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RESEARCH ADVANCES ON AIRCRAFT STRUCTURAL INTEGRITY AND SUSTAINMENT AT NRC

Min Liao*, Marko Yanishevsky*, Prakash Patnaik*
*** Aerospace, National Research Council Canada**
1200 Montreal Rd, Ottawa, Ontario, Canada K1A 0R6
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Abstract

This paper summarizes recent research advances conducted at NRC supporting aircraft structural integrity and sustainment. As a government R&TD agency, NRC carries out material and structural research for both military and civil aircraft. The efforts include innovative practical and researches in the areas of structural lifing, risk/reliability analysis; environmental effects; life extension and continuing airworthiness. Based on the lessons learned and the new challenges foreseen, NRC has been carrying out research on physics-based modelling, model-assisted non-destructive evaluation (NDE) and structural health monitoring (SHM), non-standard coupon testing and efficient structural testing, as well as integrated vehicle health management technology. Examples of best practices supporting the structural integrity and sustainment of Royal Canadian Air Force (RCAF) transport/patrol aircraft (CC-130, CP-140), fighter aircraft (CF-188), helicopters (CH-146, CH-149), and civil aircraft, such as the Harvard T-6, are presented. The presented research advances are featured with both fundamental and applied research progresses.

1 Introduction

The Aircraft Structural Integrity Program (ASIP) plays a crucial role to maintain aircraft continuing airworthiness and sustainment. Today's aircraft are often required to fly longer and more severe than the original design targets, thus the ASIP program is needed to not only maintain the structural integrity/safety, but also to be cost-effective based on actual aircraft condition. With the introduction of new designs, materials, manufacturing, inspection, and repair technologies, the ASIP program continues to face challenges to continuously improve. In the past 15 years, NRC has been carrying out fundamental and applied research on ASIP, while developing a new holistic structural integrity process (HOLSIP) [1][2] (Figure 1), along with other experts from North America, Europe, Australia, and Asia (Japan).

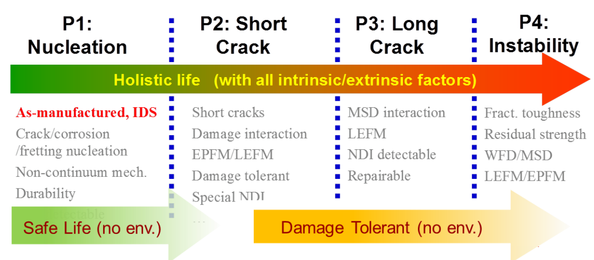

Figure 1 Holistic Structural Integrity Process (HOLSIP) [1]

In short, the HOLSIP framework aims to augment safe-life (SL) and damage tolerant (DT) paradigms with the ultimate goal to evolve HOLSIP into a new 'closed loop' paradigm covering both design and sustainment engineering. It considers both time dependent environmental and cyclic loading effects. Some key elements of HOLSIP are physics-based models, advanced NDE/structural health monitoring (SHM), probabilistic modelling and risk assessment (Figure 2). At NRC, HOLSIP has been used to link fundamental research with applied research which effectively boosted both research developments. This paper summarizes recent advances in these elements, along with test validations from coupon to component/full scale levels, with both military and civil application examples. Given the space limit, this paper has been limited to mostly metallic materials.

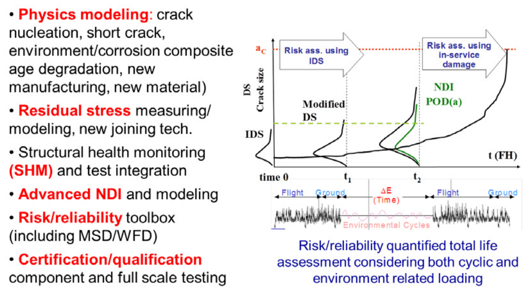

Figure 2 HOLSIP Related Tasks at NRC

2 Structural Lifing Technologies

2.1 Crack Nucleation (P1), Short Crack Growth (P2)

Among the four distinct phases of structural life (Figure 1), the nucleation phase (P1) is the most challenging one in terms of life prediction. In the HOLSIP paradigm, the ‘initial discontinuity state’ (IDS) concept was invented to describe the as-produced or as-manufactured state of the material (such as constituent particles, machining marks) [2]. NRC has carried out extensive studies on nucleation mechanisms for typical airframe aluminum alloys, and found that fatigue cracks are usually nucleated from brittle iron-contained particles, which are susceptible to fracture during manufacturing processes, such as rolling [3-5]. A protocol was developed and improved to determine the IDS, through which NRC developed the databases of IDS/particle and pores distributions, for some typical airframe aluminium alloys (Figure 3), such as 2024-T3, 7075-T6, 7050-T7452, 7079-T6, 7178-T6, and 7249-T76511.

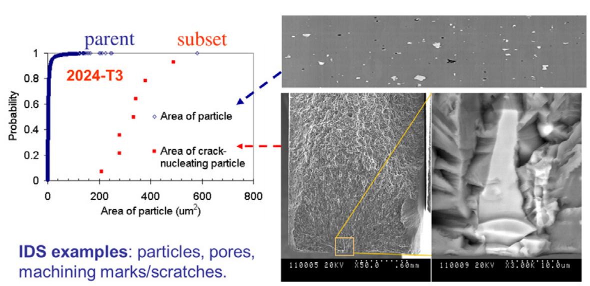

Figure 3 IDS Particles Parent Distribution and Fatigue Subset (Example on 2024-T3)

Using the IDS/particle distributions, NRC lifing analysis has matched coupon fatigue life distributions very well (Figure 4) [5]. The short-long crack growth material model was improved to simulate the crack growing from an IDS/particle (~10μm). In this case, the crack nucleation life from a broken particle was found to be negligible, as confirmed by other experimental studies (for example [6]).

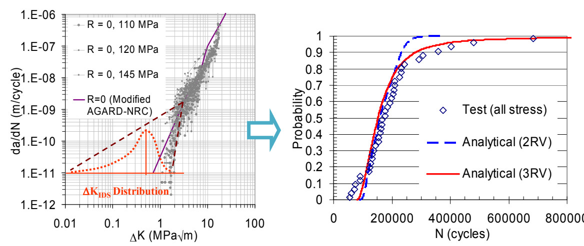

Figure 4 IDS/particle Based Life Prediction for 2024-T3 using 3 Random Variables (RV) (Particle Height, Width, and ΔK_{IDS})

The short/small crack phase (P2) can occupy a large portion of total life, especially for cracks nucleated from a broken particle/pore. It is important to generate quality short/small crack growth data including the near-threshold region. One method is to use coupons with naturally nucleated cracks, aided by replication technique, and/or marker band readings (i.e., “*small crack, regular stress*”). The process is not only tedious and costly, but more importantly the data have large scatter, and dependent on the microstructures where the crack data are taken from. Another method is to use pre-cracked coupons, by reducing the magnitude of cyclic loads (i.e., “*long crack, low stress*” that can also make $\Delta K=\Delta\sigma\sqrt{\pi a}\times\beta(a)$ close to ΔK_{th}). However, this data can be affected by crack tip closure effects left in the wake of the long pre-crack. Recently, NRC has been closely following and contributing to ASTM activities for improving testing methods in the near–threshold region, adopted the new ACR (adjusted compliance ratio) method, and improved the DCPD (direct current potential drop) crack size measurement techniques [7]. For shot peened coupons with residual stresses, an enhanced LPI (liquid penetration inspection) was developed to detect 0.254-mm (0.01”) surface cracks [8]. Using both naturally generated cracks and pre-notched coupons, NRC has generated high quality short-long crack data for 7050, 7075, and 7249 [7][9]. The high quality pre-crack data has much less scatter, and represents the average behaviour of multiple grains and microstructural features [9]. Figure 5 presents the NRC short-long crack data for a relatively new airframe material 7249-T75611. The NRC data have been adopted by the OEM (Lockheed Martin), MRO (IMP Aerospace), P-3 aircraft community, as well as AFGROW, NASGRO, and FASTRAN software, leading to substantially improved damage tolerance assessments and maintenance programs for P-3/ CP-140 air fleets.

Fundamentally the progress on short crack testing and modelling has improved the holistic life assessment. Practically, it has also affected service life assessment with widespread fatigue damage (WFD), load monitoring and load spectrum truncation for full scale testing.

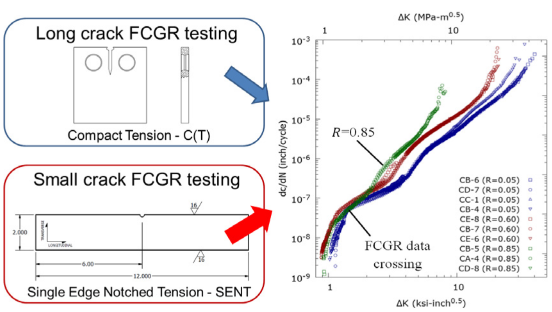

Figure 5 Short-Long Fatigue Crack Growth Rate Data for 7249-T76511

2.2 Long Crack Growth (P3), Instability (P4)

Following the C-130 water bomber accident in Walker, California in 2004, NRC has carried out and achieved some breakthrough research on MSD (multi-site damage)/MED (multi-element damage)/WFD [10]. A number of new and improved stress intensity factors (SIF) for MSD were developed, some of which were evaluated by NASA and SwRI, and then incorporated into NASGRO. As well, an in-house crack growth analysis program, CanGROW, was developed by NRC to specifically simulate the MSD problem. The unique capability of CanGROW is to grow multiple cracks simultaneously while considering their interactions. Given the complexity of MSD crack growth modelling, an automated SIF compounding algorithm was developed to identify and update the crack information, which includes extracting the location and size of a crack, determining if the crack is an edge or a centre crack, if the crack is a part-through or a through-thickness crack, defining the interactions with adjacent structural elements (edge, hole, or other cracks), verifying if crack link-up occurs and merging the cracks as required. CanGROW also includes MSD/MED residual strength analysis using the fracture toughness (Kc), the net section yield (NSY) strength and a plastic zone link-up (PZL) criteria. The effects of MSD and MED are included in the compounded SIFs, which are determined by global-local Finite Element (FE) Modelling. Figure 6 presents a MSD/MED analysis for the CC-130 centre wing critical location (CW-1), showing the life reduction of MSD compared to a single crack (SC) scenario.

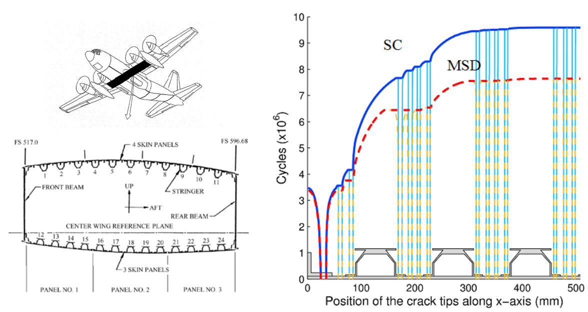

Figure 6 CC-130 CW-1 Crack Growth Curves for SC and MSD Scenarios

3 Risk/Reliability Analysis

To support the RCAF risk-based fleet management, an in-house tool, ProDTA (Probabilistic Damage Tolerance Analysis), has been developed at NRC for structural risk analysis, which takes into account both conventional fatigue damage and time dependent environmental damage (i.e. corrosion) [11]. The NRC tool has been applied for RCAF CC-130, CP-140, and CF-188 aircraft, including built-up structures containing MSD/MED [10]. ProDTA can use either a master DTA curve or Monte Carlo simulation to calculate a single flight probability of failure (SFPOF), for both SC and MSD scenarios. For the CC-130, ProDTA was first linked with CanGROW to calculate the SFPOF for two centre wing critical locations (CW-1 and CW-14), using available in-service damage data. Along with conventional fatigue reliability analysis, the NRC MSD risk analysis helped to determine the CC-130 service life limit (or life to retirement), considering MSD/MED/WFD. Through these applications, NRC has advanced risk analysis technology, and shown that, by integrating risk analysis with ASIP, the operator can better manage aircraft continuing airworthiness in a cost-effective manner [12].

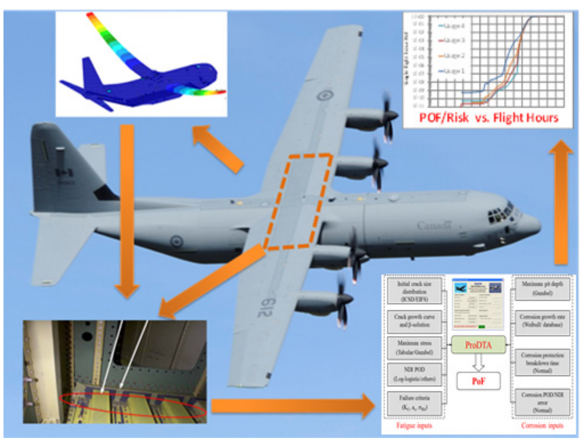

Figure 7 CC-130 MSD Risk Analysis Using NRC Risk Analysis Tool, ProDTA

4 Corrosion and Fatigue

4.1 Exfoliation Corrosion

In an effort to move away from the current costly "*find-it-fix-it*" maintenance approach toward the "*anticipate-plan*" approach, NRC has carried out extensive research to evaluate the effects of exfoliation on residual strength and remaining fatigue life, with the aim to guide the repair actions. Many static and fatigue tests were completed using pristine, artificially corroded, and naturally corroded specimens of 7075-T6511 material [13]. Both thermographic and ultrasonic NDE were performed to determine the maximum depth and 3D profiles of the exfoliation damage. Fatigue crack origins were determined with the aid of a scanning electron microscope and the nucleating mechanisms in exfoliation regions were found and documented. An analytical model was developed based on a 'soft inclusion' technique and 3D finite element modelling. This technique automatically generates the 3D geometry of the 'soft inclusion' (damage zone) from the ultrasonic NDI input (Figure 8). For engineering applications, a simplified fatigue model was developed for estimating the remaining fatigue life of the exfoliated specimens. The NRC study found that, exfoliation may not have a severe detrimental effect on residual strength and stress concentration (Figure 8); some exfoliated coupons had longer lives than those where corrosion had been ground-out; that a calibrated fatigue model was capable of estimating the remaining fatigue life. These results have helped USAF, RCAF and Swiss military aircraft operators selecting cost-effective maintenance actions on exfoliation corrosion [13, 14].

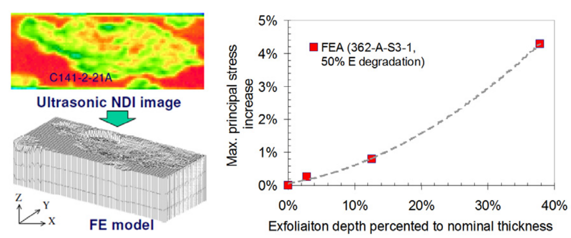

Figure 8 Exfoliation Corrosion Modelling

4.2 Corrosion Pitting

During a CF-188 full scale test, a long fatigue crack of 46 mm (1.81 inches) was discovered on the right hand upper outboard longeron (UOL) of the centre fuselage (Figure 9). Corrosion pits were found in the area near the apparent crack nucleation site following paint and filler removal. In this test, the fuselage that was used as a transition structure, had been obtained from a retired United States Navy (USN) F-18 aircraft that had been in-service for ten years (1984-1994). A corrosion fatigue analysis was carried out to reproduce the life of the UOL [15]. The analyses used different methods, i.e. strain-life (SL, by CI89), damage tolerant (DT, by AFGROW), and a holistic lifing method (by ECLIPSE from Analytical Process/Engineered Solutions (APES)). It should be noted that only the holistic method/tool accounts for the concurrent interaction between corrosion and fatigue. The corrosion pit growth rate was assumed to follow a cube root power relation. Figure 9 presents all the analysis results in comparison with full scale test results with and without corrosion damage. It is shown that, the typical DT analysis estimated a much shorter life; the SL estimated much longer life; however the holistic method/tool (ECLIPSE) estimated a life closer to actual service experience. This NRC research indicated that the holistic method is capable of quantifying the impact of an evolving corrosion pit on aircraft structural integrity.

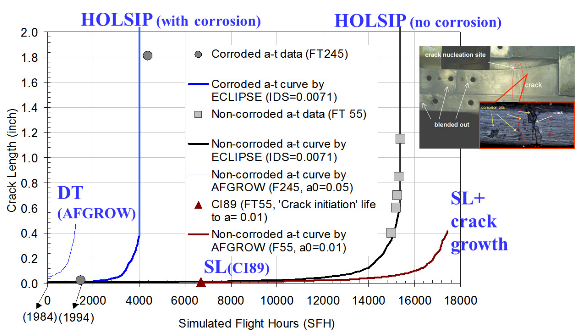

Figure 9 Corrosion (pitting) and Fatigue Modelling, F-18 Example

5 Life Extension Technology and Continuing Airworthiness

5.1 Life Extension Technology -- Residual Stress Effect from Cold-Working

Due to the lack of physics-based modelling of residual stresses (R.S.) and accurate test measurement of R.S. and its uncertainties, the benefits of fatigue enhancement technologies, such as hole cold expansion (CX) or cold-work (CW), shot peening, have not been fully utilized in the management of current fleets. In collaboration with USAF, SwRI and APES, NRC recently carried out research on the validation and transfer of CW modelling technology [16]. A parametric 3D FE model was improved by including non-linear material behaviour, large deformation, and contact modelling, to simulate a split-sleeve cold expansion process, followed by a cyclic loading process (Figure 10). Key results, such as residual stresses at the mandrel entry and exit faces, the hole expansion, and the out-of-plane deformation, were determined for each step of the processes. The residual stresses obtained from the NRC model were in good agreement with the experimental measurements from the US partners using the contour method. NRC then used the residual stress distributions obtained from both testing and simulation for crack growth life prediction using the ESRD (Engineering Software Research and Development, Inc.) CPAT and AFGROW software. Based on the life analyses with and without residual stresses, and being parametric, the NRC model easily simulated various types of variabilities and uncertainties to conservatively determine more realistic life improvement factors (LIFs). This research at NRC demonstrated that numerical simulation is a viable approach to calculate LIFs for CX holes. Along with the USAF progress, the technology has first shown some potential to allow military operators to reduce inspection requirements and increase availability, by taking advantage of the predicted residual stresses.

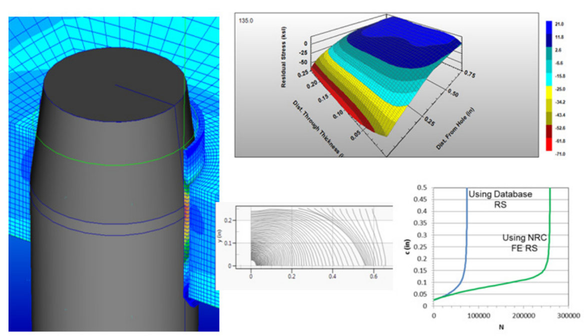

Figure 10 FEM on Cold-Work, Residual Stress Distribution, and LIF Calculation

5.2 Continuing Airworthiness -- North American SNJ-6 Aircraft (Harvard T-6)

After an accident of a North American SNJ-6 (AT-6F) airplane, in Kissimmee, Florida, in 2005, NRC was tasked by the North American Trainer Association (NATA) to carry out a damage tolerance analysis (DTA) for the cracked lower inboard attachment angle component in order to determine repeat inspection intervals [17]. To support the DTA work, NRC carried out flight tests with strain survey/ measurement, and a lab component test to determine load distribution, especially a critical bending/tension load ratio. Crack growth predictions were conducted using two different MIL-A-008866B spectra (basic and advanced trainer class), with four clipping values (5.67g, 5.0g, 4.5g, and 4.0g) and three initial crack sizes (15.24, 10.16 and 6.35 mm). A total of 24 crack growth scenarios were analyzed. A critical input to the analysis was the aspect ratio of surface crack length to depth, determined from fractography and the bending/tension load ratio measurements. With the DTA, considering the effectiveness of different NDI techniques, NRC provided recommendations to NATA and the Federal Aviation Authority (FAA) on suitable inspection intervals for different usage and NDI techniques. Based on the NRC efforts, NATA received FAA AMOC (Alternative Method of Compliance) for T-6/SNJ Emergency AD 2005-12-51, which approved the use of eddy current in lieu of fluorescent dye penetrant inspections. NATA was granted an extension to the inspection interval on the upper wing to every 1,000 hours rather than the previous 200 hours. This FAA AMOC has effect on ~15,000 Harvard aircraft worldwide.

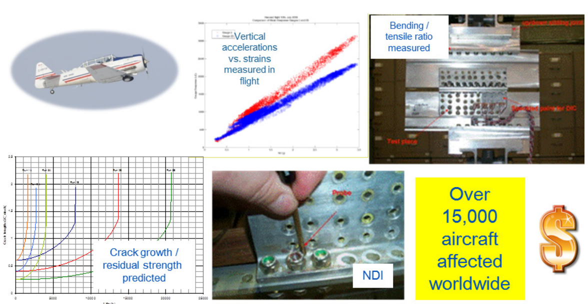

Figure 11 DTA to Support Harvard (T-6) Continuing Airworthiness

6. Helicopter Usage and Load Monitoring

To monitor individual aircraft usage and more accurately determine critical component life to ensure flight safety and optimal aircraft usage, NRC has been developing computational methods of estimating component loads and fatigue damage accumulation from existing aircraft sensor data, such as flight state and control system parameters [18]. The approach implements a number of computational intelligence methods and statistical techniques to estimate the load signal in the component, based upon which fatigue damage accumulation and load exceedance curves are calculated (Figure 12). NRC results obtained thus far have shown tremendous potential for accurate estimates not only on the primary Black Hawk S-70A-9 dataset (main rotor pushrod axial load), but also on some limited data sets from the CH-146 Griffon (main rotor yoke bending).

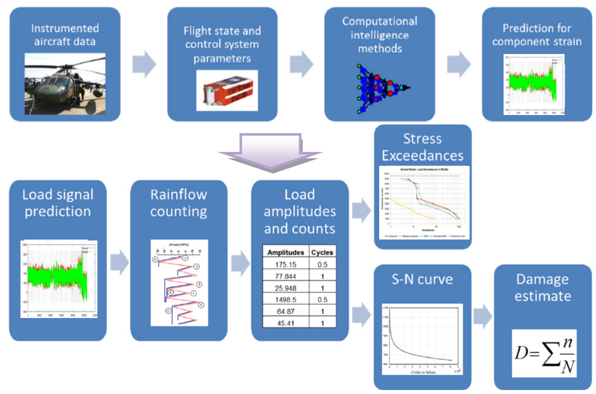

Figure 12 Component Load Signal Prediction and Fatigue Damage/Life Analysis

In addition, NRC has developed a low-cost, standalone sensor system for detecting and recording flight manoeuvre data, in support of basic usage spectrum (BUS) updates, especially for aircraft that are not equipped with a health and usage monitoring system (HUMS) or a flight data recorder [19]. The core of the system is a micro-electromechanical system inertial measurement unit (MEMS-IMU), composed of a GPS, pressure sensor, 3-axis accelerometer, gyroscope and magnetometer, and powered by a lithium ion battery (Figure 13).

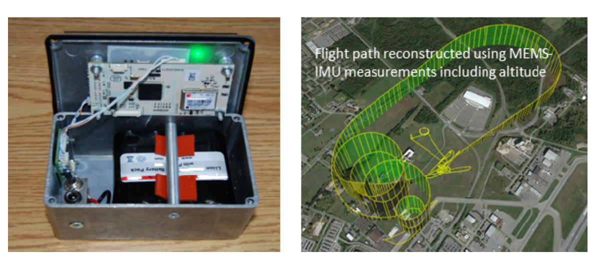

Figure 13 MEMS-IMU and Flight Test

Preliminary flight testing on a NRC helicopter (Bell 206) showed good agreement of the system measurements with the on-board inertial navigation system. Manoeuvre recognition algorithms have demonstrated accurate classification of basic manoeuvres using the MEMS-IMU recorded flight data.

7. SHM and NDE

7.1 Environmental Conditioning for SHM System Reliability Study

NRC has developed several test platforms for assessing SHM system reliability, including a wing box structure representative of the CF-188 outer wing, containing fastened metallic ribs and spars, and composite skins, and containing hidden fatigue damage of specific shape, size, and location (Figure 14) [20]. To test various SHM sensors under simulated flight environment conditions, the wing box was further developed for temperature, pressure (altitude) and humidity conditioning. For temperature loading (+60 to -60°C), the chamber could be heated using electric heaters and cooled using liquid nitrogen. In conjunction with the temperature loading, pressure (0 to 90 kPa) and humidity (ambient to 90%RH) could also be changed within the test gauge area.

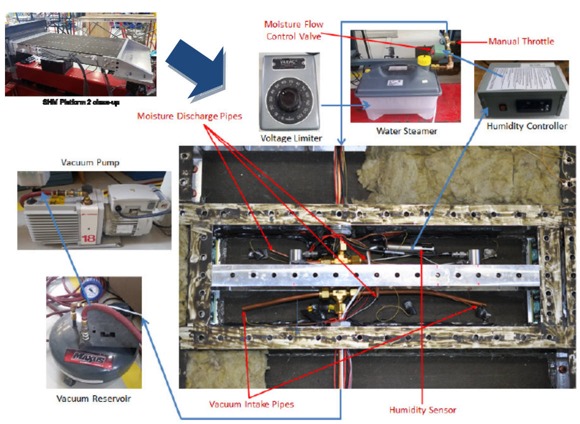

Figure 14 SHM Platform with Environmental Conditioning capabilities (Temperature, Pressure, and Humidity)

Preliminary testing under a combination of temperature, humidity, pressure, and fatigue load, has revealed that sensor bonding integrity can greatly affect the SHM system reliability. The test also showed that an NRC in-house acoustic emission (AE) system was able to detect, and locate the hidden artificially seeded fatigue crack, and monitor crack growth.

7.2 NDE Reliability – POD Study

In collaboration with RCAF, NRC carried out a comprehensive study on Generic Bolt Hole Eddy Current (GBHEC) Probability of Detection (POD) [21], to reassess the current POD value (a90/95), and to investigate POD modelling to allow portability of the data particularly to the CC-130 and CP-140 wing structures. The study used layered coupons with 3/16 inch fastener holes representative wing structures. Coupons contained both electron discharge machining (EDM) notches and lab grown fatigue cracks that were oriented in various configurations to allow for comparison of EDM indications to crack indications [22]. Data was collected using several RCAF NDE technicians from across Canada; over 30,000 data points were collected. The study showed that the reassessed a90/95 value was much less than the original value for four crack configurations (top skin corner, top skin mid-bore, faying surface corner, and bottom skin corner). Moreover a reliability assessment of cracks in real structure was estimated using POD modelling, using transfer functions (TX) and an eddy current Model Assisted approach. A POD modelling was developed as an inexpensive alternative to costly experimental POD studies (Figure 15). The model partially substitutes and complements experimental POD data to allow the portability of POD information, showing that a combination of both was a valid approach by which a generic set of data could be applied to a specific structure.

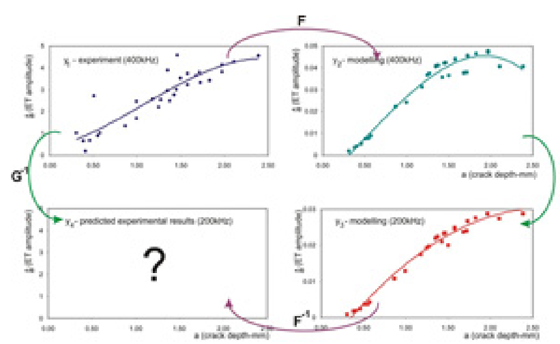

Figure 15 Modelling to Estimate POD Curves of a Real Structure using Generic POD Data

8. Component and Full Scale Testing Techniques Development

8.1 Application of Experimental Mechanics Techniques for Biaxial Fatigue Testing

NRC has recently upgraded Canada's largest planar bi-axial test frame, with a new control system and additional actuator supports. It now has the capability to operate at 22 kN [50 kips] and at frequencies of 5 Hz or higher, under in-phase and out-of-phase tension-compression loading conditions [23]. More importantly, the upgraded testing system has been set up to take advantage of advanced experimental mechanics [23]. In the past years, NRC has been developing a suite of advanced experimental mechanics techniques, including Digital Image Correlation (DIC), automated Photoelasticity, and Thermoelastic Stress Analysis (TSA). These techniques have been applied for various standard and non-standard mechanical tests especially component and full scale testing. In a recent joint effort with an external client who provided FEM, DIC and TSA techniques were used to develop a bi-axially loaded cruciform specimen (smooth and notched) (Figure 16). The DIC results were used to examine the alignment of the bi-axial test frame, while both DIC and TSA were able to detect and monitor crack nucleation and growth. The testing provided valuable data for calibrating new engine material and component designs to meet specific fatigue life requirements.

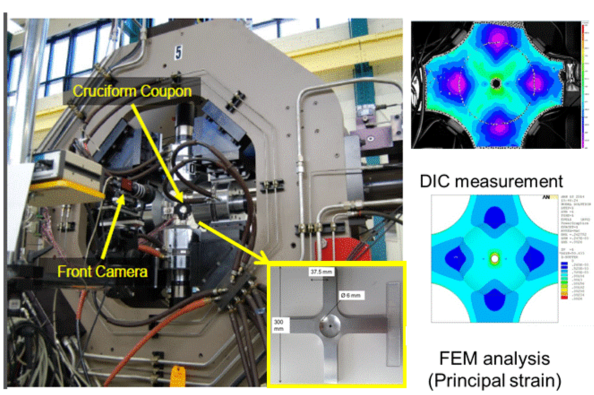

Figure 16 Bi-axial Fatigue Testing

8.2 CF-188 Wing-Fold Aft-Spar Shear-Tie Fatigue test and DTA

Due to recent revisions in the RCAF lifing policy, unmonitored CF-188 components subject to dynamic loading are now required to be certified to five lifetimes. After in-service cracks were found in several dynamically loaded components, NRC was tasked to test the CF-188 wing fold shear tie to establish crack growth rates both before and after a severe blend geometry structural modification proposed for this area (Figure 17) [24]. In collaboration with L3-MAS, NRC fatigued tested this critical area while monitoring the cracking automatically with an ultrasonic transducer tied into the control system to stop testing once a crack had developed. NRC also measured the strains at peak and valley extremes automatically using DIC. This test provided the time required to grow a 0.51-mm (0.020") deep crack under the CF-188 spectra; incorporation of a typical depot level fleet modification; and test until failure, including residual strength loads. Two quantitative fractography investigations were carried out to provide crack growth for the pre- and post-modification (blend-out repair). After the test, NRC carried out a detailed FE and fatigue analysis (Figure 17) [25], which agreed with the long stable crack growth of the tested shear-tie. The NRC effort determined that the current RCAF blend-out repair was effective in extending the life of this CF-188 component.

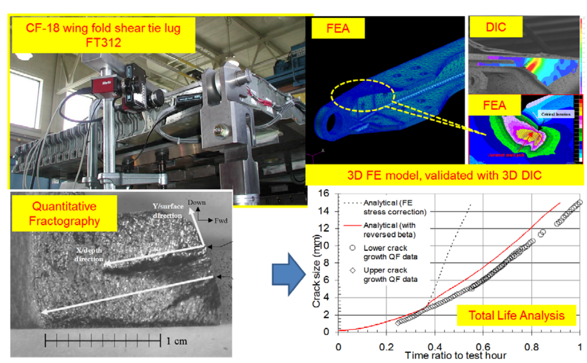

Figure 17 CF-188 Wing-Fold Shear-Tie Fatigue Test, and Fatigue Analysis

8.3 CF-188 Horizontal Stabilator (H-Stab) Fatigue Test

To extend the certification basis enabling the CF-188 fleet to continue service and meet its new Estimated Life Expectancy beyond 2025, and to avoid expensive horizontal stabilator procurement, NRC and L-3 MAS are performing a structural life extension fatigue test (durability and damage tolerance), and residual strength testing of a United States Navy retired stabilator with representative service repairs and environmental/fatigue exposure. The test spectrum includes manoeuvre and dynamic loading of the test article. As part of this testing, NRC has developed several innovative testing techniques (Figure 18), including:

- CAD test rig design achieving the complex loading conditions and displacements, as prescribed by L3-MAS FEM;
- Novel one-sided tension-compression loading fixtures, allowing faster testing and access for strain monitoring and inspection of the entire upper surface;
- Cross Coupling Compensation (CCC) to account for actuator interactions enabling faster multi-actuator tests;
- Large scale strain trend surveying and monitoring using DIC and Fibre Optic Strain Sensors; and
- Pulse flash thermography to inspect delamination or debonding damage growth in the composite skin-aluminium core sandwich structures.

Currently fatigue testing is being conducted to five lifetimes of required life extension. Residual strength tests to design and ultimate loads are planned at the completion of the fatigue testing, with or without artificially induced large damages.

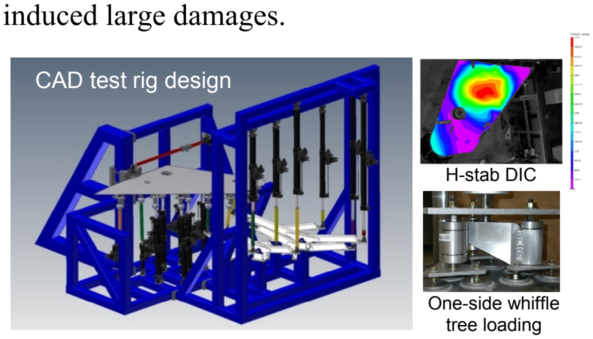

Figure 18 CF-188 H-Stab Fatigue Test

9 Conclusions

This paper presents some recent NRC research advances in the area of aircraft structural integrity and sustainment, which are aligned with the development of a new HOLSIP framework. Some fundamental advances include: fatigue nucleation physics studies, practical small/short crack growth testing and modelling; development of MSD/WFD evaluation tools; and development of risk analysis method/tools. The impact of environment on structural integrity was studied considering corrosion and fatigue interactions. Advanced NDE and SHM techniques continue to be developed to support structural integrity and sustainment. In addition, NRC has advanced experimental mechanics techniques including DIC and TSA. Novel loading fixtures and load control methodologies have been developed enabling faster component and/or full scale fatigue testing under both manoeuvre and dynamic loading. All these advances were presented through real life case studies, showing that the NRC advances, on both fundamental and applied research levels, have provided significant support to Canadian air fleet management with respect to maintain safety, increase availability, and reduce maintenance costs.

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