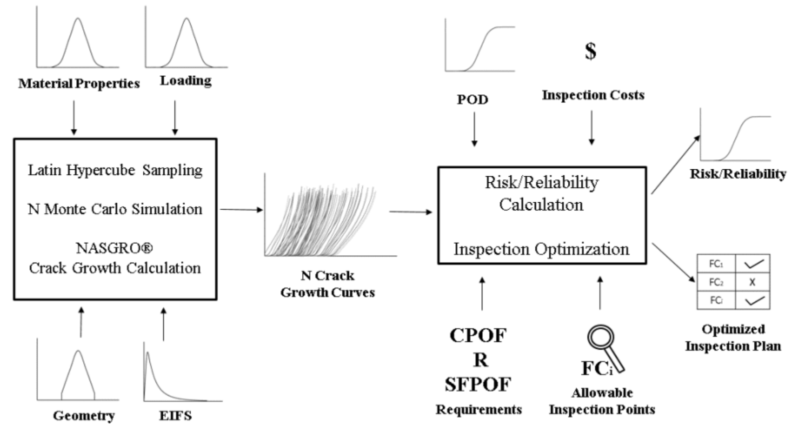


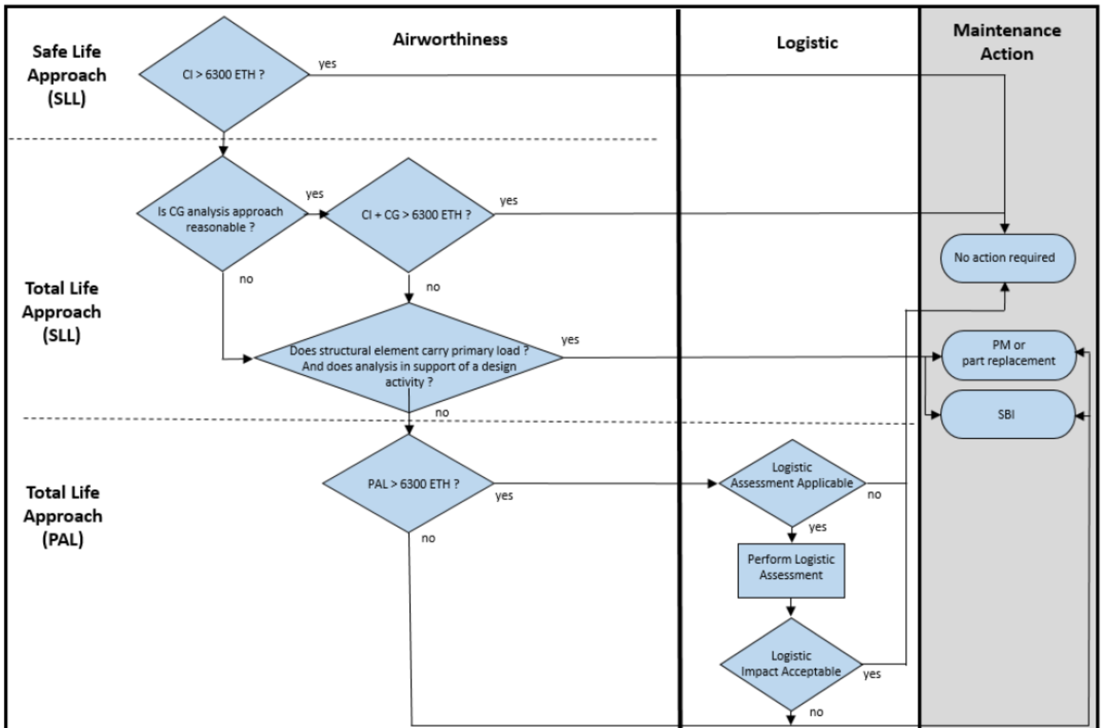
Figure 12-1 – Overview of the risk analysis process from Reference [52].

Table 12-1 – Results comparison from traditional inspection plan vs optimized inspection plan for reduced CPOF and SFPOF targets.

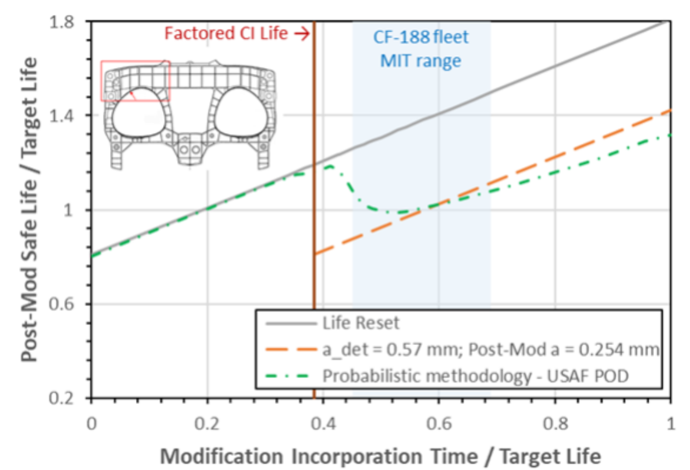
Calculation Process	Number of Inspections	Inspections Relative Cost	CPOF_DSG	Reliability_DSG	SFPOF
Traditional Inspections Calculation	6	8.49	5.525%	94.475%	$3.09.10^{-5}$
Probabilistic Propagation - Optimized Inspections	5	7.07	4.474%	95.526%	$2.73.10^{-5}$

Probabilistic Lifing of a Second Oversize Hole Modification (Canada)*

CF188 Lifing Methods (Updated)



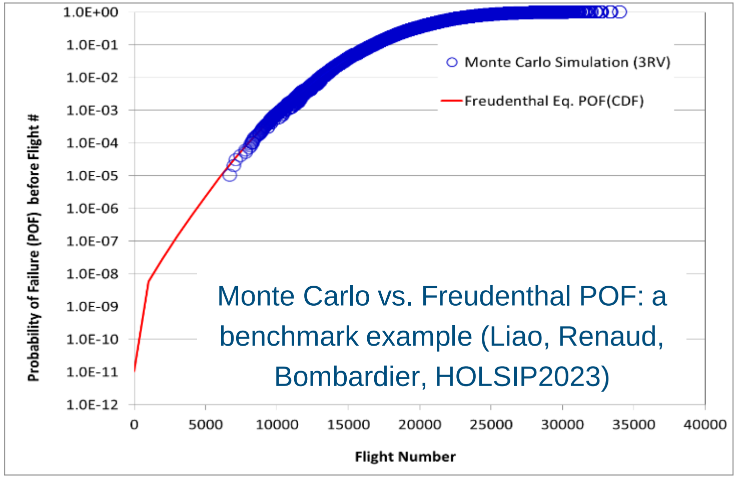
NRC assessed a MRO probabilistic methodology and enhanced it to better characterise the POD and its effect on the residual cracks, and to add the ability to apply the method tail-by-tail.



* Renaud, Liao, Dionne, ICAF2023, HOLSIP2023

Probabilistic Modeling and Risk Analysis for an Airframe Digital Twin (Canada)

- Airframe digital twin framework/tools are developed and demonstrated with a CF-188 full-scale component testing to reduce maintenance cost and increase availability, including,
  - Probabilistic load estimations and forecasting
  - Probabilistic crack growth (Monte Carlo, multiple variables)
  - Bayesian updating of crack sizes from NDI (find, no-find) results
  - Monte Carlo based risk analysis, further improved from CanGROW and ProDTA



Probabilistic Fatigue and Probabilistic Damage Tolerance Analysis (China)

- Probabilistic analyses for
  - Multiple Site Damage (MSD) for Structure Containing Holes (3.9*)
  - Engineering Calculation Method of Probability Distribution of Crack Initiation Life for WFD (4.3)
  - MSD in Longitudinal Fuselage Lap-joints (4.5)
  - WFD Test and Evaluation of Equally Straight Section in Fuselage (ex. LOV, ISP, SMP) (8.4)
- Probabilistic fatigue and damage tolerance evaluation for AM (2.1.2, 2.1.7, 4.1.1)
- Statistical analysis of fatigue threshold of typical laminates of composite fuselage (2.3.6)

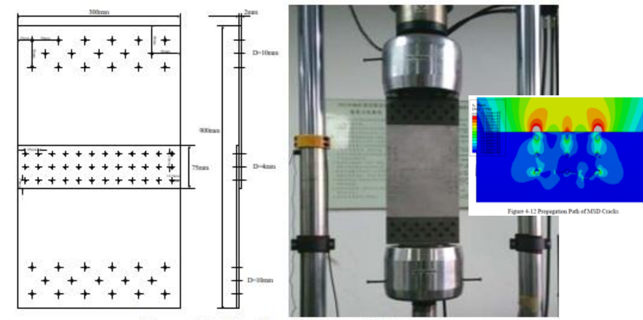


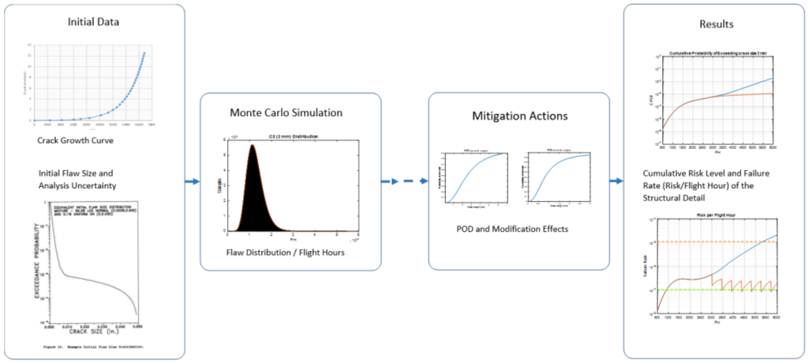
Figure 4-14 Test Specimen and Fixture

Figure 4-16 The fuselage isometric section test

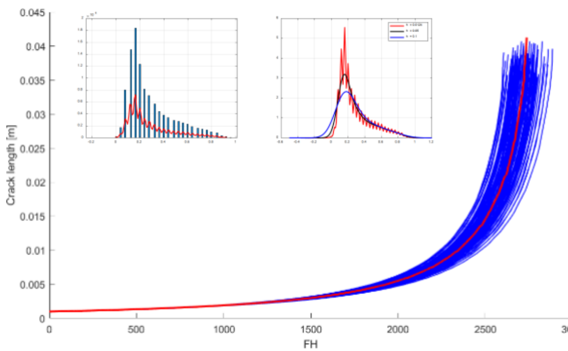
* Chapter number in ICAF2019-2023 National Reviews

Risk Assessment for Structural Integrity Management (Finland)

- A simplified tool was developed for understanding the risk levels considering the uncertainties of material and damage history, and then to provide support for decision making in ASIP, i.e. optimization of inspection intervals by combining different PODs and possible structural modifications.
- Further modeling the scatter in the life estimates based on deviation in the selected load spectrum and the effects of random simulated load spectra on the crack growth rate.



Analysis process to determine the risk level for a structural detail. Figure courtesy of Patria Aviation.



Scatter of the crack growth rates

Reliability Approach applied on Fatigue Safety Factors for Fleet Monitoring (France)

- To carry out a quantitative study about the structural failure based on random phenomena (loads, geometry, material), then the failure probability of the airframe related to a specific scatter factor is obtained.
- The main study is on the safety level of aircraft without monitoring system compared with monitored ones.
  - The first point consists in determining the probability that the real fatigue damage exceeds the calculated damage <u>with or without</u> monitoring system, and
  - The second point is to find the adequate scatter factor to obtain <u>the same safety level</u>, by a parametrical analysis to find the scatter factor that leads to the same probability between monitored and no-monitored aircraft.

Probabilistic Reliability Assessment of a Component in the Presence of Internal Defects (Germany)

- A fatigue life assessment model was proposed for internally flawed AM materials based on fracture mechanics approach which takes into account the size distribution of defects as well as their spatial distribution, influence of a vacuum-like environment at the crack tip of internal cracks, short crack behavior and some other relevant aspects.
- Using this model and some assumptions, the random defect analysis can successfully predict the scatter of fatigue life and probability of failure of an AM component (Ti6Al4V by LBW), based on the given defect population.

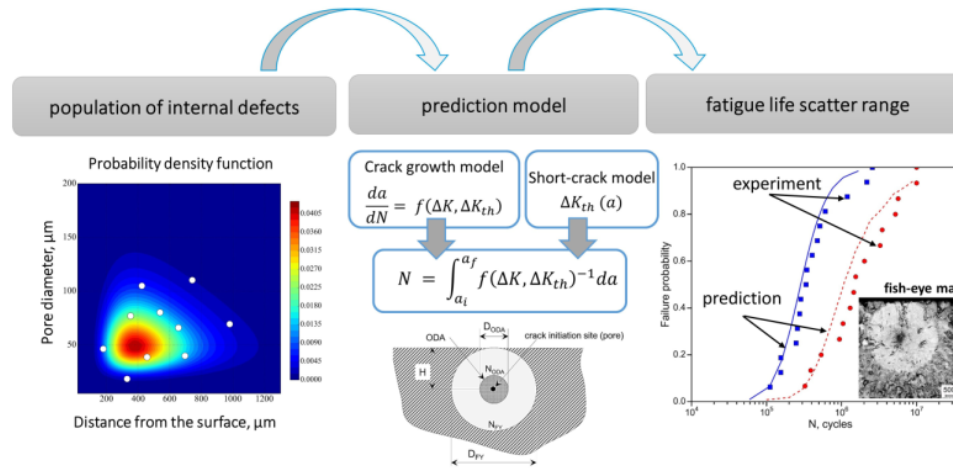
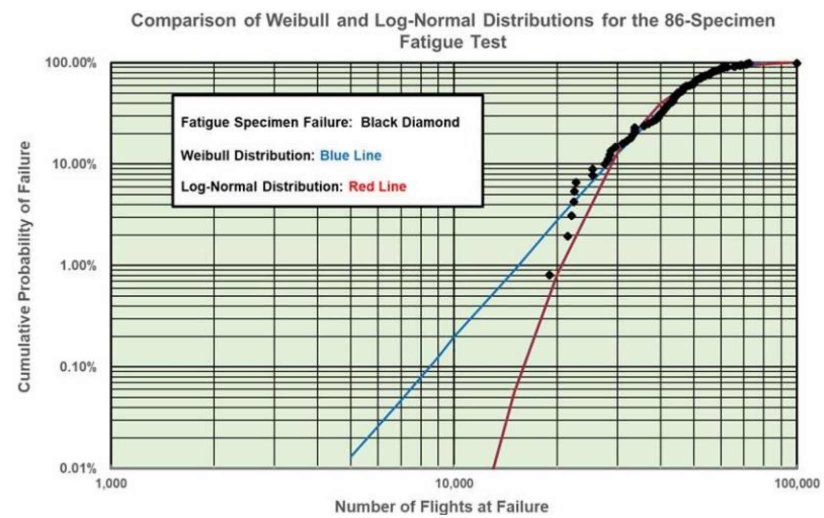


Figure 12: Schematic illustration of the probabilistic modelling for assessment of the lifetime scatter.

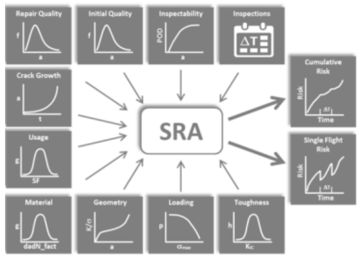
Probabilistic Studies: Weibull or Log-Normal Distributions to Characterize Fatigue Life Scatter (Israel)

- The study used SuperSMITH a Software developed by Fulton Findings to analyze a large fatigue database (86 various Al specimens) using Weibull and Log-Normal distributions. This software is based on the theoretical methods described in the "New Weibull Handbook".
- The Weibull distribution is always more conservative than the Log-Normal distribution.
- In view of these results, the author concluded (tentatively) that the Weibull distribution should be preferred to determine the safe-life of a fatigue-critical structural member that has undergone fatigue testing.



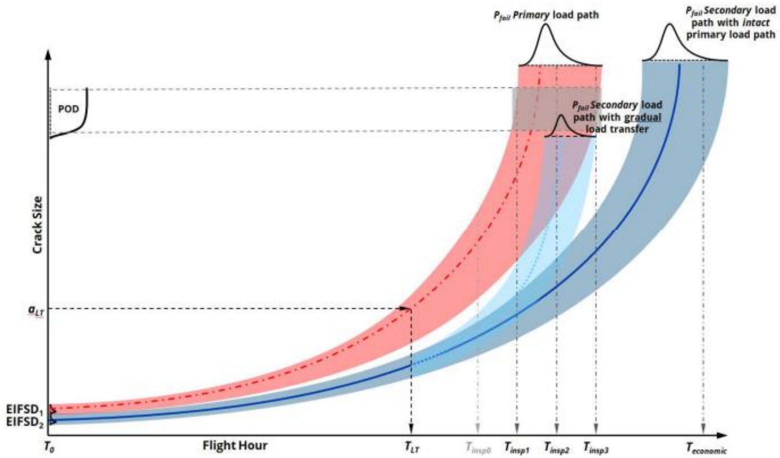
Probabilistic Fail Safe Structural Risk Analysis (Netherlands)

- The possibility that the crack can start in any of the load paths with a size that is much better represented by a distribution function than by some upper bound value, demands for a probabilistic approach. For this, a new probabilistic Fail-Safe approach has been developed.



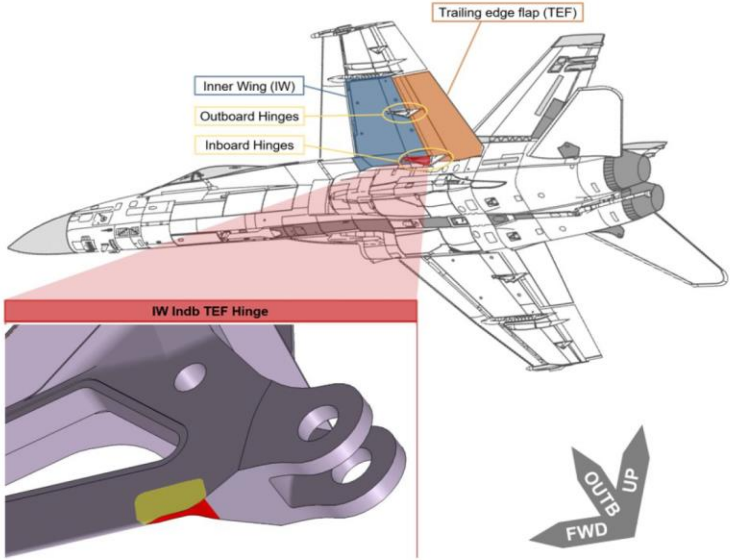
NLR tool, SLAP (Stochastic Life Approach)

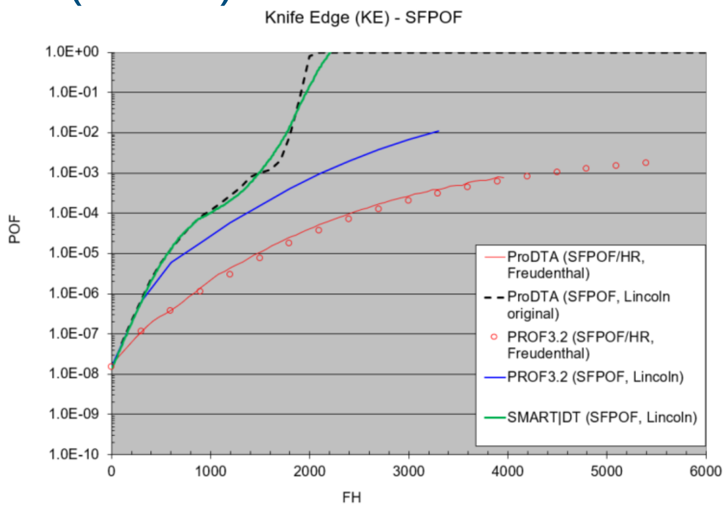
- The approach is an extension of the single load path structural risk analysis.
  The methodology has been implemented in the NLR in-house tool SLAP++ (Stochastic Life Approach). This tool also provides functionality to support the generation of the necessary structural risk analysis input.



Structural Risk Assessment with SMART|DT (Swiss)

- First practical application of probabilistic risk analysis with SMART|DT for F/A18 case studies to learn more about structural risk assessment compared to traditional damage tolerance analysis.
- The study was performed in collaboration with a graduate student from the Zurich Institute of Applied Sciences (ZHAW).



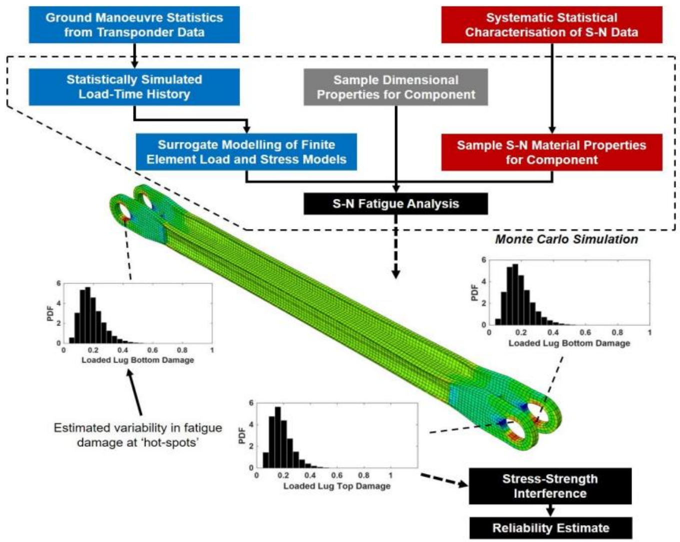


SHPOF results from SMART|DT, ProDTA (NRC), and PROF (USAF)

Probabilistic Fatigue Methodology for Safe-Life Design and Analysis (UK)

- A probabilistic fatigue methodology was developed for safe-life components and an overview is shown in the Figure. The methodology was demonstrated on case studies using components that were representative of typical aircraft landing gear components.

- The recent introduction of 'big-data' sources has significantly reduced the challenge of data availability within probabilistic approaches to fatigue design. A highlight of this project was the exploitation of real-time aircraft tracking from transponder data using Flightradar24® to characterize the variability in aircraft ground maneuverers.



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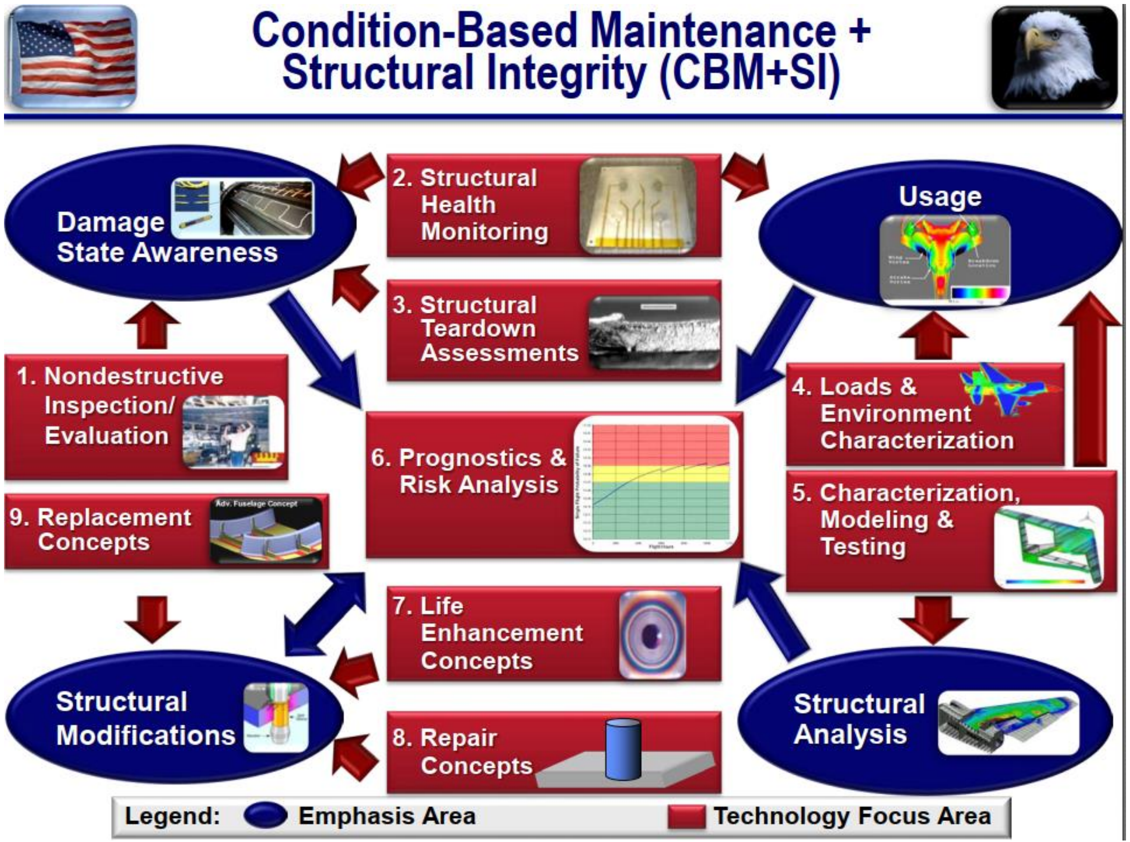
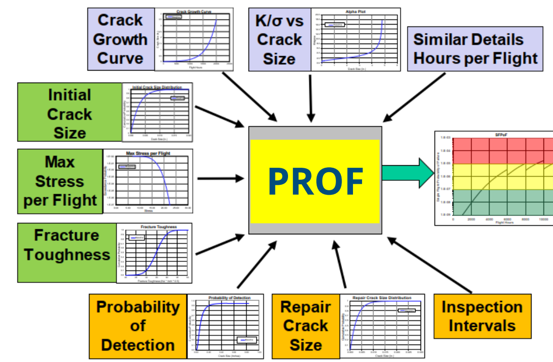
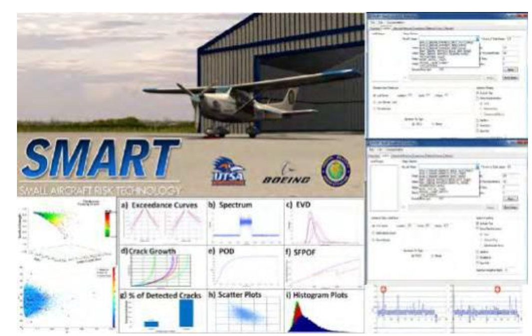
Structural Risk Analysis Methods and Tools Development and Applications (USA)



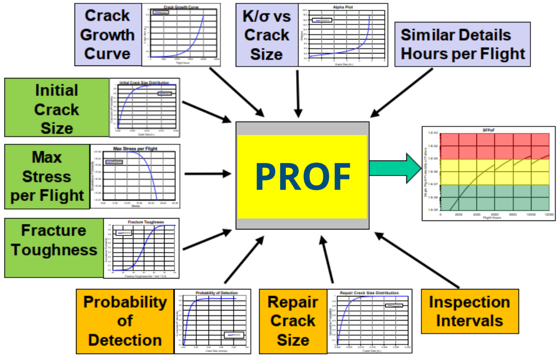


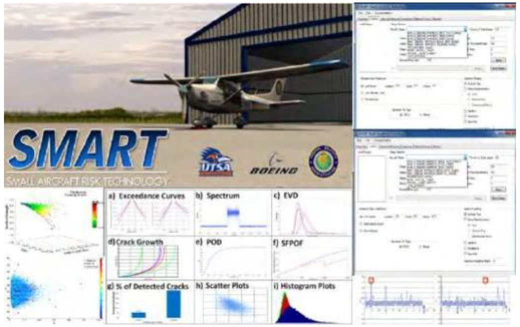


* Chapter number in ICAF2019 National Review

Structural Risk Analysis Methods and Tools Development and Applications (USA)

- Evaluation of Structural Risk Analysis Methods Using F-15 Experience (9.7.2*).
  - Compared Lincoln and Freudenthal methods in PROF
  - Presented the value of USAF damage tolerance approach and the benefits of performing structural risk analysis
- More risk analysis applications reported for F-16 (9.7.1), T-38 (9.11.5), and A10 (9.11.12, 9.11.14) to alleviate inspection burden and extend inspection intervals with advanced DTA and NDI.
- SMART Software (9.7.4): a risk analysis tool sponsored by FAA (2007-2023) to proactively manage the risk for small airplanes with fatigue failure.
  - SMART|LD: probabilistic fatigue analysis
  - SMART|DT: probabilistic damage tolerance analysis





* Chapter number in ICAF2019 National Review

Summary

- ICAF community continues contributing to the best practices of probabilistic modeling and structural risk analysis.
- Probabilistic modeling clearly shows the benefits to reduce conservatism used by safety factors in a deterministic analysis,
  - As shown in MSD/WFD assessment, composites and AM fatigue life estimation, aircraft digital twin development, and virtual/smarter testing.
- Structural risk analysis tools have been further improved, showing more confidence and robustness as shown in the comparisons of tools&results.
- Practical applications of structural risk analysis clearly show the benefits to enhance ASIP, especially with more data and advanced fracture mechanics models, it can support,
  - Optimization of inspection intervals, reduction of maintenance costs,
  - Identification of data needs, sensitivity study of various inputs,
  - Structural life extension, safety–by-inspection, various ASIP tasks (ex. MIL-STD-1530D).

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Discussions: Challenges, Gaps, and Future Works

- How to further validate structural risk analysis in the digital age?
  - In-service findings? More sensor data, digital records of maintenance? Sharing data?
- Robust, efficient, trusty structural risk analysis tools
  - More verification/comparison of different tools? (HOLSIP2024 Risk Analysis Session)
  - Machine learning, surrogate modeling?
  - More practical applications/examples? (ASIP, ICAF, AA&S, HOLSIP…)
- How to determine fatigue scatter of new materials/manufacturing/hybrid structures?
  - from more testing to more modeling? probabilistic modeling for virtual testing?
- Shift of safety culture/mindset from deterministic methods (ex. safety factor) to probabilistic methods (ex. PoF) in aircraft structural integrity community
  - Training? Education?
- Other gaps/challenges in near-term? and long-term?

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THANK YOU

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Backups: List of the ICAF inputs reviewed

Australia ICAF National Reviews 2023, 2021, 2019:
- Effect of using a bounded initial crack size distribution in probabilistic risk analysis of fatigue failures of military aircraft – R. F. Torregosa, W. Hu and H. Stone [DSTG/Airbus Australia Pacific], 2023.
- Aircraft Structures Fatigue Activities – A. Groszek and J. Moews [QinetiQ Australia Pty Ltd], 2021.
- C-130J Wing Fatigue Test – Deterministic Interpretation of Failure of the Butt Line 61 Wing to Fuselage Interface. (Kai Maxfield, Matthew McCoy*, Robert Ogden, Vuitung Mau* and Anthony Zammit* [DST/* QinetiQ]), 2019
- Developments in Risk-Based Fatigue Failure Prediction for Application to Military Aircraft (Ribe Torregosa and Weiping Hu [DST]) , 2019

Brazil ICAF National Reviews 2023, 2021, 2019:
- A Probabilistic methodology for analysis of secondary cracks in riveted structures (Ref. [34]), 2023
- Aircraft structural reliability/risk estimate with limited data using possibility theory (Ref. [42]), 2023
- On the development of statistical knock-down factors for WFD assessment (Ref. [40]), 2023
- Aircraft Structural Inspections Definition Considering Probabilistic Analysis of Failures Based on Variability of Crack Growth Parameters and Probability of Detection (Ref. [52]), 2019
- Widespread Fatigue Damage Evaluation for Multi Elements Based on a Probabilistic Approach (Ref. [55]), 2019

Canada ICAF National Reviews 2023, 2021, 2019:
- 3.5 Development and Demonstration of Damage Tolerance Airframe Digital Twin Methods and Tools* , Yan Bombardier, Guillaume Renaud, and Min Liao, 2023
- 4.2 Probabilistic Lifing of a Second Oversize Hole Modification Guillaume Renaud*, Éric Dionne, and Min Liao, 2023
- 3.5 Airframe Digital Twin (ADT) Technology Development and Demonstration, Min Liao, Guillaume Renaud, Yan Bombardier, Jean-Rene Poulin, Gang QI, Gang Li, 2021
- 3.7 Demonstration of an Airframe Digital Twin Framework using a CF-188 Component Test *, G. Renaud, M. Liao, and Y. Bombardier, NRC Aerospace, 2019

China ICAF National Reviews 2023, 2021, 2019:
- 3.9 A Probabilistic Damage Tolerance Analysis Method of Multiple Site Damage for Structure Containing Holes, 2019
- 4.3 An Engineering Calculation Method of Probability Distribution of Crack Initiation Life for Widespread Fatigue Damage, 2019
- 4.5 Analysis and Test Research on Multiple Site Damage in Longitudinal Fuselage Lap-joints, 2019
- 5.13 Research on Flight Load Pattern Recognition Methods and Applications, 2019
- 2.1.2 Fatigue Failure Mechanism and Life Model in Additive Manufactured Titanium Alloys, 2021
- 2.1.7 Fatigue Evaluation Method of Titanium Alloy Additive Manufacturing, 2021
- 2.3.6 Experimental Research on Fatigue Threshold Value and Low-Load Cut-Off of Typical Laminates of Composite Fuselage, 2021
- 4.1.1 Determination and Analysis of Material Dispersion Coefficient of Aging Aircraft, 2021
- 7.1 Experimental Study on Mechanical Properties of Laser Powder Bed Fused Ti-6Al-4V Alloy Under Post-Heat Treatment, 2023
- 8.4 Widespread Fatigue Damage Test and Evaluation of Equally Straight Section in Fuselage, 2023

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Backups – List of all inputs reviewed

Finland ICAF National Reviews, 2021, 2023:

- Risk Level Assessment for Structural Integrity Management, 2021
  - [23] Hukkanen, T. 2019. Risk Analysis of Changes in Hornet SSP Modification Program. Technical Report № HN-L-0316 (in Finnish, classified). 101 p. Halli: Patria Aviation Oy.
  - [24] Hukkanen, T. 2019. Analysis Method for Risk Level Assessment in Structural Integrity Program. Technical Report № HN-L-0341 (in Finnish, classified). 46 p. Halli: Patria Aviation Oy.
- 2.2.4.2 Creating an operational spectrum for the wing of the FINAF Hawk aircraft, 2023
- 2.3.3 Risk-based Aircraft Structural Integrity Management, 2023

France ICAF National Reviews: 2019:

- 5.1. RELIABILITY APPROACH APPLIED ON FATIGUE SAFETY FACTORS FOR FLEET MONITORING (DGA AERONAUTICAL SYSTEMS), 2019

Germany ICAF National Reviews 2019:

- 5.3 Probabilistic reliability assessment of a component in the presence of internal defects F. Fomin, N. Kashaev (HZG), B. Klusemann (HZG, PPI) , 2019

Israel ICAF National Reviews: 2021:

- 2.1 Widespread Fatigue Damage – What could possibly go wrong? (Y. Freed, IAI) , 2021
- 2.2 Investigation of the Effect of Secondary Bending on Multi-Site Damage Scenarios in Hard-point Joints (Y. Freed, IAI) , 2021
- 4.1 Nearly Identical Twins or Distant Cousins, Revisited. Weibull or Log-Normal Distributions to Characterize Fatigue Life Scatter – Which is Recommended? (A. Brot, Brot Engineering Consultant), 2019
- 6.1 New Book – "Stochastic Crack Propagation, Essential Practical Aspects" (G. Maymon, RAFAEL) , 2019

Swiss ICAF National Reviews: 2023:

- 4. Structural Risk Assessment with SMART|DT (RUAG AG / ZHAW) RUAG AG, Viola Ferrari, Michea Ferrari; NRC (Canada), Min Liao; ZHAW, Michel Guillaume, 2023
- 12. Evaluation of Risk for Stress Corrosion Cracking using FMEA (RUAG AG) RUAG AG, Andreas Uebersax, Raphael Zehnder, Daniel Rölli, Sandro Christen, 2023

The Netherlands ICAF National Reviews: 2019, 2021:

- 4.2. Probabilistic Fail-Safe structural risk analyses F.P. Grooteman (NLR) , 2021
- 4.1. Adaptive Prognostics for Remaining Useful life of Composite Structures Nick Eleftheroglou, Dimitrios Zarouchas, Rinze Benedictus (TU Delft) 2021
- 5.1. Extreme Prognostics of Composite Structures Nick Eleftheroglou, Dimitrios Zarouchas, René Alderliesten, Rinze Benedictus, TU Delft, 2019
- 5.2. Structural risk assessment tool Frank Grooteman, Netherlands Aerospace Centre NLR, 2019

Backups – List of all inputs reviewed

UK ICAF National Reviews, 2019, 2021
- 2.1 Probabilistic Fatigue Methodology for Safe-Life Design and Analysis Joshua Hoole1, Pia Sartor1, Julian Booker1, Jonathan Cooper1, Xenofon V. Gogouvitis2, Amine Ghouali3 and R. Kyle Schmidt4, 2021
- 7.3 A Framework to Implement Probabilistic Fatigue Design of Safe-Life Components J. Hoole 1, P. Sartor 1, J. Booker 2, J. Cooper 1, X.V. Gogouvitis 3, A. Ghouali4, R. K. Schmidt, 2019

USA ICAF National Reviews 2019:
- 9.7.1. Fracture Mechanics and Risk Methods Used to Analyze the F-16 Upper End Pad Radius Mark Ryan, Lockheed Martin Corporation – F-16 Program
- 9.7.2. Evaluation of Structural Risk Analysis Methods Using F-15 Experience Charles Babish, USAF Life Cycle Management Center – Wright-Patterson AFB
- 9.7.3. Risk Analysis Including Proof Testing in Bonded Composite Design Andrew Ollikainen, Northrop Grumman Corporation
- 9.7.4. Risk Assessment and Risk Management Methods for Small Airplane COS, SMART Software, Sohrob Mottaghi, FAA William J. Hughes Technical Center; Michael Reyer, FAA Small Airplane Directorate; Harry Millwater, University of Texas at San Antonio; Juan Ocampo, St. Mary's University
- 9.11.5. T-38 Upper Cockpit Longeron Cracking: Unknown Unknowns are Unknown Until Known David Wieland, Laura Domyancic and Marcus Stanfield, Southwest Research Institute (SwRI); Robert Pilarczyk, Hill Engineering, LLC; Michael Blinn, USAF Life Cycle Management Center – T-38 ASIP
- 9.11.8. Methodology for Flaw-Tolerant Design and Certification Barna Szabo and Ricardo Actis, Engineering Software Research & Development (ESRD) Inc.; Dave Rusk, USN – Naval Air Systems Command
- 9.11.12. Composite Spectrum Analysis Jake Warner, USAF Life Cycle Management Center – A-10 ASIP
- 9.11.14. Inspection Interval Extension Analysis Utilizing Usage Severity Differences Michelle Warmoth, USAF Life Cycle Management Center – A-10 ASIP

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