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DAMAGE TOLERANCE DEMONSTRATION TESTING FOR THE AUSTRALIAN F/A-18

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Abstract. *Over recent years Australia has been involved in a number of full-scale fatigue testing programs in support of the through-life structural integrity of the Royal Australian Air Force's (RAAF) F/A-18 fleet. It was recognised early in the acquisition cycle that the certification testing conducted by the manufacturer failed to considered damage tolerance requirements and would be unlikely to cover the typically more severe and diverse RAAF operations. Given similar aircraft structural integrity management philosophies, major benefits were to be realised through collaboration with the Canadian Forces (CF). In particular, as fatigue testing under representative CF/RAAF loading was the basis for both countries' structural integrity management, the International Follow-On Structural Test Project (IFOSTP) was successfully concluded.*

This paper emphasises the Australian components of IFOSTP, including the damage tolerance testing and demonstration for the aft fuselage that incorporated the simultaneous application of both manoeuvre and dynamic buffet loads. Many of the innovations and consequences of this work program are highlighted, and may be applicable to future fighter aircraft structural integrity programs.

1. INTRODUCTION

Between the Canadian Forces (CF) and the Royal Australian Air Force (RAAF), 210 F/A-18A/B aircraft were purchased from Boeing, the 'Original Equipment Manufacturer' (OEM), with deliveries between 1982 and 1990. Both countries operate the aircraft in similar roles that are very different to its intended role in the United States Navy (USN). The USN certification test was performed for a carrier based operation with a USN specified design usage spectrum that is significantly less severe for most primary structural elements, compared with that of the RAAF and CF. Additionally, there were significant configuration differences between CF/RAAF fleets and the certification test article; and limited damage tolerance data were collected. These issues led to concerns over the useful life of the airframe. Given their similar aircraft structural integrity management philosophies based on the UK defence standard [1], both parties saw that major benefits could be realised through collaboration. In particular it was determined that a program of full-scale fatigue testing should be conducted under representative CF/RAAF loading, the results of which would become the basis for F/A-18 structural integrity management in both countries; thus the

International Follow-On Structural Test Project (IFOSTP) was born. This highly technical project fostered many initiatives in the field of full-scale fatigue testing. Many of these were only feasible due to the collaborative nature of IFOSTP [2].

After reviewing the results of the early tests carried out under IFOSTP it became clear that, since the life of some items was marginal and it was desirable to avoid unforeseen modifications, consideration to other factors that could increase the risk of unscheduled modification would be necessary. Principally the lack of in-service induced degradation (e.g. corrosion, mechanical damage, etc) in these laboratory tests was identified as a primary risk to the lives established during the test interpretation. To address these interpretation issues and to reduce the risk of blindly accepting the fatigue test results, fatigue life expired ex-service centre fuselage bulkheads in the form of almost complete centre barrels (CBs) have been obtained from USN and CF centre barrel replacement (CBR) programs, and further fatigue cycled and torn down to inspect for in-service degradation. This program is called Flaw IdentificatioN through the Application of Loads (FINAL). Such an addition is not usually included in a full-scale fatigue test program, although in this case the opportunity to obtain the used CBs, along with the foreseen risk of several unknown factors on the interpreted fatigue lives made such a program very attractive. Details of the FINAL program can be found in [3].

This paper summarises some of novel test developments including demonstration of airframe damage tolerance of the aft fuselage.

2. INTERNATIONAL FOLLOW-ON STRUCTURAL TEST PROJECT

The IFOSTP was a collaborative program between the RAAF and the CF and is the most significant input to the structural lifing policy and life cycle management of the two F/A-18 fleets. From the analysis of initial usage, it was determined that the aircraft were accumulating fatigue damage faster than predicted by the design assumptions. Consequently, it was determined that on average, only two thirds of the initial required life of the aircraft could be achieved without additional certification testing. This had immense operational and economic implications.

From this common experience came a decision to proceed with a collaborative program of more representative testing, which led to a series of full-scale tests on the F/A-18 airframe. Both air forces were keen to define the drivers for the structural cost of ownership, and the structural life of type in CF/RAAF service, so that informed decisions could be made on structural integrity management and capability replacement options. The airframe had been the subject of several manufacturers' fatigue tests but these were evaluated as being not fully representative for the following reasons:

- both the CF and RAAF usage was significantly different than that assumed for design. The representative wing root bending (WRBM) moment spectrum (IARPO3a) is compared to the USN/OEM design spectrum (ST16) and the RAAF derived spectrum (APOL) in *Figure 1*;
- configuration differences between the OEM's test articles and the CF/RAAF aircraft were significant;
- many components had been re-designed and incorporated based on analysis only without verification testing;
- the USN approach to certification testing, using a severe spectrum derived from the three worst "points-in-the-sky (PITS)" and a scatter factor of two, was not consistent with the CF and RAAF airworthiness policies;
- the OEM's testing of the aft fuselage had only included the aerodynamic buffeting of the aft fuselage and empennage through the application of quasi-static loading;
- the OEM's fatigue testing of the wing had not considered aerodynamic buffeting of the outer wing, aileron and trailing edge flap; and,
- damage tolerance and fail-safety (including residual strength) had not been considered in the OEM's testing (note: the aircraft was designed on a safe-life basis).

The basis of IFOSTP was that representative testing might allow increased service life and more cost effective maintenance and repair decisions through the elimination of conservative interpretations of the previous tests. IFOSTP and its associated testing consisted of three major full-scale fatigue tests, and supporting stand-alone component tests [4,5]. The centre fuselage test (designated FT55) and the wing test (FT245) were conducted in Canada whilst the aft fuselage and empennage test (FT46) and two stand-alone Y488 centre fuselage bulkhead tests (FT488/1 and FT488/2) were conducted in Australia [2]. Both countries also carried out many supporting coupon test programs, e.g. [6-8] and Australia also conducted enhanced teardown of ex-service centre fuselage sections [3].

The test spectra were a compromise between the two fleets and were considered realistic and representative of their in-service usage [2]. In support of these tests, both countries also conducted a series of comprehensive flight trials. These data were used, in conjunction with on-board recorded data from fleet aircraft, computational fluid dynamics analysis and wind tunnel testing to develop the test loads.

The agreed objectives of the program were to:

- determine the economic life, and in the process, the safe-life of the major structural components under spectra representative of CF/RAAF operations;
- obtain, where possible crack growth data to support management on a safety-by-inspection basis;
- validate modifications and repairs; and
- establish an engineering database for life-cycle management through to retirement.

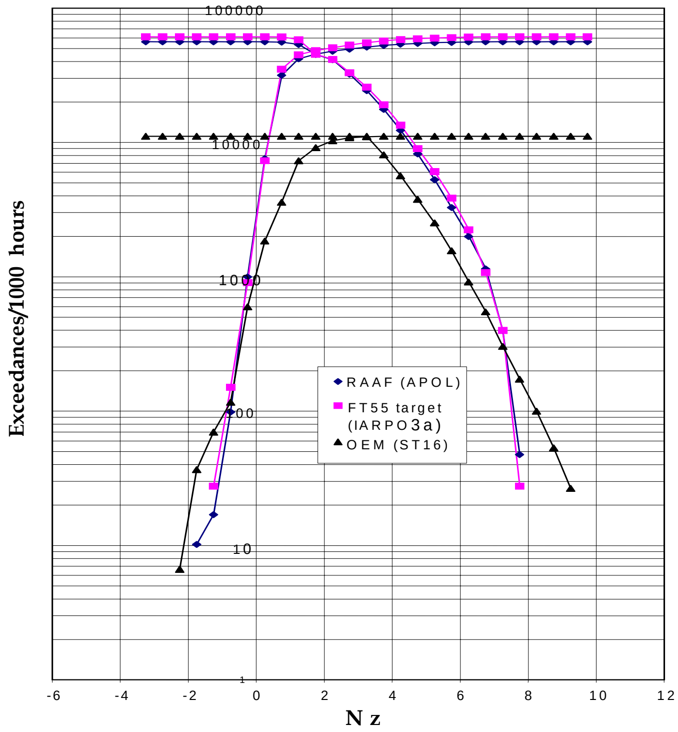

Figure 1: Nz exceedance plot comparison of the RAAF usage, FT55 applied and the original OEM test spectra.

3. FT46 - AFT FUSELAGE TEST

The F/A-18 is an extremely manoeuvrable, versatile, high performance fighter/attack aircraft. The inner wing Leading Edge Extension (LEX) provides fuselage and inner wing lift enabling it to achieve angles of attack (AOA) in excess of 60 degrees. The twin vertical tails canted slightly outward exploit the high-energy vortices generated by each LEX to provide good directional stability at these high AOA conditions (*Figure 2*). Unfortunately, these vortices break down at AOA>10 degrees, buffeting the structure and exciting the resonant frequencies of the empennage, producing high acceleration levels (Table 1) that result in high stress levels in key structural components. The problem was so severe that the manufacturer retroactively strengthened the fin attachments by fitting additional cleats at the base of the tails to increase the tail attachment strength, and fitted aerodynamic fences (known as "LEX fences") to the LEX to reduce buffet severity.

There is a synergistic interaction between the quasi-static manoeuvre loading and the higher frequency buffet loading with respect to fatigue damage. The general effect is that the buffet cycles are applied at high mean loads, which increases their contribution to fatigue damage. This phenomenon is well understood and the OEM attempted to apply representative (i.e. correct mean plus buffet) loads during the aft fuselage structural fatigue compliance tests. Separate dynamic fin tests were performed in which dynamic loads alone were applied to test the upper half of the fins. However, the loads were not applied realistically in terms of frequency and count but rather as calculated resultant loads at the normal quasi-static fatigue test rates. The primary objective of the Australian IFOSTP loading development process was to ensure that FT46 was loaded such that its dynamic response matched as closely as possible that of an aircraft in flight. To accomplish this, a manoeuvre loading system was required that would not significantly affect the dynamic characteristics of the structure. Spectra representing usage both before and after the addition of the LEX fence were tested. The testing and results are detailed in [9-12].

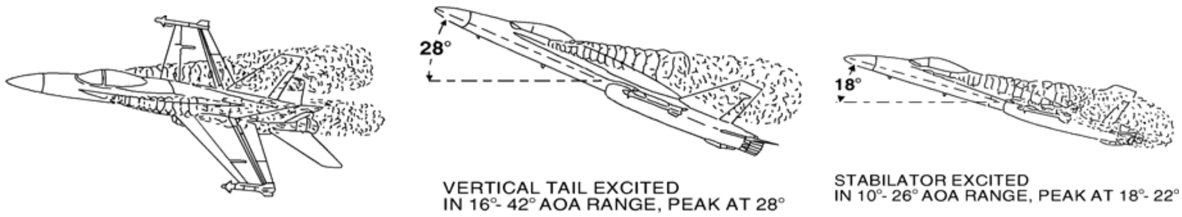

Figure 2: Empennage Buffet at High AOA

Table 1: Empennage Peak Modal Response Characteristics (Note: Modes are closely coupled and thus the peak response represents the superposition of both.)

Dynamic Mode	AOA (deg) for Peak Levels	Q (psf) Range for Peak Levels	Approx Freq. (Hz)	Approx Aft Tip Peak Accel.
VT 1st Bending Mode 1	32-36	175-225	16	± 170 g
VT 1st Torsion Mode 2	24-28	400-500	45	± 500 g
Stab. 1st Bending	36-39	225-300	12	± 100 g
Stab. 2nd Bending & 1st Torsion	16-20	350-400	38/46	± 350 g

Actual modal vibrations were generated at the correct frequencies and simultaneously applied with the corresponding manoeuvre loading. The Australian participants developed the test rig and unique loading system, the test loading sequence of manoeuvre and buffet loads, and equally important, the control systems [13]. A new airframe (less wings, forward fuselage and auxiliaries) was purchased for the test.

3.1 Test System

The test system was developed during a five-year program utilising ST01, an early centre/aft static test fuselage provided by the USN. The availability of this test article was crucial to the development program, since it enabled the loading and control systems to be developed without risking the FT46 test article. The essence of the load application system was a unique rolling sleeve pneumatic actuator that has soft spring stiffness and low mass.

Using this system, the distributed manoeuvre loads were applied without affecting the effective stiffness and mass of the empennage components.

Figure 3: Rolling sleeve airbags (red) and electromagnetic shaker (blue) in place on the horizontal tail

Concurrently, electromagnetic shakers applied the dynamic loading, while an active reaction control system maintained almost zero displacement of the test article tail area to minimise shaker stroke requirements during high manoeuvre loading. In this manner the significant number of dynamic cycles occurring over the service life of an aircraft was economically applied to a test article in real time. Combined closed loop operation of the air springs and hydraulic actuators was successfully developed. The controller developed at DSTO controlled 65 inter-dependant load channels such that the manoeuvre loads were controlled to within 2% of the required spectrum loads and the mode shapes and frequencies of the main control surfaces were maintained to approximately ±5% of those measured in flight.

The final test arrangement is shown in *Figure 4*. Several opposing air springs were used on each empennage surface to allow bi-directional loading. Thrust loading, engine ‘g’ loading, empennage drag loading and fuselage side loading were also applied in a time coordinated fashion.

3.2 Aft Fuselage Results

Active testing initiated in February 1996 and ran for 1270 SFH of the Pre-LEX spectrum. This was followed by a series of modifications to the test article and the test rig before the

Post-LEX spectrum phase, which began in August 1998. The test article accumulated a total of 23,090SFH in July 2002.

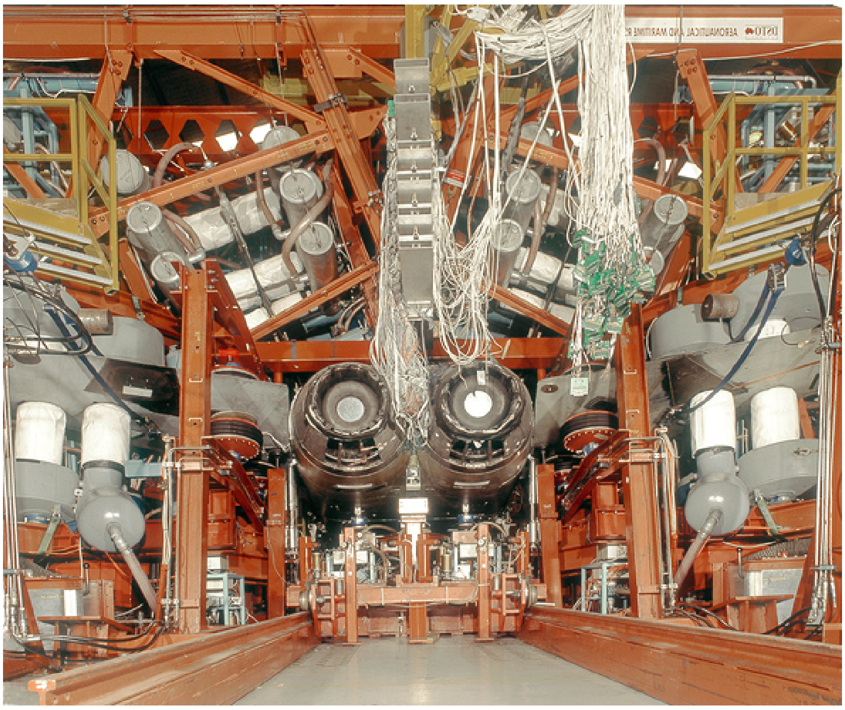

Figure 4: FT46 in test rig (rear view)

A total of 148 major deficiencies were observed. More than half the deficiencies (75) were detected in the first 6,000 SFH. By the second lifetime (12,000 SFH) another 25 had been detected and a total of 131 deficiencies had been recorded by 18,000 SFH. Most of the early deficiencies were from the vertical tail attachments to the stub frames. Most stub frames had cracks that were left to grow for significant periods of testing but needed airworthy class repairs before 18,000 SFH. Two significant failures on FT46 were the failure of the aft most support frame (at Y598), which needed to be replaced at 17,374 SFH and the failure of both dorsal longerons that were completely severed at 20,997 SFH.

Although the whole of the empennage has not been subjected to a sampling inspection in the fleets, several of these defects have already been observed on some fleet aircraft. Several stub deficiencies have been detected, correlating well with the test results.

3.3 Quantitative Fractography

To assist the analysis of cracking found during the FT46 testing and tear-down DSTO/RAAF policy was to remove cracking intact if possible and use Quantitative Fractography (QF) to determine the initiating discontinuity and the crack growth rate where possible. In many cases the analysis of these cracks yielded valuable information about the way the cracks were growing, the likelihood of the cracking resulting in complete failure of the component and, through test interpretation, the time at which such a failure could been expected in the fleet. By way of an example, cracking in the starboard Y598 bulkhead stub at 7846.3 hours is described.

This cracking occurred in the starboard FT46 Y598 bulkhead stub and was disclosed by strain gauge reading variations and subsequent NDI. Dye-penetrant indications of the cracks are shown in Figure 5. The cracking was removed and broken open to reveal several fatigue cracks that had linked to form a single crack front. The dominant region of initiation consisted of multiple origins along the rear surface of the stub. The origins of the cracking were examined in an attempt to determine the initiating detail (Figure 6). This indicated that etch pitting associated with the production etching carried out prior to Ion Vapour Deposited (IVD) aluminium coating (a corrosion protection coating) was the source of fatigue crack initiation. Many origins had occurred along the rear face of the flange.

Although the fracture showed evidence of minor corrosion, there were still areas where a repeat in the loading pattern typical of the block loading applied to the test article could be seen. These repeats in the loading pattern are usually best observed optically with specialised high-powered optical microscopes using long working distance lenses and interference contrast – equipment that DSTO has developed into a semi-automated system to aid in QF investigation. One of these repeats is shown in Figure 7, while a plot of the measurements of the crack depth versus test article life is presented in Figure 8 with a log crack depth scale. Previous investigations of this material when cracked under program loading have shown that given that the location is unaffected by fluctuating residual stresses, section changes or load shedding, this type of plot usually produces a reasonably linear result [14,15] i.e. crack growth is exponential, and commences growing from close to the first application of load.

Using the crack growth curve and the knowledge that the crack growth was approximately exponential an estimate of the time when the crack would reach a certain size was made. In conjunction with an estimate of the critical crack size, the life to failure of this crack in a typical fleet aircraft could be established.

3.4 Damage Tolerance and Residual Strength Testing

The CF and RAAF defined an RST requirement at the completion of fatigue cycling to demonstrate the damage tolerance of the structure. Due to the maturity of the fleets, operational data were used to assess the maximum loads likely to be encountered by each structural component in the life of the fleet. Based on this determination, appropriate load cases were developed to demonstrate residual strength of the test article at the end of fatigue cycling [16]. The nature of the tests required different approaches to RST for the centre fuselage/wing tests and the aft fuselage test.

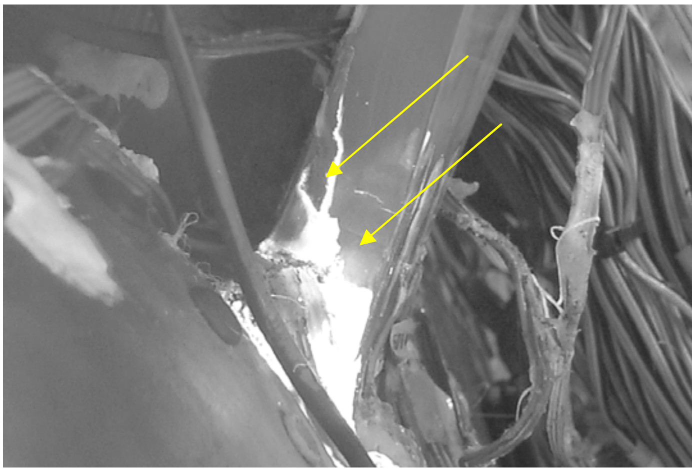

Figure 5: The flange with the cracking indicated by dye penetrant. Note that the cracking appears to be the result of several separate initiations.

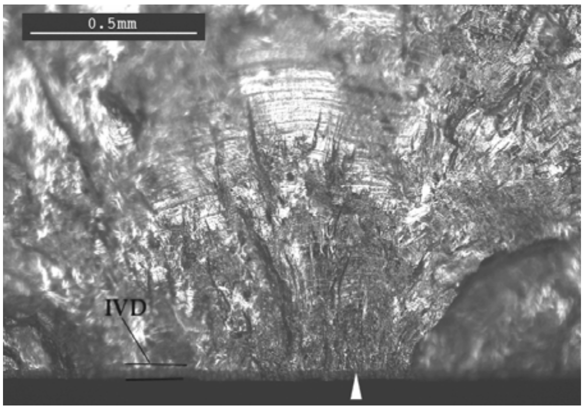

Figure 6: The initiation region on the fracture surface showing the primary origin (white triangle) and numerous other crack origins. The IVD is evident on the surface and its approximate thickness is indicated.

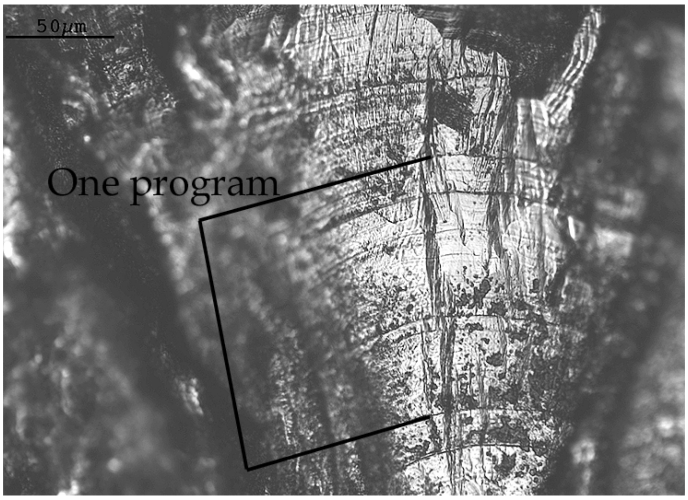

Figure 7: A region of the fracture surface showing a single repeat of the spectrum.

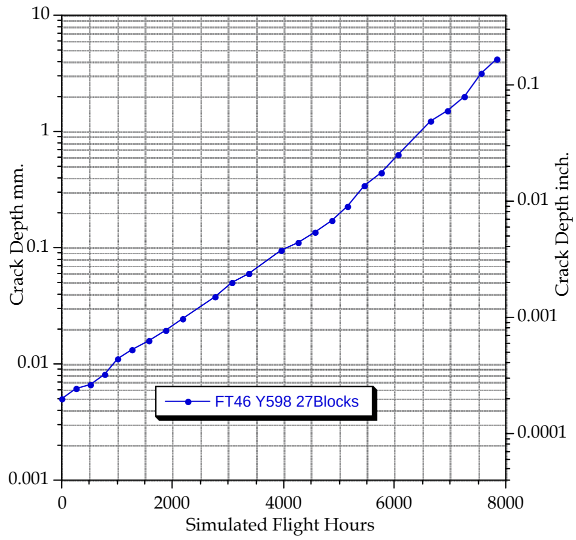

Figure 8: Plot of the crack growth as measured from the flaw to the outer edge of the cracking. Note, little evidence of the difference between the pre and post-LEX spectra can be seen.

Since the RAAF F/A-18 fleet had already completed half of its planned 6,000 hour life, it was decided to base the FT46 RST on the 3,000 hours of life remaining for those load cases which fell outside the design envelope due to buffet [16]. For FT46 components, the post-LEX load exceedance data from the test spectrum for each major component was extrapolated using a Gumbel distribution to predict the largest expected loads in the entire aircraft life (6,000 hours) and for the aircraft's remaining life (3,000 hours) respectively. The Gumbel distribution was used as it gives an accurate fit for extreme values. It was found that the ratio between the largest loads applied and the largest load predicted in 6,000 hours was approximately 1.2. As the 1.2 factor is commonly specified for use in RSTs [1], the 1 in 6,000 load case was considered acceptable for the FT46 RST for those load cases where the buffet had produced fatigue loading outside the original design cases.

The RST was successfully completed [16] and the test article was torn down to reveal many cracks. A considerable number of these have been investigated with QF. Of particular interest for QF analysis are areas that were determined to have been under tested that produced cracking. The QF analysis along with coupon test programs (as mentioned above) has in several instances allowed extrapolation to lives beyond the hours that were applied to the test article.

Twenty-seven load cases were selected [16] to cover all the main aft fuselage components (including the engine mount structure). For each case, an extreme load line was chosen from the spectrum and all channels were scaled by the factor determined from the Gumbel extrapolation. While only the pneumatic and hydraulic actuators were used for this purpose, the loads simulated during the RST were derived to include both manoeuvre and dynamic loading. These cases effectively simulated extreme manoeuvre events for the aircraft. One of the loading envelopes used to establish the RST loading points is shown in Figure 9. The black line is the design limit envelope while the points are loads taken from the test spectrum and therefore service aircraft. The mismatch between the service loading and the design envelope is notable and was the main reason for adopting a prediction of the 1 in 6,000 and 1 in 3,000 load case rather that simply 1.2 times the design limit load cases. The Figure also shows the load cases chosen for this loading action in the RST of FT46 as 'lettered' cases.

Limitations on the test rig and the requirement to use distributed loading (scaled up flight loading where most of the actuators were active during most of the load cases) prevented all of the 1 in 6,000 load cases from being achieved, nevertheless the loads that were achieved on the test article were sufficient to clear all structural components to at least the 1 in 3000 load case, and most to the 1 in 6000 load case. Where the OEM design limit envelope was more severe than the 1 in 6000 load case the factored design limit case was usually chosen [16].

The first phase of the RST was successfully completed in October 2002 (see Figure 10 for example of the deflection experienced by one of the stabilators). In order to further demonstrate the damage tolerance and/or fail-safety of the structure several more RST phases were conducted. Each phase introduced additional levels of damage from that existing at the end of cycling. This included the removal of several repairs and the simulation of up to two severed stubs (out of a total of 6) for a vertical tail. In some instances the fatigue cycling had failed to produce detectable cracking in areas predicted to do so by analysis of previous testing. Thus damage was also introduced at several locations throughout the structure. In general the cracks were simulated using a jeweller's saw or electro-discharge machining.

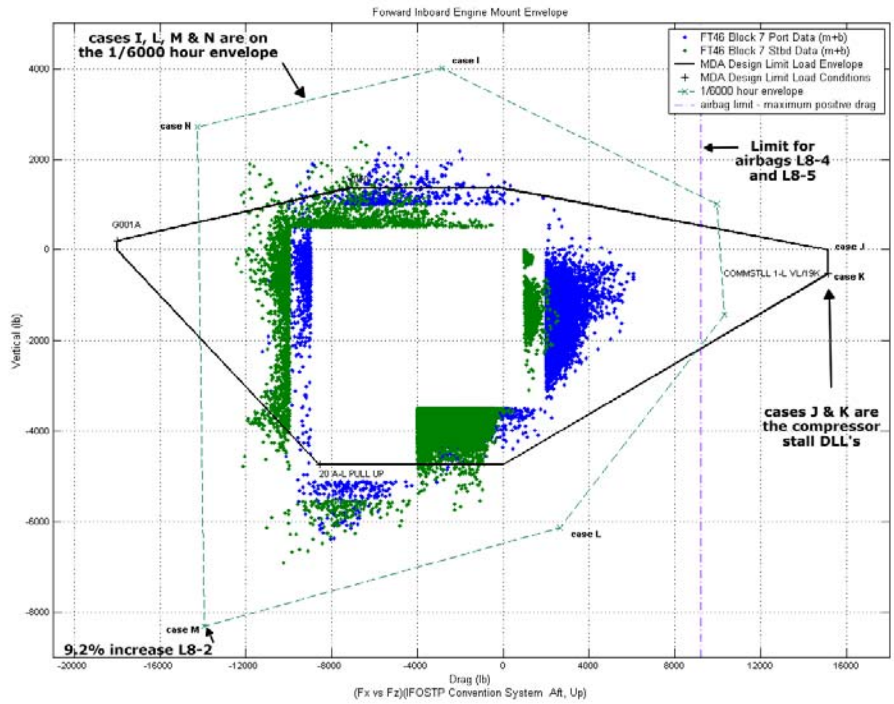

Figure 9: One of the loading envelopes used to establish the RST loading points. The black line is the design limit envelope while the points are loads taken from the test spectrum and therefore service aircraft.

Table 3 shows some of the repairs removed (from [16]). When simulated (saw cut) damage was added the tip-shapes were made more crack-like by cycling the appropriate component at 50% of its maximum reference load for 50 cycles. This type of loading had been found to be successful at producing fatigue crack extension of fine saw cuts in the earlier FT55 RST test.

As a result of the removal of repairs and the simulation of structural disconnections in the final Phases of the RST (Cases 9 &10 in Table 3), the fatigue damage present in the structure (combined with the substantial reduction in the strength as a result of removing bolts to simulate severed vertical tail stub frames) resulted in the remaining stub frames failing, see Figure 11 and Figure 12. This procedure was carried out on both sides of the test article producing very similar results. In both cases the fatigue damage in the other frames combined to cause the failure. Nevertheless the load that was achieved in both cases was about equal to the design limit load case indicating the considerable toughness of the vertical tail even when extensively damaged. This result will be of great use in deciding the inspection and repair regimes that will be promulgated to the fleet as a result of this testing. Subsequent to the damage tolerance testing, FT46 was systematically torn-down to detail any damage that had not be detected during routine test inspections [17,18].

Figure 10: FT46 Stabilator at maximum down bending during FT46 RST.

Table 3: The removal of repairs previously installed and the inductions of damage used to test the fail safety of the F/A-18 tail structure

RST case	Items to be tested during this Phase	% of target load achieved
1.	Test FT46 in the condition at the end of fatigue cycling	100 on most parts
2.	Remove all bolts attaching vertical tail aft spar to starboard Y598 stub former (simulating one cracked-through stub).	100
3.	Remove repair from port Y598 stub former.	100
4.	Remove composite patches/repairs from control hole and loom hole cracks in the Y598 and Y590 stub frames	100
5.	Remove starboard Y574 stub frame repair	100
6.	Remove starboard engine bay door repair	100
7.	Remove the port dorsal deck longeron repair	100
8.	Remove the starboard dorsal deck longeron repair	100
9.	Remove all bolts attaching the aft spar to the starboard Y590 stub former (simulating two cracked-through stubs)	80, other subs failed
10.	Remove all bolts attaching vertical tail spars to the port Y598 and Y590 stub formers (simulating two cracked-through stubs on the port side)	79, other subs failed

Figure 11: Overview of the failure of the Y566 stub at 79% RST load following simulated failure of the Y598 and Y590 stubs.

Figure 12: Close up of the expelled fragment location.

4. CONCLUSION

Significant technical innovations were achieved through IFOSTP including:

- the first use of test spectra and load sequences derived directly from operational aircraft with a digital flight control system employing variable control laws and free manoeuvring;
- development of methodologies that allowed accurate prediction of major section loads for each flight manoeuvre in a very large spectra and the recreation of load distributions on a continuous time base using operational flight data;
- development of test load distribution methods for the wing test that accounted for large control surface influences and optimised chordwise as well as the traditional spanwise distributions;

- the first successful simultaneous application of coordinated dynamic and manoeuvre loads representative of flight conditions on multiple components of a full aircraft test structure;
- development of a unique pneumatic “soft spring” manoeuvre loading system including accurate and rapid response controllers;
- design and development of the FT46 controller with 65 actuators of differing type (pneumatic, electromagnetic and hydraulic) with many channels where actuator interaction (dependency) is significant;
- implementation, on the FT-245 wing test, of a control and data acquisition system with new end point error checking and notification processes including sophisticated on-line trend monitoring;
- advanced the application of bonded composite patches for repair in the area of design development tools as well as the ability to repair highly loaded and cracked structure at geometrically complex components;
- advancement of the field of QF that allowed these techniques, with knowledge of local stresses, to be used to accurately predict component time to failure from limited crack growth information;
- application of evolving technology and use of databases to store, retrieve and catalogue IFOSTP information. This has led to several useful fleet management tools;

The IFOSTP tests and associated research and engineering activities have generated high quality structural integrity information. This information has been pivotal in defining major structural refurbishment activities in the both the RAAF and CF fleets, that should enable each fleet to achieve its respective service retirement date. The information has established life of type limits and has enabled accurate estimation of the cost of structural refurbishment. Whilst other factors also affect whether a weapon system should be replaced early, the IFOSTP information has facilitated the ability to make informed decisions on return on investment for the F/A-18.

The results from IFOSTP have yielded unprecedented information to allow the fleet managers the ability to cost and effectively shape their life cycle management programs along with the associated infrastructures. Specifically, they have allowed both countries to change the basis of certification for the aircraft, including allowances for damage tolerance. Although use is still made of information obtained from the OEMs original certification tests, IFOSTP tests are the cornerstone of the F/A-18 structural integrity management for the RAAF and the CF.

The following illustrates how the original IFOSTP objectives were satisfied and the implications for the fleet:

- IFOSTP confirmed that the safe life of the centre fuselage, under CF/RAAF usage and airworthiness policies, was of the order of two thirds of that specified by the OEM.

More importantly, IFOSTP identified previously unknown locations subject to cracking;

- to maintain the fleet beyond the two-third safe life, a series of structural inspections, modifications, and repairs are required. These were incorporated into the test articles for performance assessment. In several cases, they were applied early enough to allow the repairs to be certified through testing;
- a clear path for management of the fleet and its associated costs up to planned withdrawal date has resulted from IFOSTP. Both countries (with some differences) have developed cost effective mid-life structural refurbishment programs that minimize the impact on the operational availability of the fleets. Furthermore, the structural modifications can be co-ordinated with the avionics upgrade programs planned for the aircraft. Also, it was determined that a number of centre fuselage replacements would be required. This has allowed the set-up of a centre barrel acquisition and replacement trial well in advance of the required fleet induction time.

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