From Science to Engineering Practice - Evolving a Structural Integrity Framework

ASTM 2016 Fatigue Lecture

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with David Hoeppner and Min Liao

National Research Council Canada
Conseil national de recherches Canada

To my HOListic Structural Integrity Process (HOLSIP) co-conspirators

Content

- HOLSIP - why “conspiracy”?
- About NRC and our collaborators
- We are still learning the hard way
- Engineering and Science
- HOLSIP the framework
- Selected Applications
- Future – the unfinished business

HOLSIP – why ‘conspiracy’

“Conspiracy” – collaboration of boondoggle bunch`

- In early 2000’s word ‘holistic’ was associated with alternative (not science based) medicine rather than with:
  - ***Holistic = Emphasizing the importance of the whole and the interdependence of its parts.***
  - USAF was no longer interested in funding the core members: U. Utah (D. Hoeppner), APES Inc. (C. Brooks) and NRC (JPK and N. Bellinger)
- 2002 The series of annual HOLSIP workshops was launched = boondoggles
- 2016 – February 21-26 – 15th HOLSIP workshop was held at Snowbird Utah.

NRC and collaborators

HOLSIP workshop attendees

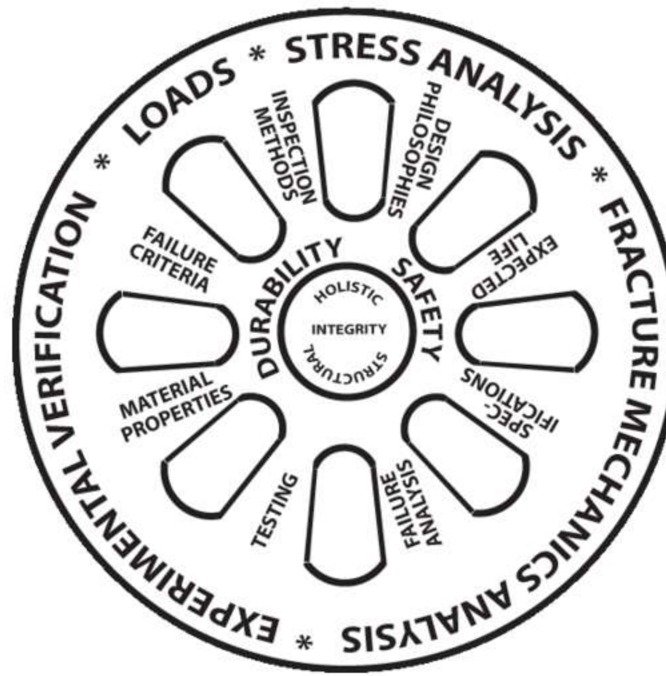
- Australia, North America, Asia (Japan), Europe
- Air forces (5), Industry (OEM 4, MRO, other), Airworthiness, Safety, RTO (5), University (6)
- Research, Technology Development, Product Development, Sustainment (MRO),

Aircraft airframes and engines, pipelines, civil structures

HOLSIP 15 (2016)

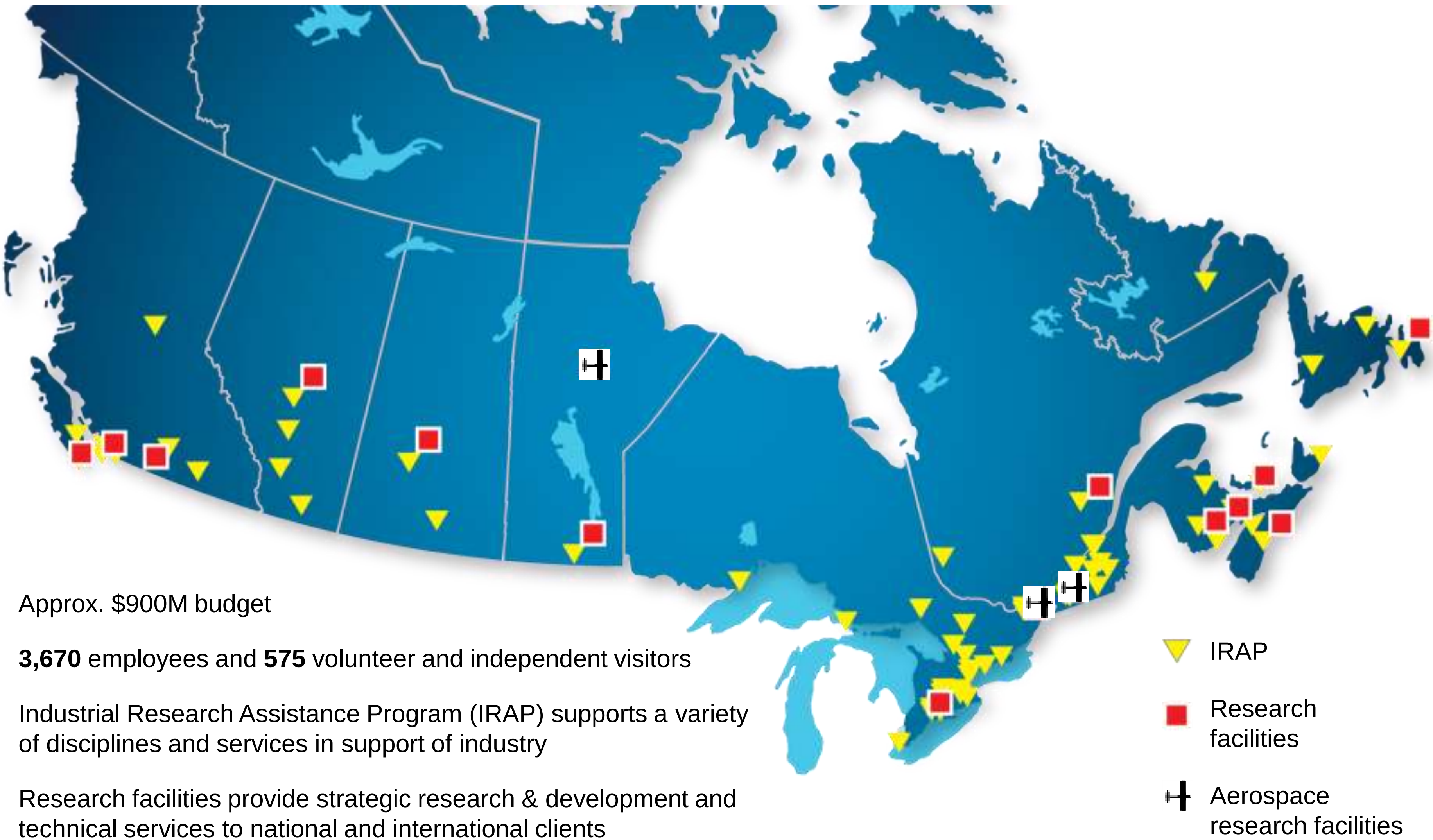
University of Utah / FASIDE

THE UNIVERSITY OF UTAH®



NRC·CNRC

About NRC



- Approx. $900M budget
- **3,670** employees and **575** volunteer and independent visitors
- Industrial Research Assistance Program (IRAP) supports a variety of disciplines and services in support of industry
- Research facilities provide strategic research & development and technical services to national and international clients

Facilities – $500M Research Infrastructure


Aerodynamics


Structures, Materials and Manufacturing


Flight Research


Gas Turbines

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analytical processes / engineered solutions > AP/ES >

- home
- vision
- projects
- personnel
- resources

AP/ES consists of former aerospace OEM and government engineers with over 75 years collective experience in the aerostructures industry.

Contact

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Saint Louis, MO 63139

314.644.6040 (tel)
314.644.1309 (fax)

Email
Printable Map

Fatigue & Fracture

AP/ES has diverse expertise in disciplines such as damage tolerance, crack nucleation, durability, corrosion fatigue, holistic life assessments, spectrum analysis and generation, and mechanical testing.

Process Development and Automation

Software developers with extensive engineering experience can create custom solutions to meet a customers' needs. Automating repetitive analytical tasks, parsing and evaluating results, linking and porting software, and developing specialized programs, macros, and reports are all day-to-day examples.

Stress & Failure Analyses

Experienced aircraft stress analysts, finite-element modeling specialists, microstructure experts, and unique fractography capabilities get to the root causes of your engineering problems.

Service Life Assessments

Using advanced and existing technologies, AP/ES and strategic partners can provide customers with criticality overviews and specific structural integrity evaluations tailored to their unique structural systems and fleets. Assessments address the impacts of maintenance and inspection programs on cost, fleet readiness, and structural safety.

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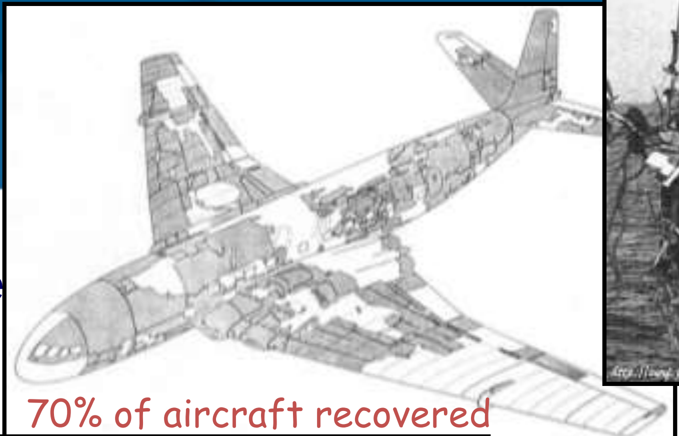
We are still learning the hard way

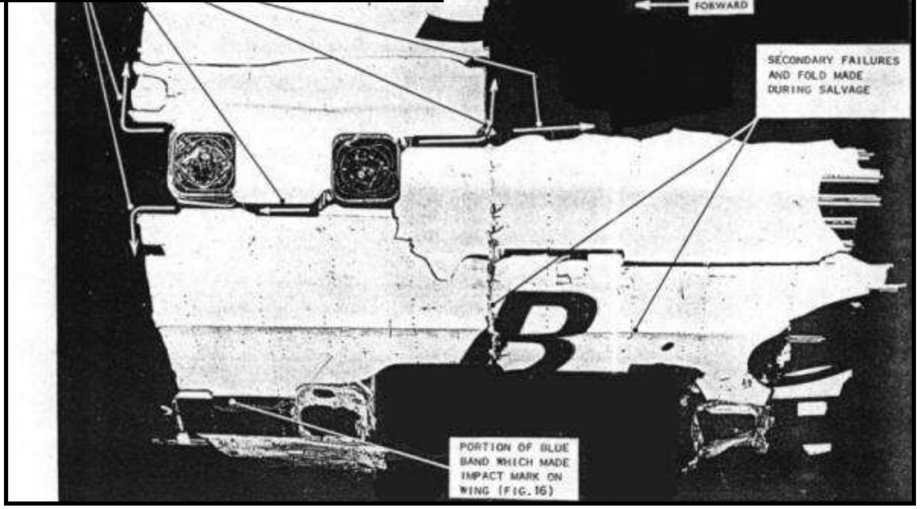
No-Life Paradigm

- Between May 1953 and April 1954, three *Comet aircraft* disintegrated in flight, after which all Comet 1 aircraft were withdrawn from service.
- Afterwards a full-scale test was carried out in which the fuselage was submerged in water to simulate the pressurization cycles.
- From the resulting cracks, the relevant fuselage piece of a failed aircraft was recovered from the ocean floor, which showed the "unmistakable fingerprint of fatigue".
- Fatigue cracks due to the stress concentration at nearly-square rear window cutouts caused failures.



70% of aircraft recovered

Recovery effort



Recovered section showing cracks at window cutouts

Safe-Life Paradigm

- RB211 SITUATION ON THE LOCKHEED TRISTAR (1972, 1973)
  - Two in-flight first stage fan discs burst. One in Dec., 1972 (six days before EA 901), second Jan. 12, 1973-TWA 28
  - No fatalities, but all IMI 685 fan and compressor discs replaced by RR and Lockheed.

RB211, L1011-TWA 28

Safe-Life Paradigm

- UA 232-DC10 ACCIDENT SIOUX CITY, IOWA (1989)
  - In flight compressor fan disc failure of CF6-6 engine. 113 fatalities. 171 survived.
  - Previous spool failures had occurred (different Ti alloy but same basic problem).
  - Sister discs were cracked.

Photograph taken of the aircraft on final approach to Sioux City. Note the missing tail-cone and damage to the horizontal stabilizer

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Damage Tolerance (Metals)

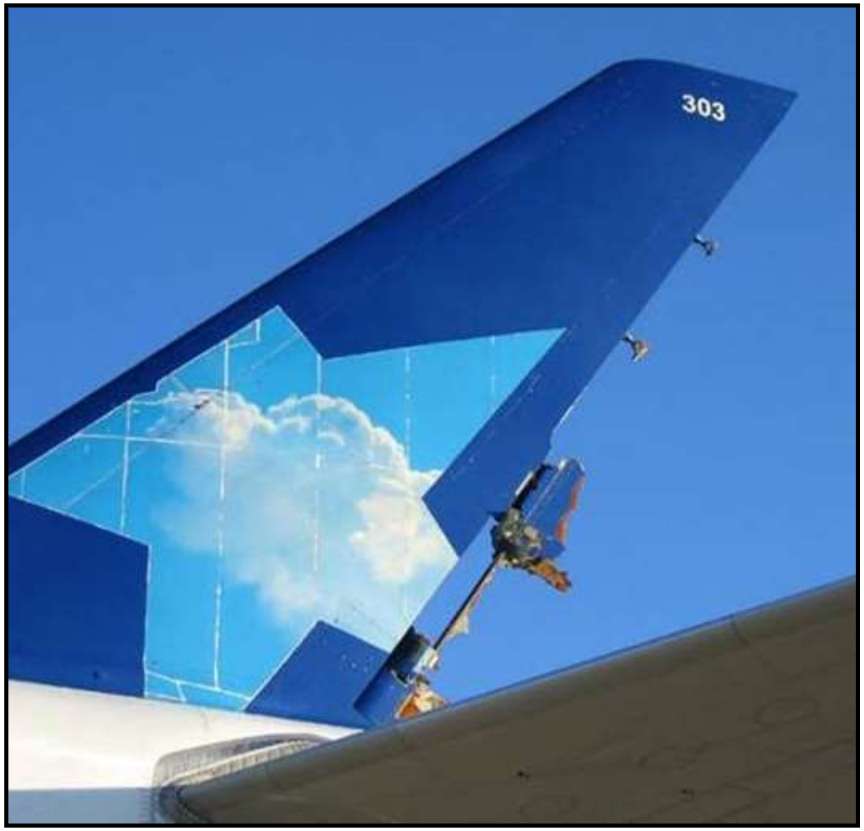
- ALOHA AIRLINES 243 ACCIDENT (1988)
  - The aircraft lost 1/3 of its crown due to a stress fracture while cruising at 24,000 feet. 1 fatality.

Damage Tolerance (Metals)

- CAUSE OF SOUTHWEST B733 NEAR YUMA (2011)
  - MISALIGNED rivet holes where two parts of the fuselage were assembled.
  - Wear-induced cracks
  - Riveted joints that failed were not extensively checked because they were thought not to be susceptible to fatigue.

Damage Tolerance (Composites)

- AIR TRANSAT AIRBUS A310 C-GPAT
  - On 6th of March, 2005, over international waters a rudder detached from the vertical stabilizer.
  - Rudder is an all-composite structure consisting of two sandwich panels, hinge side spar, top and bottom ribs.
  - “No-Growth” design



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Engineering and Science

Engineering is not science, it is art

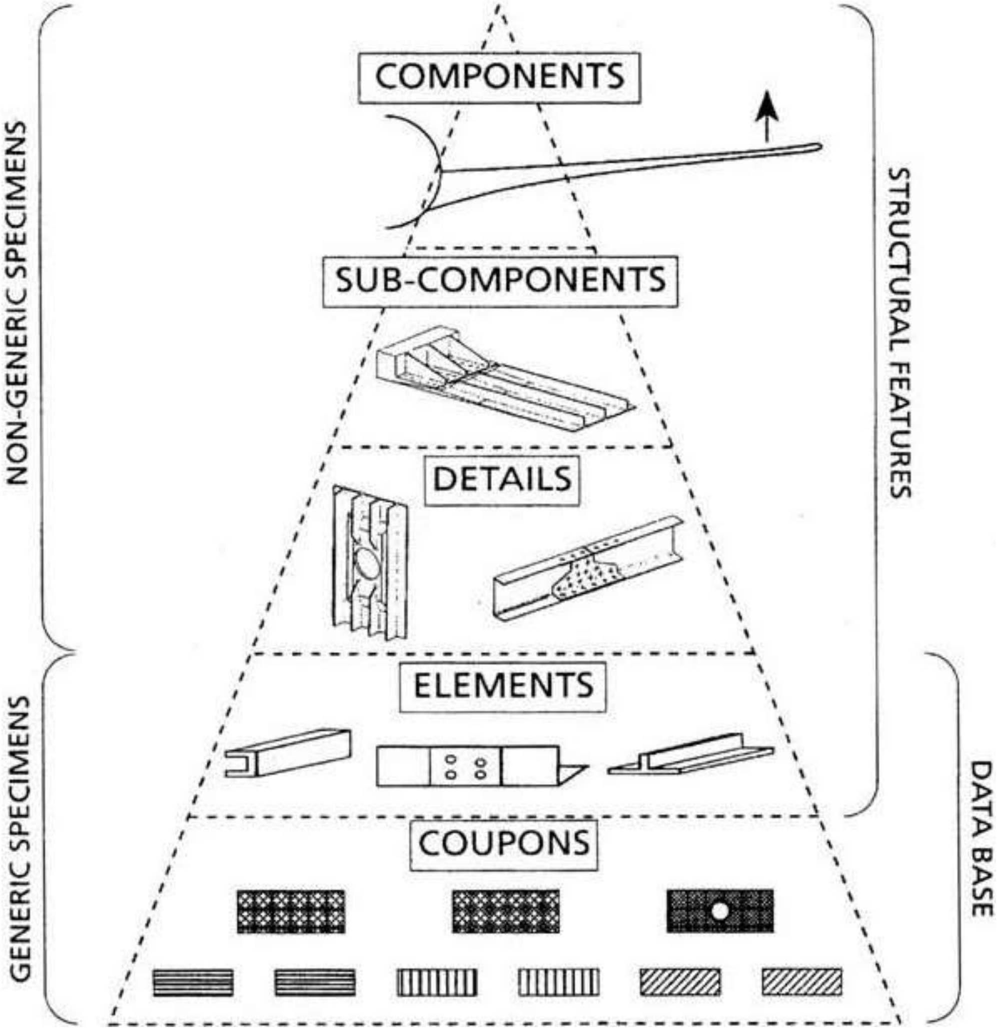
- Practitioners do not see themselves as creative artists pushing the boundaries of possibility

Aircraft Art, Forte di Belvedere
Florence, Italy

Damage Tolerance (Composites)

Tests form the basis for validating no-growth approach to damage tolerance requirements but assumes that all damage modes are known.

- Must show catastrophic failure due to fatigue, environmental effects, manufacturing defects, or accidental damage will be avoided throughout the operational life of the aircraft.
- Extent of analysis or tests will depend upon applicable previous fatigue/damage tolerant designs, construction, tests, and service experience on similar structures. (When will this happen given the tailored design of composite structures)



Taken from Advisory Circular No: 20-107B

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Composites - fatigue

- No-life **AGAIN!!!!?**

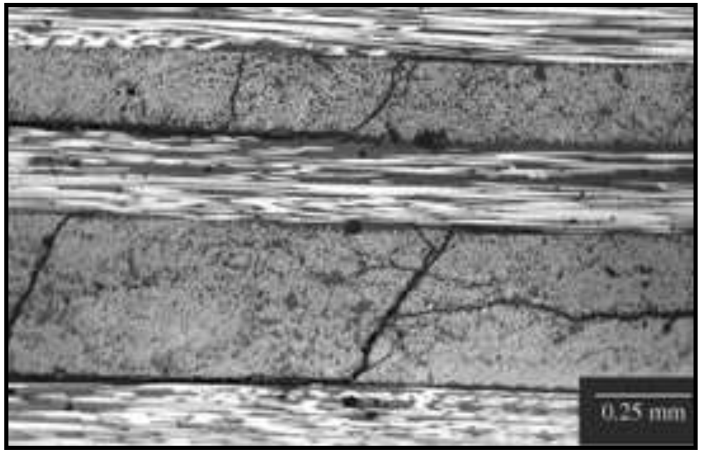
- Service experience
  - Low strain levels (<4,000με)
  - Older materials
  - Conclusion – fatigue resistant materials

- Lab experience
  - Small coupons
  - Specimen geometry – edge problem
  - Long period without evident damage – low number of cycles to failure when damage can be observed

- Large transport composite wing weight saving requires higher strains closer to 6,000 με?

Composite Materials

- Physics based models (degradation, strength, failure) are still needed and not yet available.



NASA-Led Consortium Will Bring Science To Art Of Composites

Aviation Week & Space Technology

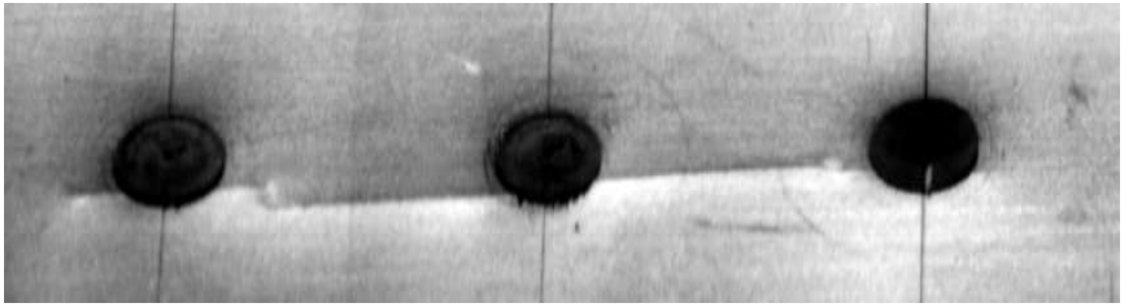
Graham Warwick

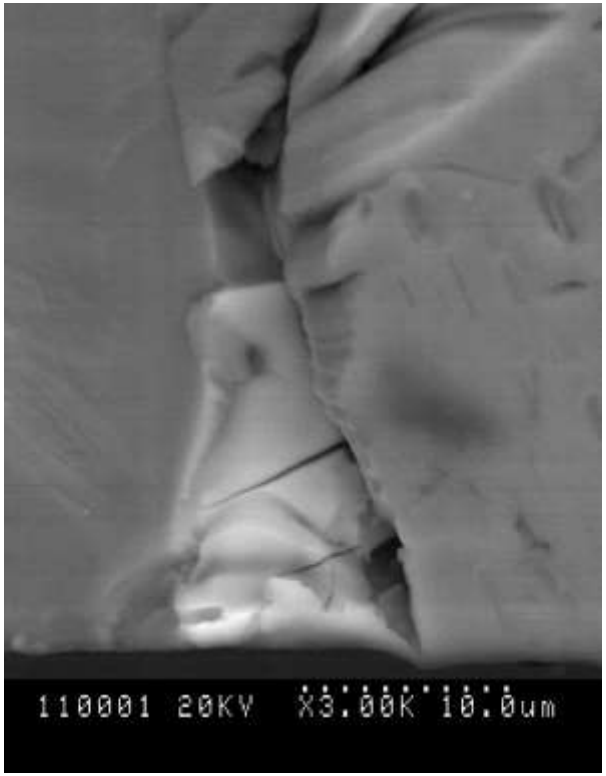
Mon, 2015-04-27 04:00

Metal fatigue more unfinished business

- Early stages not well modeled:
  - dichotomy between Durability and DT
  - EIFS problematic, post-diction
  - “initiation” concept
- Environments not considered

Discontinuity
Heterogeneity





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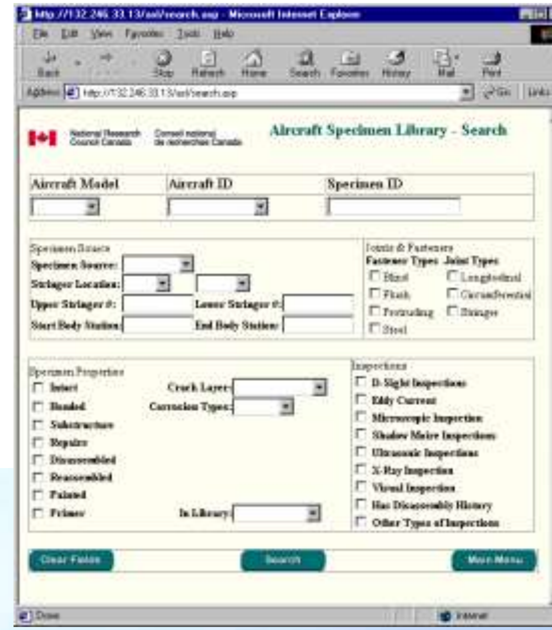
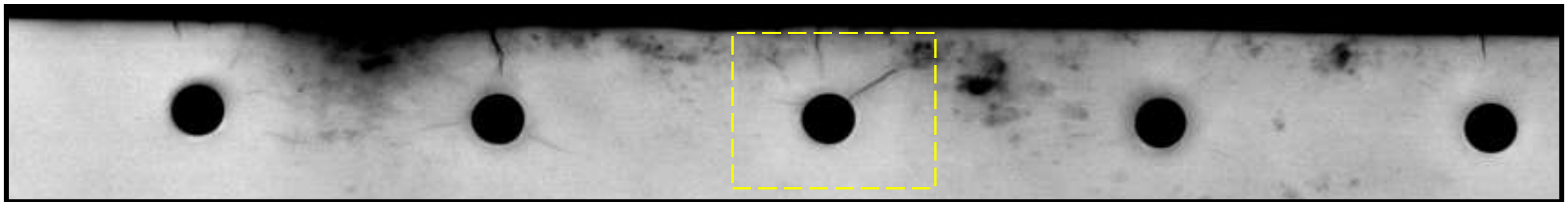
NRC Aerospace Aging Aircraft Specimen Library



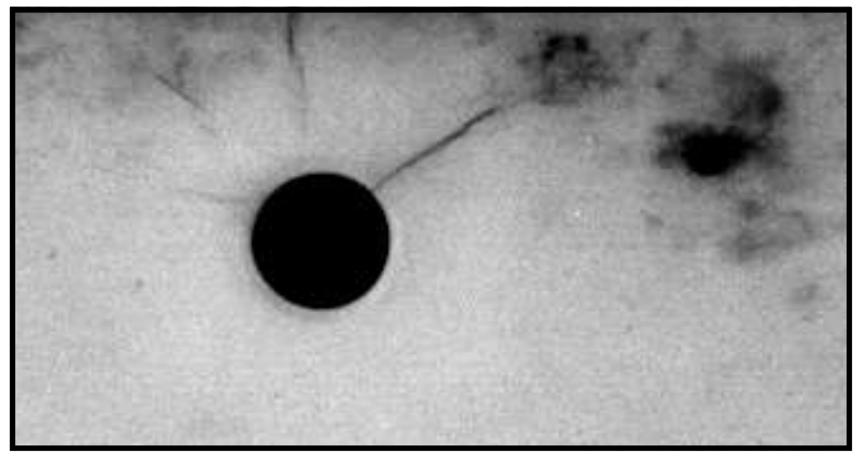
Lap Joint Specimen Teardown

47-18A, Boeing 727-200 N4747, S4R - BS1020

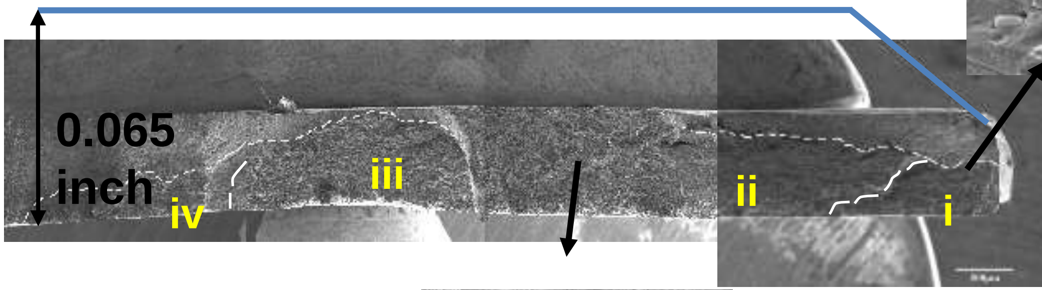


- **Upper rivet row inner skin, faying surface.**
- **Dark areas contain ~10% thickness loss maximum.**
- **Cracks in the areas adjacent to maximum corrosion pillowing.**

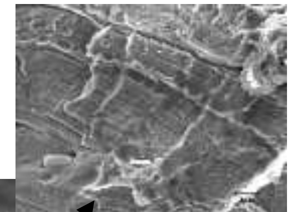
X-ray images

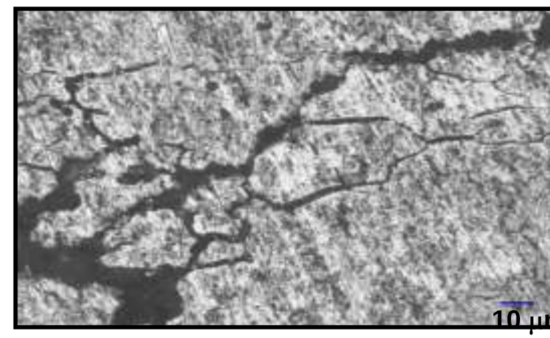


Fatigue and Corrosion Pillowing



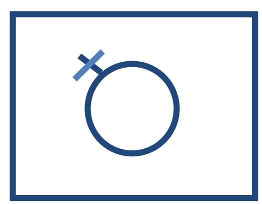
Fatigue striations along crack front

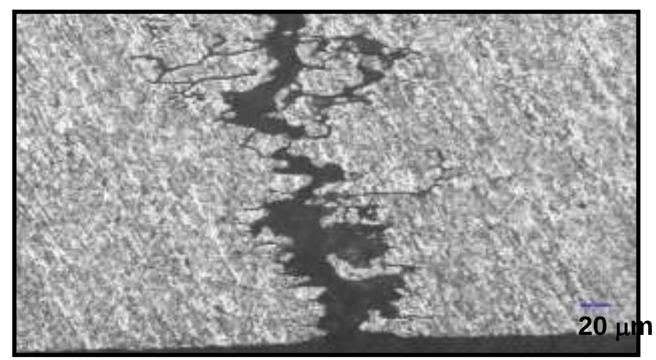




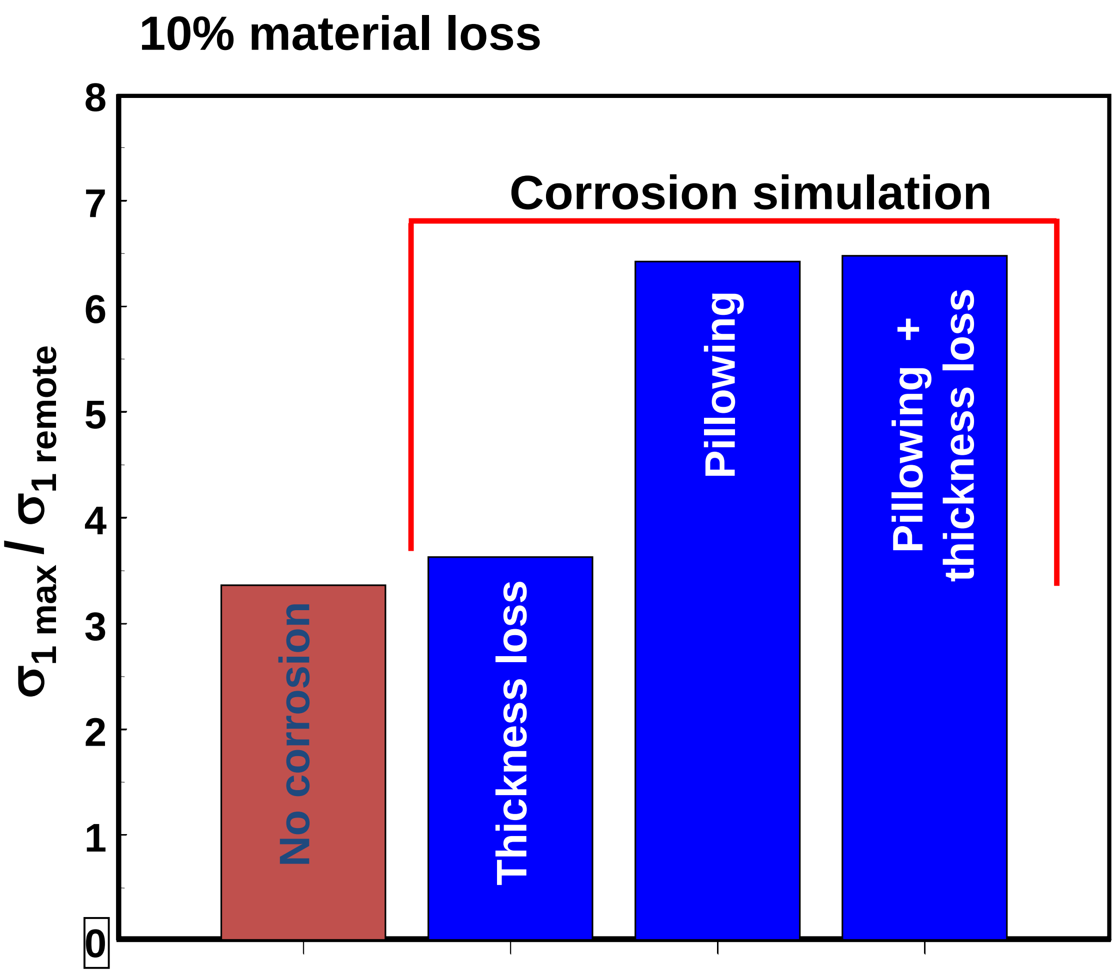
Intergranular fracture

Pillowing cracks found in 10 different a/c from 3 manufactures

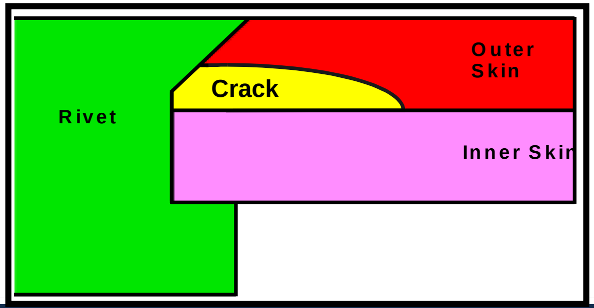




Effect of Corrosion on Stress



- **Finite element models generated with and without thickness loss.**
- **Results show strains significantly increase due to pillowing as compared to thickness loss effect.**



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HOLSIP the framework

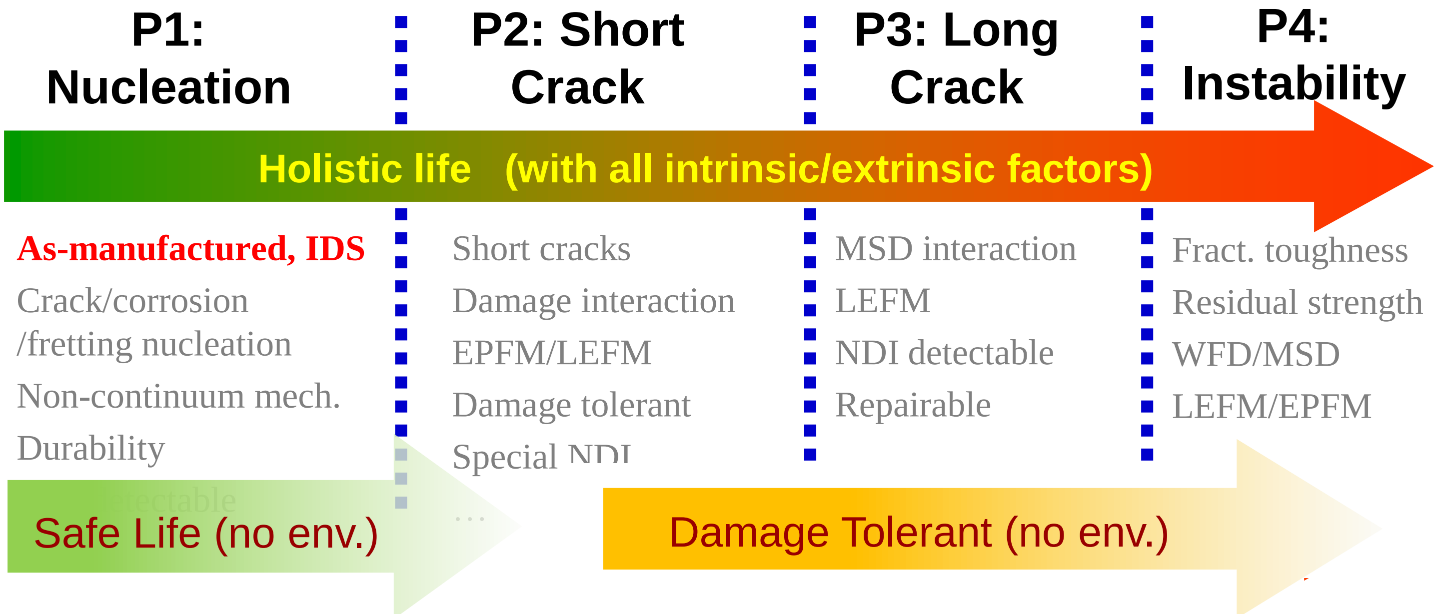
In the absence of physics based failure models

- Each time new material is introduced – new black box to build structures from
- Old approaches to support SI – bound by assumptions known to retired practitioners and typically based on simple strain analysis
- Start again with each generation – typically only one new platform designed in 20 years

Holistic:

emphasizing the importance of the whole and the interdependence of its parts

Holistic structural integrity Process (HOLSIP)



HOLSIP framework: to currently augment *safe-life* and *damage tolerant* paradigms with the *ultimate* goal to evolve HOLSIP into a new paradigm for <u>both design and sustainment engineering</u>

Key elements: physics & probabilistic models, loads monitoring, environmental effects, advanced NDE/SHM, and risk assessment.

Developers: NRC, APES, U. Utah, Tri/Austin, AFRL/USAF, JAXA …

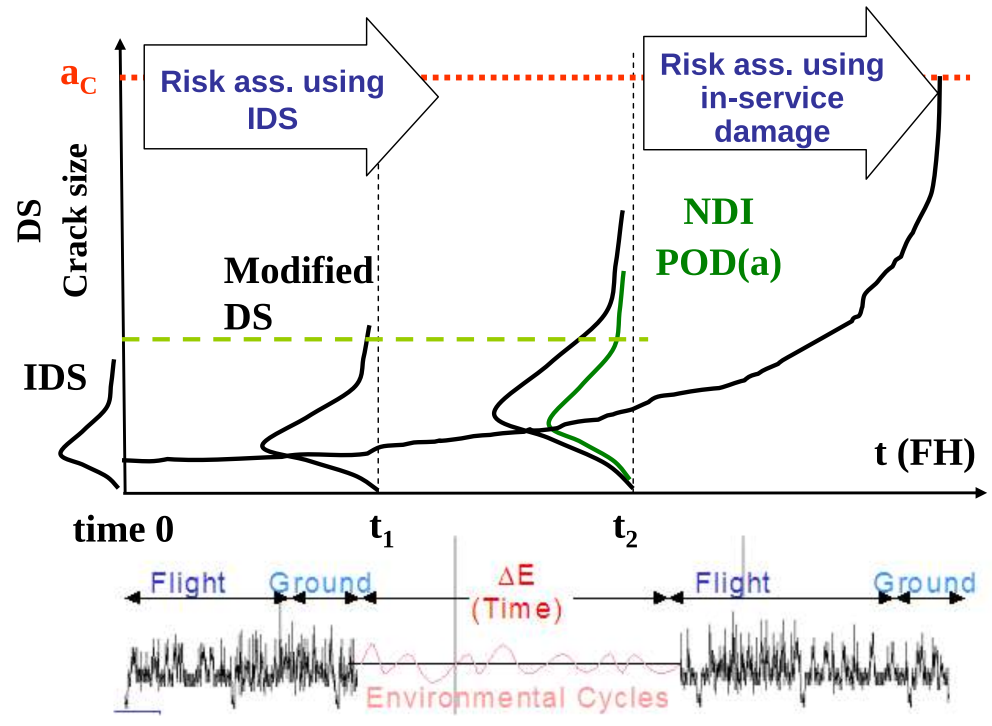
Holistic structural integrity Process (HOLSIP)

Precise communication

*HOLSIP terminology

Major HOLSIP Related Tasks at NRC

- **Physics modeling**: crack nucleation, short crack, environment/corrosion composite age degradation, new manufacturing, new material)
- **Residual stress** measuring/ modeling, new joining tech.
- Structural health monitoring **(SHM)** and test integration
- **Advanced NDI** and modeling
- **Risk/reliability** toolbox (including MSD/WFD)
- **Certification/qualification** testing



Risk/reliability quantified total life assessment considering both cyclic and environment related loading

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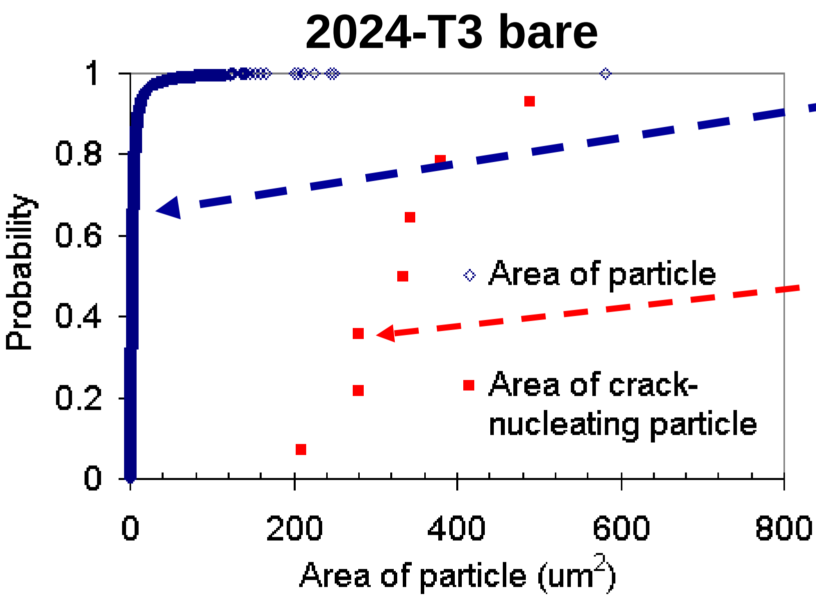
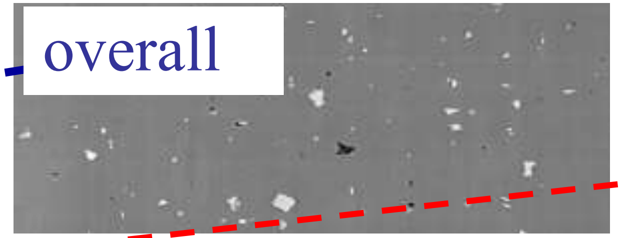
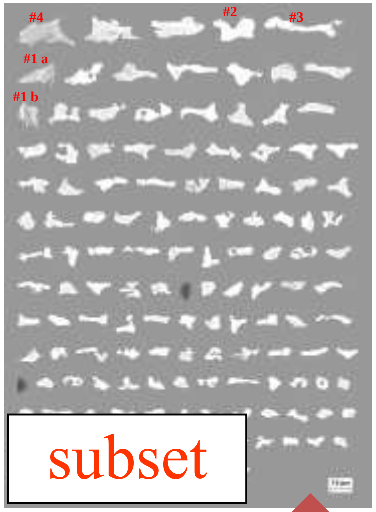
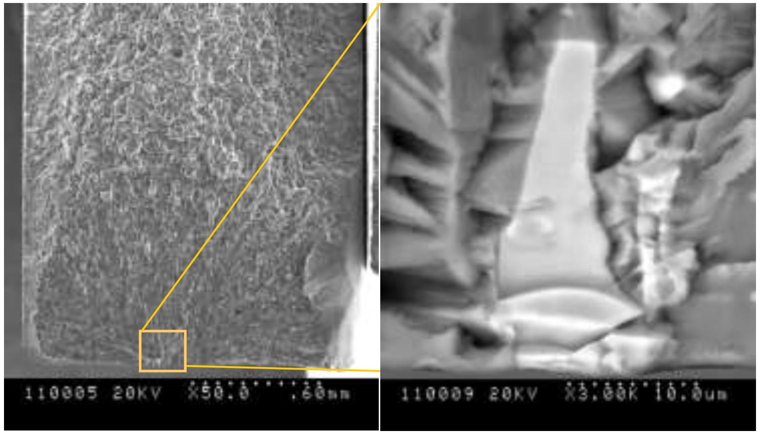
Initial Discontinuity States (Material Characterization)

Initial Discontinuity States (IDS): Initial population of discontinuities that are in a structure made of a given material as it was manufactured in a given geometric form









IDS fatigue subset measured from fracture surfaces

IDS examples: particles, pores, machining marks/scratches

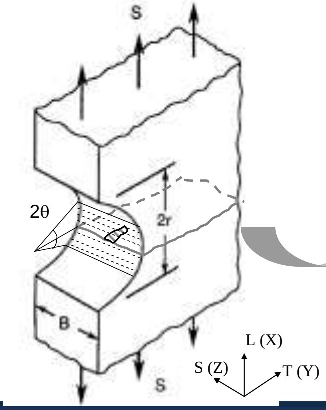
Correlation between overall IDS distribution and its fatigue subsets

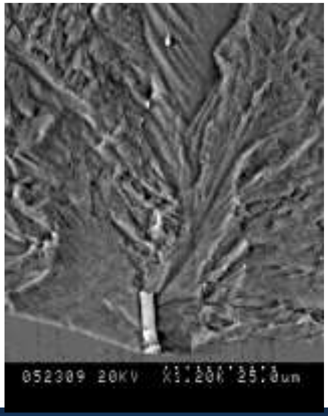
Extreme value model: IDS fatigue subset is in the right tail of the overall IDS distribution, which can be determined using the extreme value theory in the highest (95%) stress region, ex. Lognormal (overall IDS)→ Frechet (IDS subset).

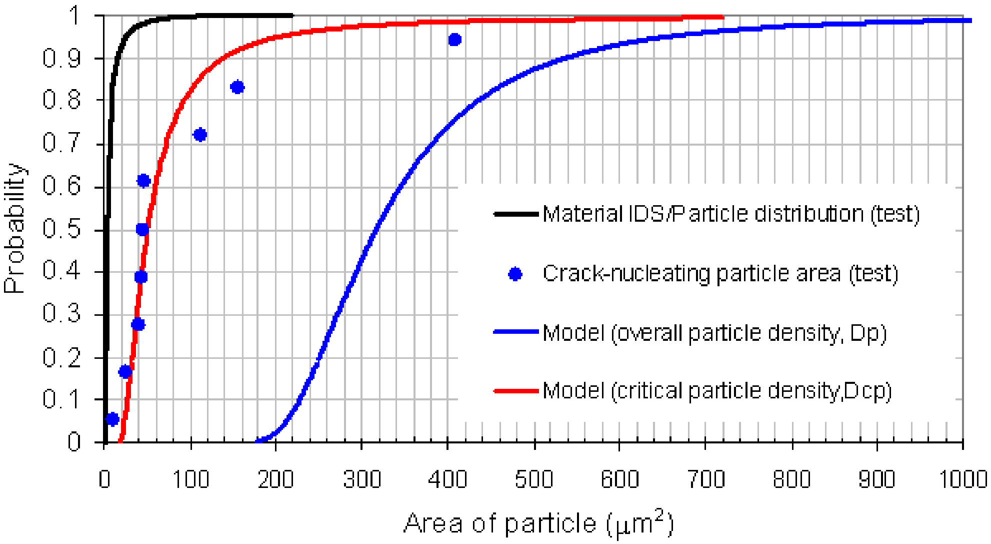
$$F_S(x) = \exp[-(\frac{a}{x-\tau})^b], x \geq 0, a, b > 0$$

$$a = \exp[\sigma\sqrt{2\ln(N_S)} - \sigma[\frac{\ln(\ln(N_S) + \ln(4\pi))}{2\sqrt{2\ln(N_S)}}] + \mu$$

$$b = \frac{\sqrt{2\ln(N_S)}}{\sigma}$$



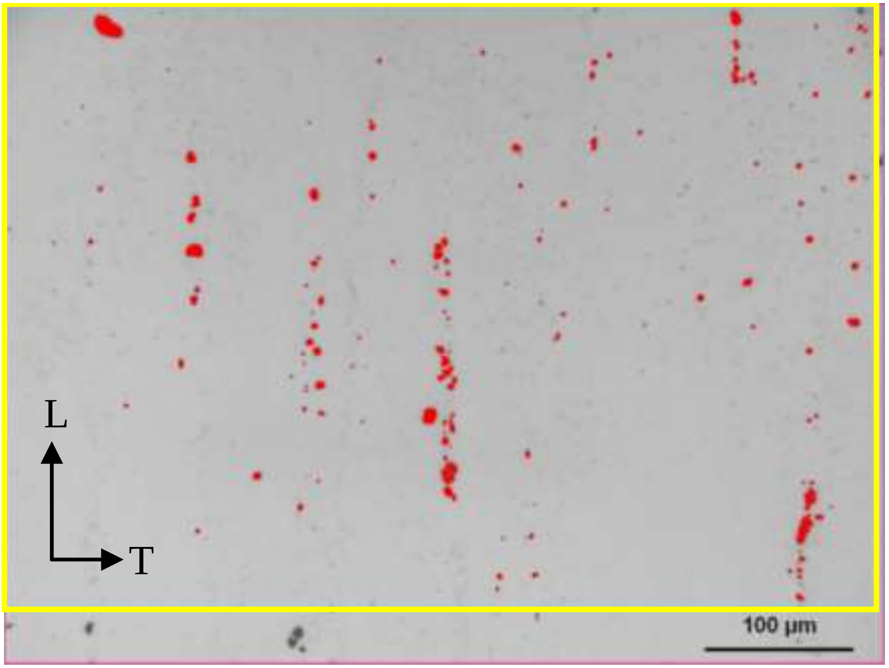




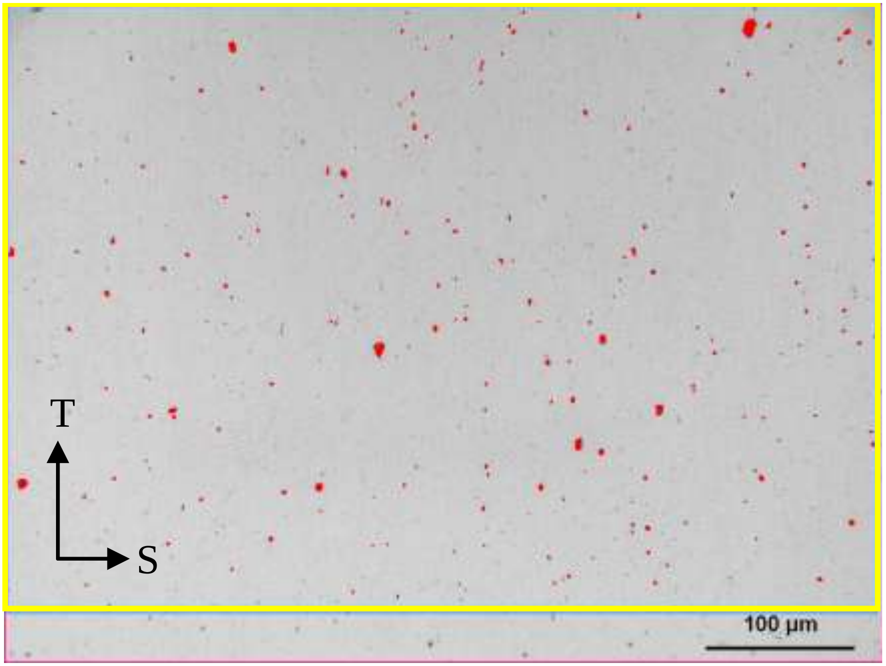
Model and test results for crack-nucleating particle (area) for 7050

IDS Study for New Material 7249-T76511

Microstructural analysis: **IDS (initial discontinuity states) study**



a) L-T plane



b) S-T plane

- The analysis showed that the 7249 alloy has finer microstructures, *especially smaller particles, compared to the legacy 7075-T6 material* (from a previous CFSD), providing some physics for explaining the near-threshold FCGR difference between these two materials

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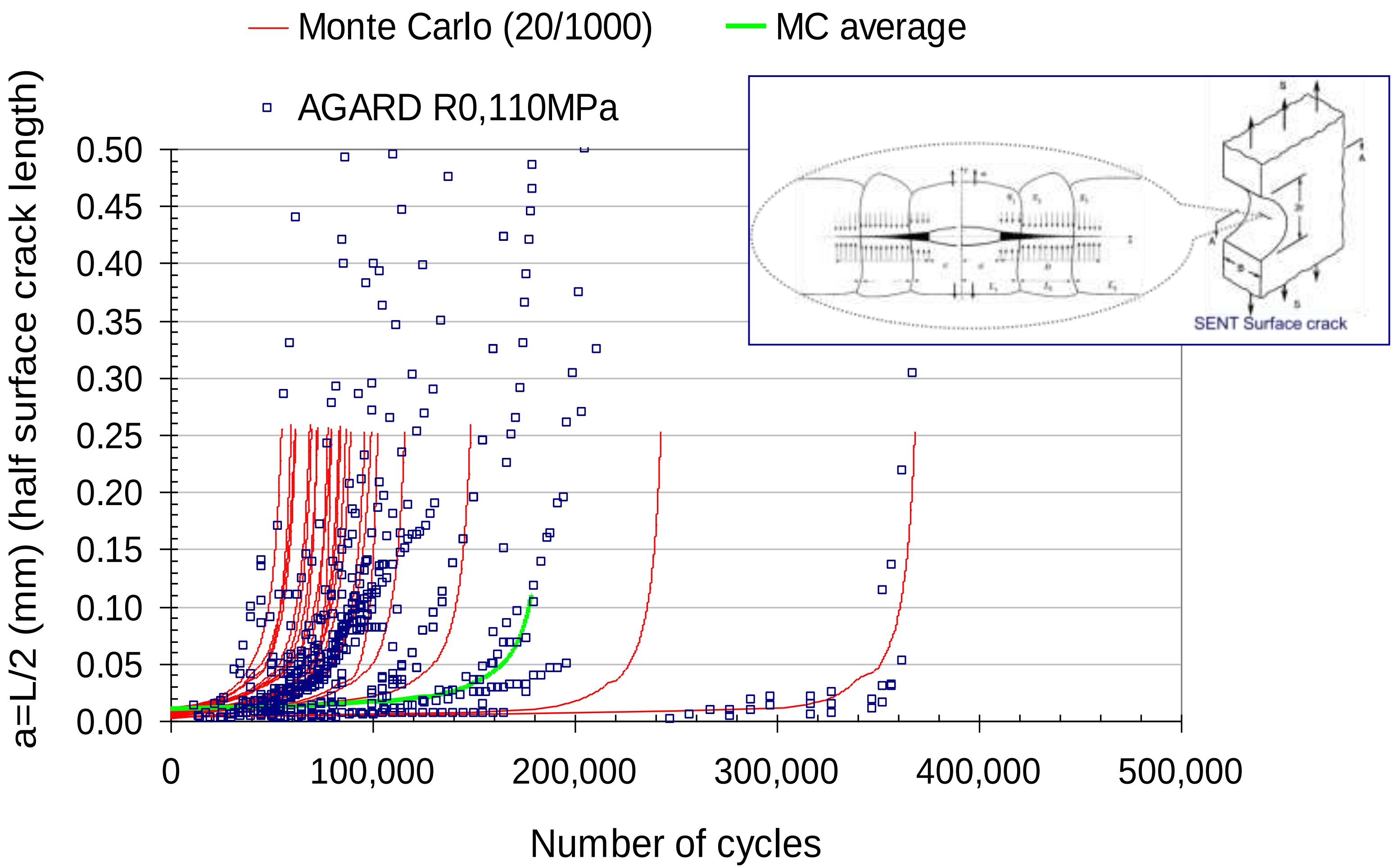
Probabilistic Short Crack Modeling (CTOD based)

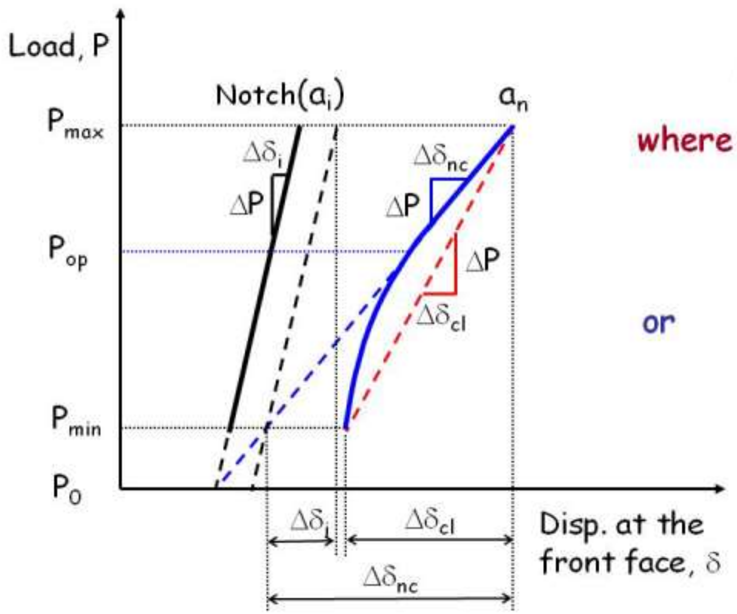


a – N results for 2024-T351(SENT)

Analysis (a0: IDS/particle) vs. Test (AGARD 1982)

Quantify Residual Stress Effect on Crack Growth using ACR Technique

- The adjusted compliance ratio (ACR), developed by K. Donald, is an experimental method for estimating ΔK_{eff} .
- The ACR method intends to measure the crack closure effect below the 2% crack-opening load, and ***quantify the remote closure effect induced by residual stress (from forging or welding)***



$$\Delta K_{ACR} = ACR \cdot \Delta K_{app}$$

where

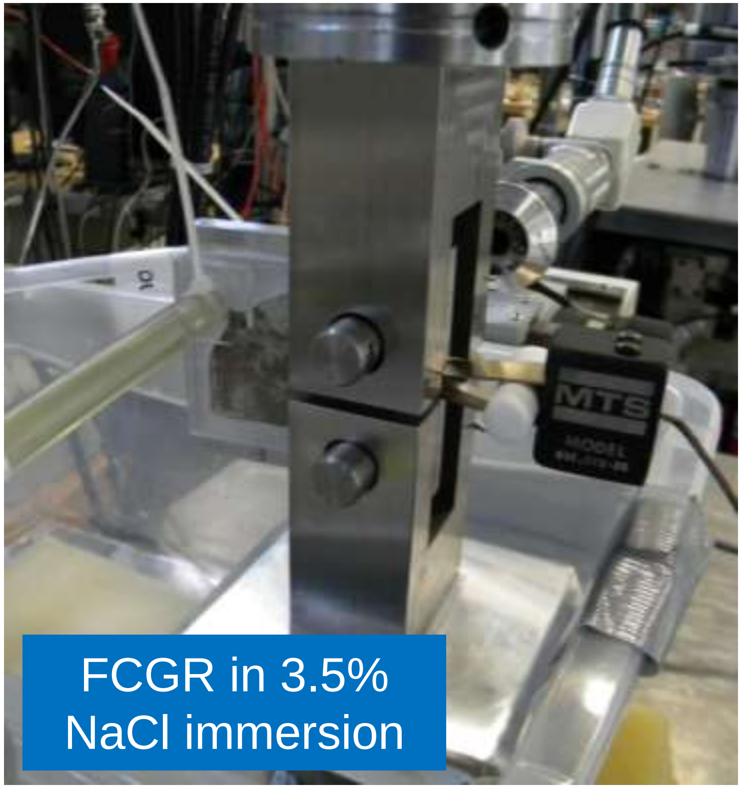
$$ACR = \frac{\Delta\delta_{cl} - \Delta\delta_i}{\Delta\delta_{nc} - \Delta\delta_i}$$

or

$$C = \delta / P$$

$$ACR = \frac{C_s - C_i}{C_o - C_i}$$

Source: K. Donald, What is ACR?



Record of Airworthiness Risk Management (RARM, RCAF, 2003)

- Hazard Id.→Risk Ass.(RA)→Risk Ctrl.→RARM Approval→Risk Tracking
- Affecting all RCAF air fleets (DND-AD-2007-01)

Quantitative vs. *Qualitative* risk index

Effect Severity / HAZARD PROBABILITY	Catastrophic Category A	Hazardous *(Severe Major)* Category B	Major Category C	Minor Category D	Negligible Category E
Frequent All $>10^{-3}$ UAV $< 10^{-2}$	A1 - Extremely High	B1 = Extremely High	C1 - Medium	D1 - Low	E1
Reasonably Probable All $<10^{-3}$ UAV $< 10^{-2}$	A2= Extremely High	B2 = High	C2 - Low	D2	E2
Remote Civil $< 10^{-5}$ Military $< 10^{-5}$ Military (E-seat)$< 10^{-4}$ UAV $< 10^{-3}$	A3 = High	B3 = Medium	C3	D3	E3
Extremely Remote Civil $< 10^{-7}$ Military $< 10^{-6}$ Military (E-seat)$< 10^{-5}$ UAV $< 10^{-4}$	A4 = Medium	B4	C4		
Extremely Improbable Civil $< 10^{-9}$ Military $< 10^{-8}$ Military (E-seat)$< 10^{-7}$ UAV $< 10^{-6}$	A5	B5	C5	D5	E5

Risk (Safety) Thresholds
- Civil Derivative A/C
- Military A/C
- Military A/C with Ejection Seats
- Unmanned Aerial Vehicles

Within Accepted Level of Safety (Basis of Certification)

TAM, C-05-005-001/AG-001, DTAES/DND, 2001

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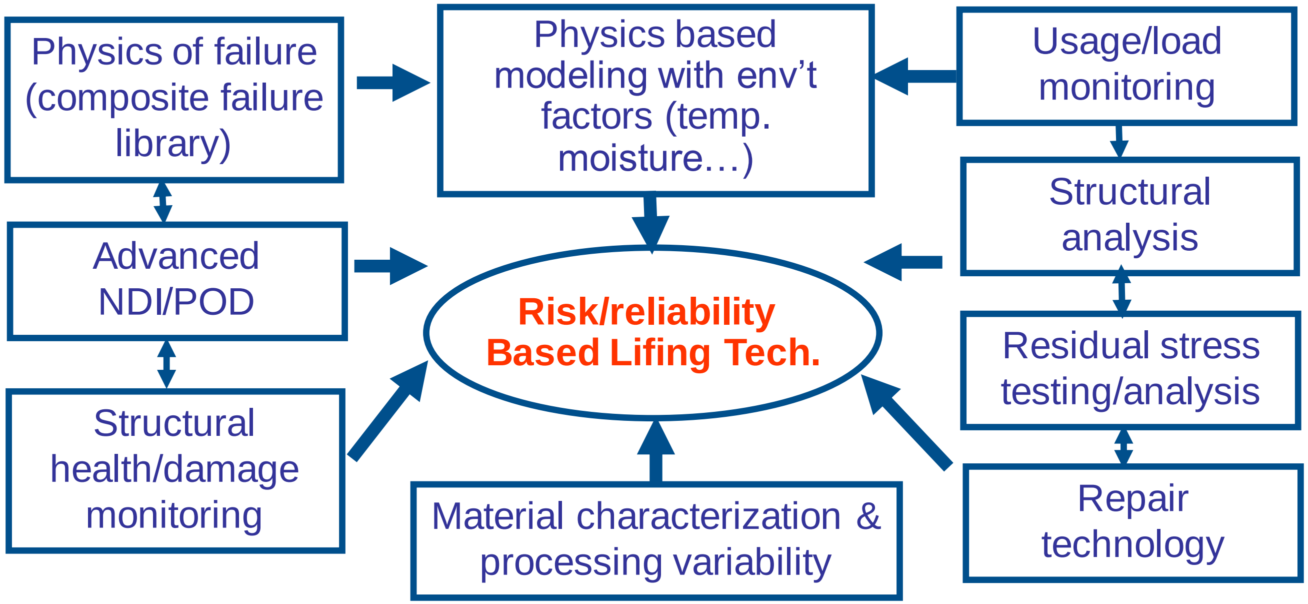
Holistic Structural Integrity Process (HOLSIP) for Composites/Hybrids



Structural integrity is the condition which exists when a structure is sound and unimpaired in providing the desired level of structural safety, performance, durability, and supportability (MIL-STD-1530/USAF ASIP)

HOLSIP 15 NRC Progress Report - Feb 2016

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Overview of Some Recent Structural Integrity Research at NRC

Min Liao

Thrust Lead
Air Defence Systems (ADS) Program

HOLSIP 1
Snowbird,
February 21-2

National Research Council Canada / Conseil national de recherches Canada

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Contents

- Relevance to HOLSIP
  - NRC HOLSIP framework
- Progress of Full-Scale Testing Research *(skip here)*
- Progress of Aircraft Lifing Research
- Progress of Fatigue Enhancement Research
- Progress of SHM Research
- Progress of NDE Research
- Progress of Composite Research *(skip here)*
- Summary

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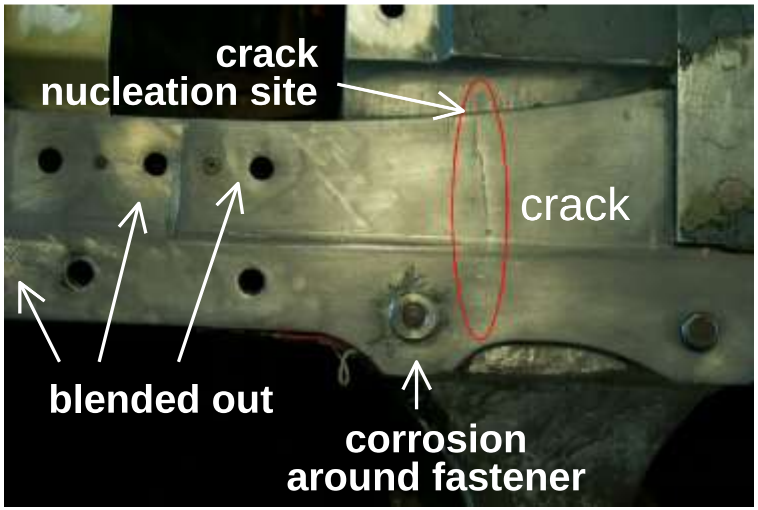
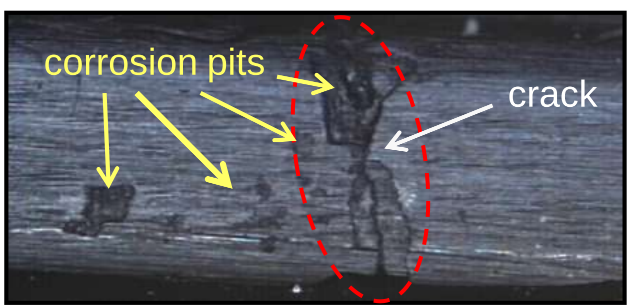
Selected Applications

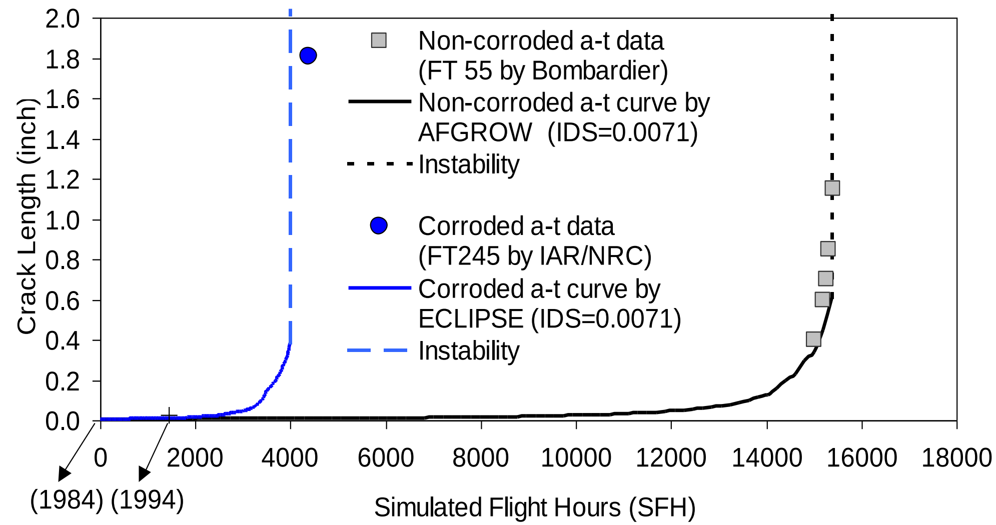
Corrosion Fatigue Holistic Analysis for F-18 Longeron





side view of longeron at crack nucleation site by replica

2932 simulated flight hours in full scale test

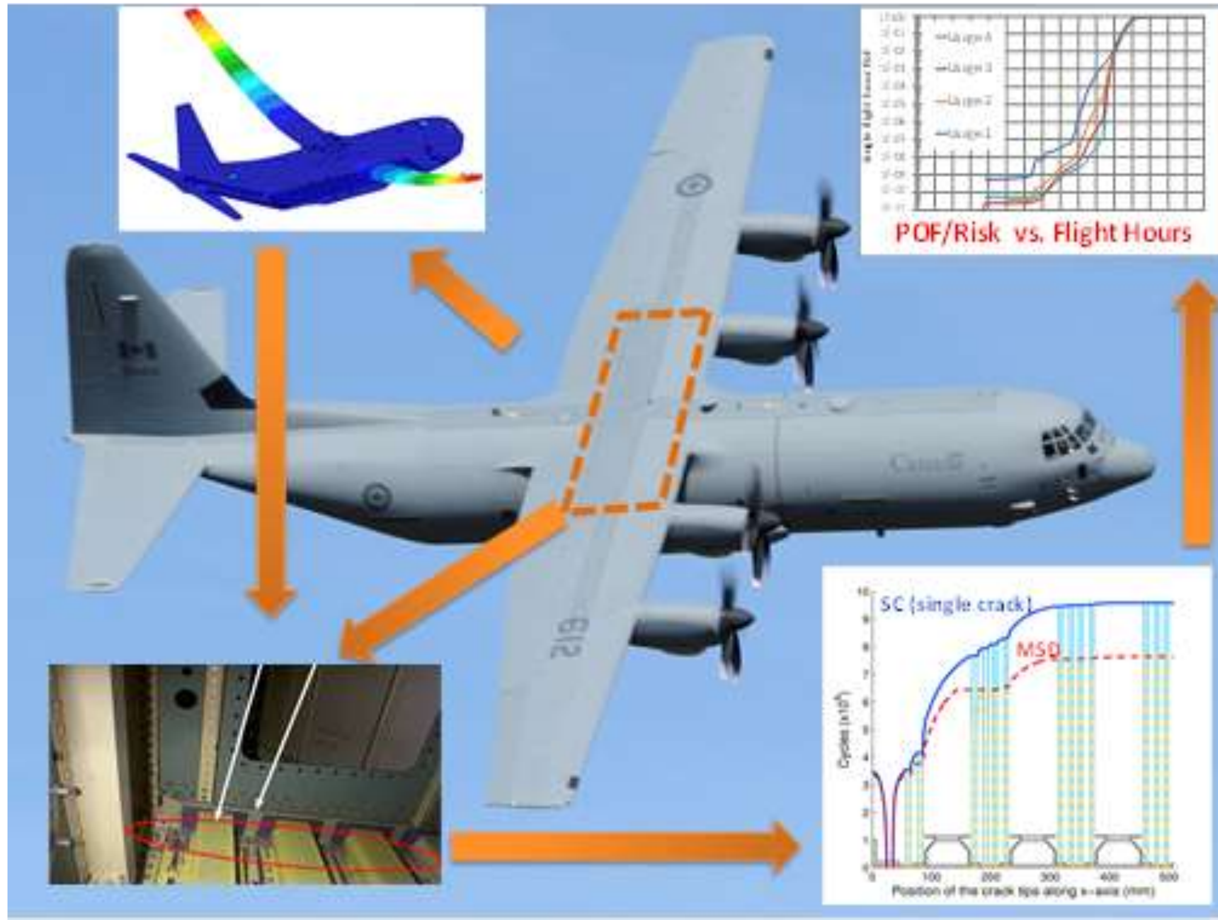


DDT analyses do not generally include possibility of change of criticality of structure – from durability to DT driven.

Corrosion can have such impact.

Advanced Damage Tolerant and Risk Analysis Tools Developed under HOLSIP Framework

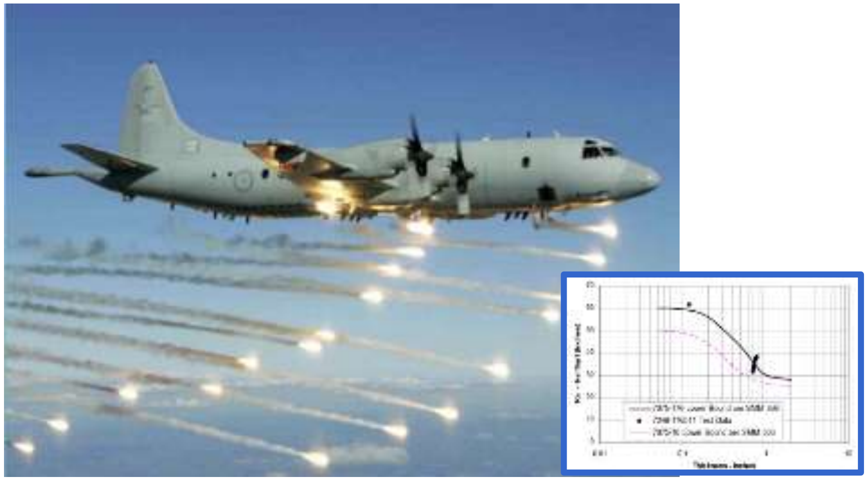
- NRC developed advanced DTA and risk analysis tools (CanGROW, ProDTA) under HOLSIP framework
- NRC tools provided significant support to risk-based management for various RCAF aircraft fleets



Risk analysis to determine the service life limit of CC-130 center wing with MSD/MED

(Liao, Renaud, Bombardier ICAF2015)

CP-140 Aurora 7249-T76511 Aluminium Material Testing



Objectives: Obtain additional Al7249-T76511 material property data to support RCAF for decision-making on ASIP and reduction on maintenance cost by refining the material models of the CP-140. Required data includes:

- Fracture toughness for thin extrusions (Kc)
- Fatigue crack growth rate (FCGR) properties for negative and high stress ratios (R).

Outcomes

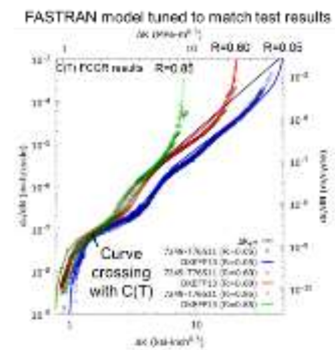
Fracture toughness for 4 different material thicknesses (20 coupons total; 5 replicates).

Fatigue crack growth rate (FCGR) test data for two positive and two negative stress ratios (12 coupons total)

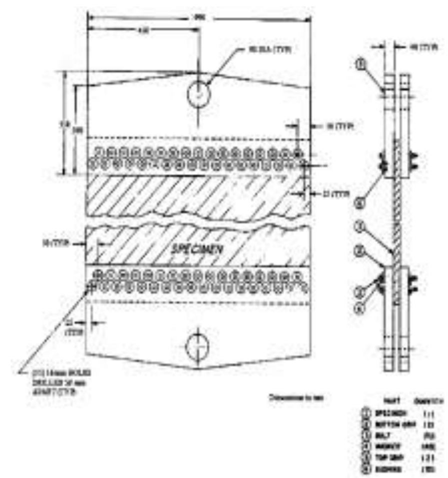
Partnership/Leveraging: IMP Aerospace, Lockheed Martin, P-3 ASIWG, DRDC

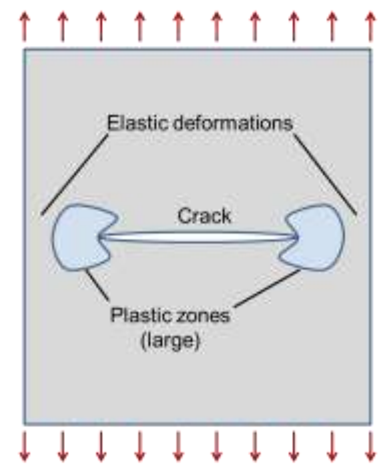
Technical Highlights

M(T) Test Trials (under DRDC Project)

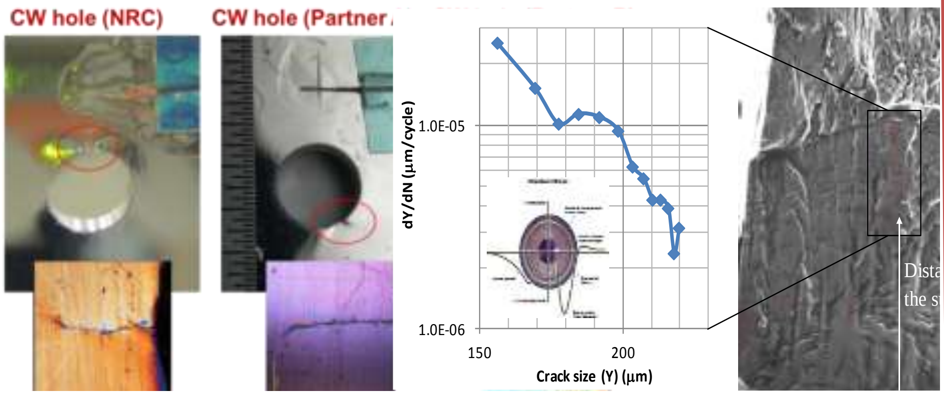


Fracture toughness test design (E561)



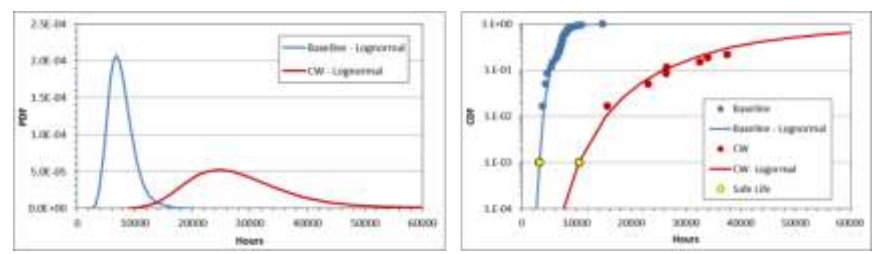


Validation and Transfer of Cold-Work (CW) Modeling Technology (FY15-16)



Technical Highlights

- Brief Review of RCAF, USN, and USAF Practice
- USAF Residual Stress Database Investigation
- NRC Cold Expansion Simulation (3D FE)
- NRC Crack Growth Simulation, evaluating CPAT and BAMF



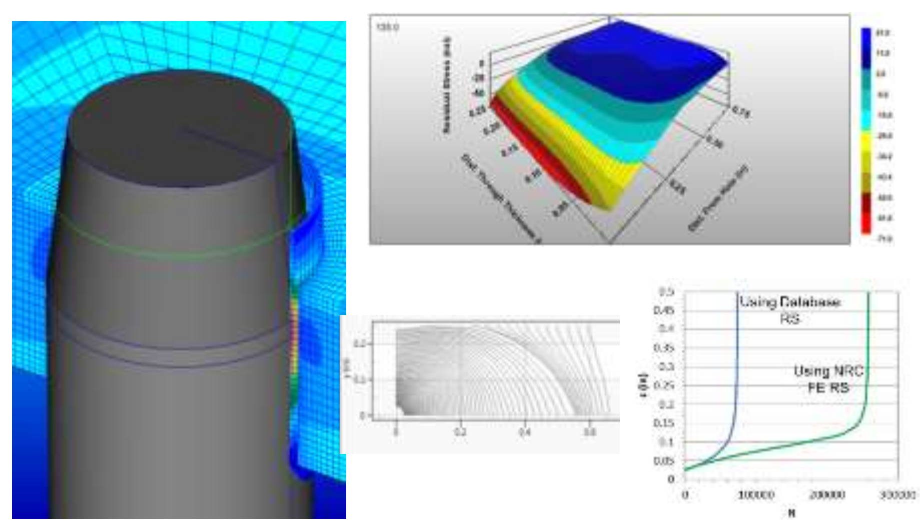
Objective:

Improve and validate methods/tools to determine practical Cold Work (CW) Life Improvement Factors (LIF) using 2D and 3D simulation, and residual stress database.

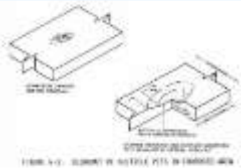
Background:

NRC and IMP recently completed cold worked hole tests for two locations of the new 7249 Al CP-140 wing (ASLEP). The LIFs determined in the lab (ideal conditions) need to be reduced to reflect in-service experience and conditions.

Partnership/Leveraging: IMP, P-3 ASIWG, USN, USAF, RMC



Additive Repair Technology Development Program – Cold Spray



Objective:
The objective of this project is to develop an additive material (Cold Spray) repair capability for the Canadian Forces. The research focus is the restoration of parts reworked (blended) beyond current repair limits.

Background:
Cold Spray is a metal spray process typically used to deposit a sacrificial layer of metal on a component for corrosion protection. Recent developments such as hand held kits, improved materials and processes has opened the possibility of using this technology for structural repair on aircraft.

Impact/Benefit/Return on Investment:
The impact is significant. Additive manufacturing processes have the potential to eliminate the costly replacement of frames and fittings, such as the CH124 Sponsor attachment fitting and the CH149 Main landing gear frames. Potential savings are likely to exceed several million dollars

Milestones

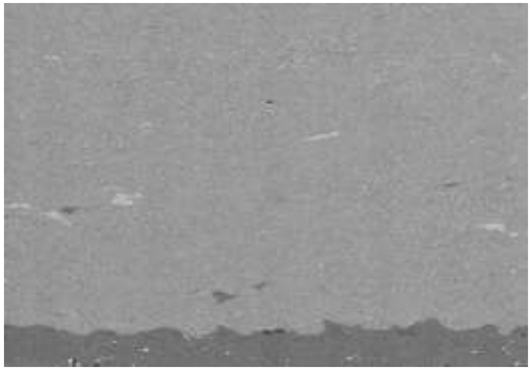
1. Evaluation of sprayed material strengths vs requirements
2. Selection of suitable repair alloy for 7075 forgings
3. Development and initial test of a repair process
4. Exposure and durability testing of repair components
5. Completion of the test program
6. Delivery of repair scheme

Deliverables / Outputs

1. Repair material compatibility report
2. Program tests report
3. Additive repair scheme for 7075 forgings.

Technical Highlights

Sprayed density looks promising for 7075
Property testing to commence early Feb



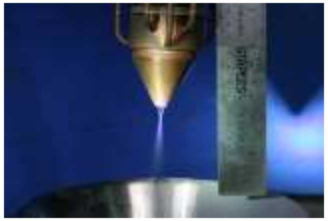
Discussion Paper on Certification of Additive Manufactured (AM) Components

Objective: *To prepare a discussion paper on certification of additive manufactured (AM) components. This paper will highlight the concerns relating to AM and the possible solutions that will allow these manufactured parts to be certified.*

Background: *AM is one of the most important technology trends in aerospace and defence. However, there are many issues/challenges for applying AM on primary aircraft structures/critical parts, one of them is the quantification and certification..*

Impact/Benefit: *Discussion paper documenting the major issues/concerns relating to the certification of AM components*

Return on Investment: *Increase fleet availability, reduce maintenance cost.*



Sea King tail wheel support lug repair

RR501 fuel nozzle repair

FA-18 engine mount bracket repair

Client(s): *DND, DTAES 7-2*

Sponsor(s): *DTAES 7-2*

Notes/Comments:

Technical Tasks

1. *Identify possible certification issues relating to additive manufactured components, such as quality, repeatability and residual stresses.*
2. *Support TTCP AER TP4, SA 4B.5, and coordinate with TTCP AER TP-4, MAT TP-1 and MAT TP-5*

Milestones

1. *Review, gather information, draft report* — *03/16*
2. *Update draft paper with DND and TTCP data* — *11/16*

Deliverables/Outputs

- Preliminary draft of discussion paper on Mar-16
- Final report on Nov-16

Technical Highlights

TTCP presentation and Draft report discussing

- major concerns/issues
- recommendation on R&D

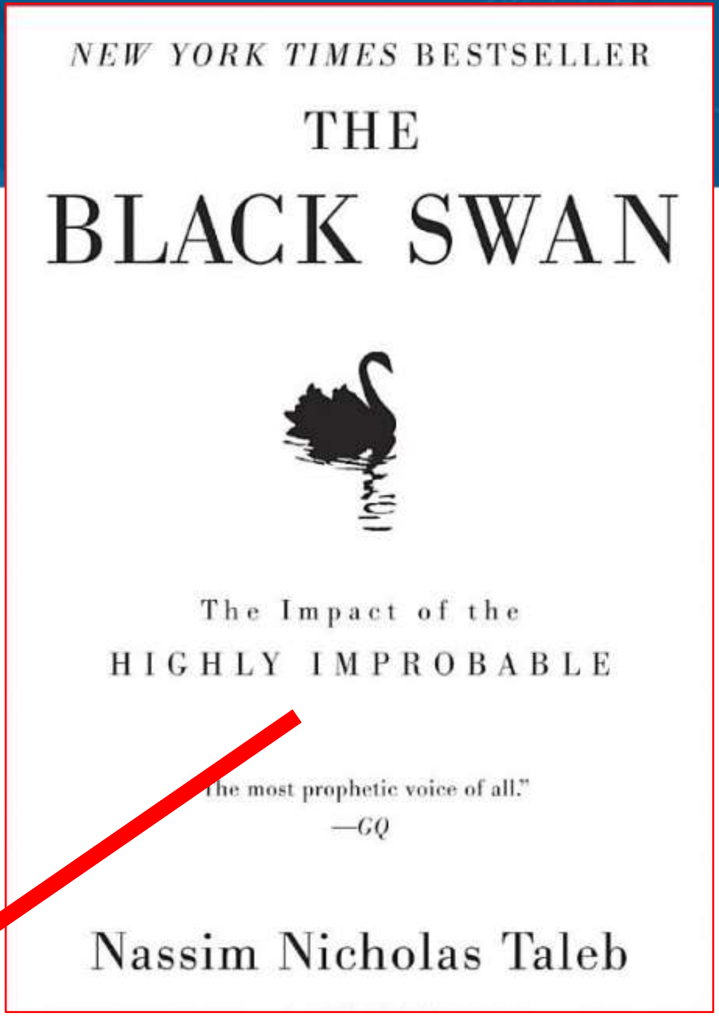
Future – the unfinished business

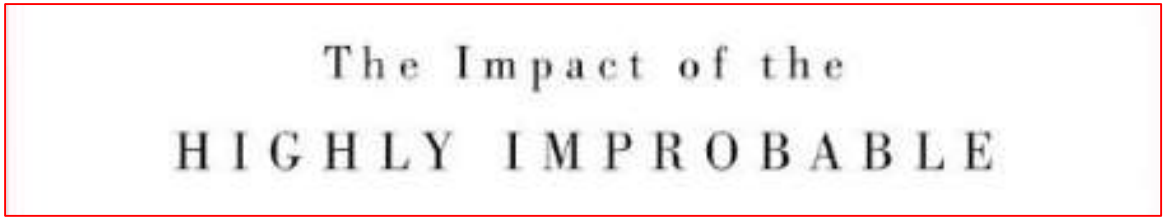
Quo Vadimus?

- Concern – new generation of practitioners (OEMs) do not seem to participate in information exchanges as the previous generation did.
  - “This is a secret” and “We are the best!” – syndrome?
- So much yet to be learned.
- Capture and share – open “learning" systems needed.
- Importance of standards and definitions.
- Will this ‘SI business’ ever be finished?

Black Swan

- Do we understand the risks?





NRC·CNRC

Thank you

NRC·CNRC