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Flaw Identification Through The Application Of Loading (FINAL)

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ABSTRACT: The teardown and inspection of aircraft, which have completed a significant period of service, is a central requirement of many Aircraft Structural Integrity Management Plans (ASIMP). The reasons for this include a need to inspect for the potential onset of wide spread fatigue damage and to assess the impact of corrosion and in-service mechanical damage. Furthermore, service life data from fleet aircraft are required to confirm laboratory fatigue test results and substantiate the assumptions made during safe-life calculations or probabilistic risk and reliability studies. A teardown and inspection of the fracture critical F/A-18 wing attachment bulkheads (or centre barrel - CB) has been initiated to achieve these goals for the RAAF's F/A-18 fleet. Use is being made of ex-service CBs supplied from the Canadian Forces and U.S. Navy (USN) CB replacement programs.

Investigations suggest that the largest "likely" cracks in the critical bulkheads will be less than 1 mm deep at the time a CB is replaced. Since the detectable crack depth threshold for current NDI (using high frequency eddy current (HFEC) detection) is 1.0 mm or greater, these cracks may not be found.

To significantly improve the probability of detecting cracks that are below the lower threshold of NDI, an increase in their size by accelerated fatigue testing of the CBs has been implemented. Cyclic loads (using the mini-FALSTAFF spectrum) are applied to the wing attachment lugs of ex-service CBs in a test rig to simulate in-flight wing loads. The loading is of sufficient magnitude and duration to ensure that any existing cracks will be grown to a size that ensures their detection under laboratory conditions. Quantitative fractography has been performed on observed cracking to obtain crack growth data and to determine the size, nature and cause of discontinuities that initiate fatigue cracking. This paper will provide a summary of the teardown philosophy, methodology and preliminary results.

1. INTRODUCTION

The Royal Australian Air Force currently employs the Boeing F/A-18 Hornet as a land-based front-line fighter aircraft. It was originally designed, built and tested for the requirements of the United States Navy (USN) who operate it mainly as a carrier based fighter/attack aircraft. Because of the operational differences between RAAF and USN, the RAAF in collaboration with the Canadian Forces (CF), who had similar needs, developed a full-scale fatigue test program to determine the safe-life of the F/A-18. This program, known as the F/A-18 International Follow On Structural Test Project (IFOSTP) [Simpson et al, 2002], included a fatigue test of the centre fuselage called FT55. This test showed that the safe–life of the centre barrel is insufficient to meet planned withdrawal between 2012 and 2015 for all aircraft in the fleet.

The F/A-18 centre barrel (CB) carries wing loads into the fuselage through its three main structural elements, the Y453, Y470.5 and Y488 bulkheads. The three main bulkheads are fracture critical and loss of structural integrity in any of these members may cause the loss of the aircraft. These three bulkheads are made of 7050-T7451 aluminium alloy, which has been coated for corrosion protection with a thin layer of almost pure aluminium by the Ion Vapour Deposition (IVD) process. As a precursor to this coating, the items to be coated are acid etched to improve coating adhesion. This etching leaves numerous tiny pits in the surface of the coated parts.

A centre barrel replacement (CBR) program was investigated to address some of the deficiencies highlighted by FT55. The USN and CF have already commenced their own CBR programs. For RAAF implementation, two main problems with the CBR program were highlighted; the program may be difficult to run in-country because of logistical concerns, and the availability of aircraft during the program may be insufficient to meet the operational needs of the RAAF. For these reasons, combined with the expected expense of such a program, the RAAF are examining alternative strategies to minimise the CBR program.

This strategy, referred to as SRP1++ [RAAF, 2002] or Hornet Up Grade (HUG) phase 3, includes a series of modifications made at critical locations late in the life of the F/A-18 to extend the life of some aircraft in the fleet so that they may achieve planned withdrawal date without CBR. The actions that will be taken in SRP1++ will be based mainly on experience from the early life of the fleet and the results of the F/A-18 fatigue tests including IFOSTP. Because of the lack of data from high life fleet aircraft, a number of risks exist in implementing a SRP1++ program, including:

1. Influence of in-service defects including mechanical damage and corrosion.
2. Influence of widespread fatigue damage (and thus potential new fatigue critical locations not previously seen in other F/A-18 fatigue tests).
3. Ineffective repairs.

The teardown and inspection of ex-service centre barrels has been highlighted as a method of reducing the risks involved in a SRP1++ program. Because the USN and CF are currently undertaking CBR programs, a number of ex-service centre barrels are available. Unfortunately the sizes of the average largest cracks present on ex-service centre barrels are expected to be less than 1 mm [White et al., 2002]. This is below the threshold of current practical Non-Destructive Investigation (NDI) methods, meaning that it is difficult to gain service data from ex-service centre barrels in their current condition. To overcome this obstacle, the Flaw IdeNtification through the Application of Loads (FINAL) program was proposed. This program involves the application of representative Wing Root Bending Moment (WRBM) fatigue loads to ex-service CBs in a test rig. The fatigue cycling should grow existing flaws to a size where they may be detected under laboratory conditions. After fatigue cycling of each CB has been completed, a teardown including thorough inspection and quantitative fractography (QF) will be preformed. The data from this will be used to address the following aims of FINAL:

1. To determine if in-service aircraft contain CB damage not accounted for in the fatigue test program, including mechanical damage and corrosion that are the result of the service environment.
2. To get a more complete picture of the types of defects or degradation that lead to cracking in the fleet.
3. To ensure that future decisions on the CBR program are based on as much relevant information about the structural integrity of the in-service CB as possible; and
4. To provide data that will enhance current risk and reliability method deliberations with regard to the F/A-18 aircraft (see [White et al., 2002]).

This paper details the cycling and teardown process of the FINAL program as well as some preliminary results. FINAL is supported by the RAAF HUG3 project office.

2. FATIGUE ENHANCEMENT METHODOLOGY

When tearing down an ex-service structure to compare the critical locations with full-scale fatigue test article data, it is expected that any cracking in the structure will be very small. The safe-life method of ensuring airworthiness dictates that full-scale fatigue testing is carried out for 3 or more times the expected life of the airframe as recommended by DEFSTAN 970 [UK Defence Standard, 1999]. Thus, if the mean crack reaches failure at the end of these 3 life times, it is expected that this same crack would have been very small while the aircraft remained in fleet service (one third the total time that the crack was growing). For example, if the crack growths exponentially with time (see [Barter et al, 2004]), and the critical crack size is approximately 10mm with a typical initial size of 0.01mm, then its depth at one-third the test life is approximately 0.1mm. This crack size would be very difficult to find without knowing the <u>exact</u> position in which to look. For this reason, it is necessary to grow cracks from an ex-service aircraft to a reasonable size prior to any teardown. This is achieved by applying WRBM fatigue cycling to the ex-service CBs. The requirements for such a fatigue enhancement test to provide useful data were as follows:

1. The loading should be applied in blocks that are easy to "read" during QF so that the demarcation between the service loading and the fatigue enhancement can be easily distinguished on the crack surfaces. This allows the size of cracks present at the end of service life to be determined; and
2. The loading should be simple enough to be applied in a reasonable time frame so that the set-up and testing phase of this process is minimised. Since this is not a fatigue test, the load sequence does not have to be accurate or representative of fleet usage.

3. TEST RIG SETUP

The test rig, shown in Figure 1, was designed to simulate wing loads at the wing attachment lugs. Pairs of actuators apply equal and opposite loads to the ends of beams that are attached to the sides of each bulkhead. The WRBM produced by the actuators is transferred as a couple at the wing attachment lugs. The CB has been rotated by 90 degrees to allow it to sit on one set of beams. The rig is self-reacting so that the top and bottom beams apply equal and opposite bending moments to opposite sides of the test article.

Each actuator is controlled separately, making it possible to proportion the bending moment applied to each bulkhead. This allows the loading of the CB to be tailored to match in-flight load distributions. It is also possible to continue cycling after bulkheads have failed by switching off the actuators attached to the failed bulkheads. As a result, each bulkhead is cycled until failure, maximising the amount of growth to existing flaws. This in turn increases the chances of finding the maximum number of flaws.

Figure 1: An F/A-18 centre barrel mounted in the FINAL rig (location of first failure highlighted)

Instrumentation has been applied to the test article to assess the distribution of load between the three bulkheads and to compare the applied loads to previous F/A-18 fatigue tests.

The rig does not apply landing loads to the CB. Accordingly, defects in areas where the in-service loading is dominated by landing loads are unlikely to be grown significantly by the fatigue cycling process. Landing loads have not been identified as being critical to the Australian fleet.

A truncated version of mini-FALSTAFF (Fighter Aircraft Loading STandard For Fatigue Evaluation) sequence is applied to the test articles. The FALSTAFF loading sequence was developed to represent the standard load history at the wing root of a fighter aircraft [Aicher et al, 1976]. The sequence is equivalent to 200 flights. A normalised mini-FALSTAFF sequence was generated using the NRL developed software

[Genesis 4 Fatigue, 2001]. This sequence was normalised by dividing each load by the maximum in the sequence.

The normalised sequence was multiplied by the peak IFOSTP FT55 WRBM of 6462 in-kip to produce a WRBM sequence. The WRBM applied at each bulkhead was derived from the horizontal lug loads at the design load cases given in Reference 5. Comparison of the WRBM at the three bulkheads allowed the actuator loads applied to each bulkhead to be tailored to match this load distribution.

4. INSPECTIONS

Two inspections are performed on each of the test articles. An inspection is performed before fatigue cycling to allow prompt reporting of information regarding significant existing flaws. Another full inspection is performed upon the completion of fatigue cycling when the CB has been dismantled. Parts exhibiting cracking may be subjected to QF where they are broken into fragments and the crack surfaces examined under a microscope. The QF gives information relating to the type of defect causing cracking and the rate of crack growth.

The inspection procedures for the two main inspections are basically the same. The first stage of inspection is a close visual inspection of the entire structure, followed by\ eddy current inspection of potential cracking locations in the main bulkheads, including those areas where cracks were detected in previous fatigue tests.

After the final eddy current inspection, the three main bulkheads are inspected using fluorescent dye penetrant. Before this can occur, the paint and IVD coating must be removed to improve the fidelity of the dye penetrant inspection. This removal is achieved by dipping the bulkheads in a nitric acid solution. Cracks that are found during earlier inspections are removed prior to this process to prevent damage to crack surfaces, which would make QF difficult.

5. PRELIMINARY RESULTS

The fatigue cycling of the first CB was recently completed and some preliminary results are available. The first test article came from a CF aircraft that had flown to its safe-life limit of approximately 3500 hours. DSTO received a copy of the maintenance records, which detailed a few locations where cracks were blended out during service.

There was a great deal of mechanical damage found during the initial inspection. In general, the quality of holes was poor and there were many dents and scratches. It is suspected that many of the latter were produced during the CB removal. The only confirmed cracks found during the pre-cycling inspection were in the Y488 bulkhead at the main landing gear up-lock holes, a known problem area, for which repairs have been designed.

During FINAL fatigue cycling, failure occurred at five locations. Indications were found at a further two sites when the opposite mirror location to a failure was inspected. The final eddy current inspection of the torn down structure is still to be completed.

The failure of the Y488 bulkhead's lower flange, duct flange and the connecting web, shown in Figure 2, was the first to occur during cycling. Figure 3 shows the fracture surface. Failure of this location can be attributed to the localised high stresses as can be seen from the Nastran finite element analysis of the region, Figure 4. Overall there were three failures of the Y488 bulkhead and one failure of each of the other two bulkheads. More failures occurred on the Y488 bulkhead because the first two failures were repaired to allow further cycling to reveal more flaws. Generally however, it is planned that cycling of a bulkhead will cease after it has failed.

Some of the QF results from this failure are shown in Figure 5 and these confirm the hypothesis that cracking in this type of structure under these loading conditions (in the absences of residual stresses and/or load shedding) follows the form:

$$Ln(a) = \beta N + Ln(a_o) \quad \text{or} \quad a = a_o e^{\beta N} \quad \text{Equation 1}$$

where N is the “fatigue life”, β is a parameter that is geometry, material and load dependent, *a* is the crack depth and time *N*, a_0 is the initial crack-like flaw size (depth of the crack at the start of loading), see [Barter et al., 2004].

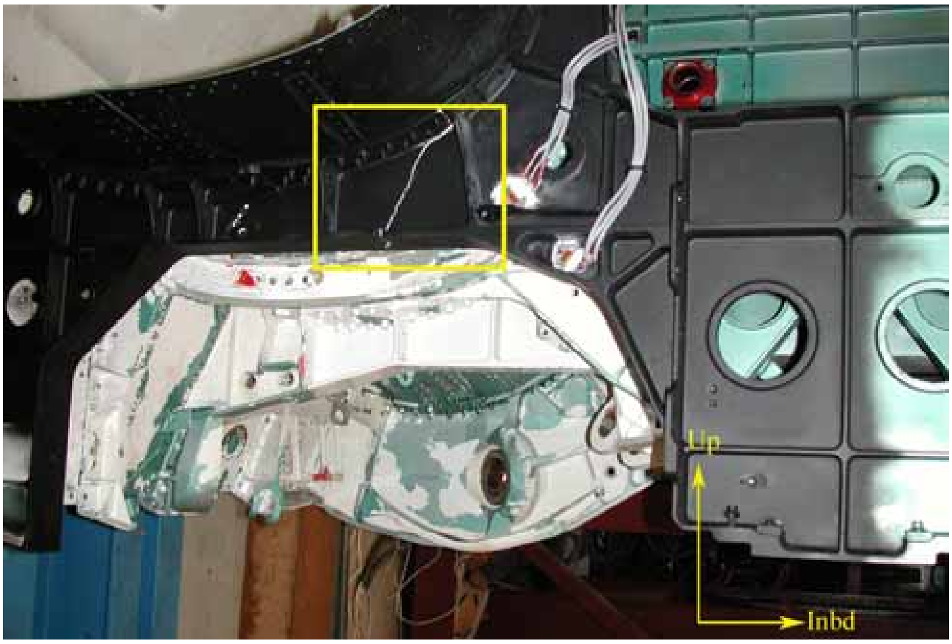

Figure 2: The first Y488 bulkhead failure of CF-18 CB

All of the failures will be excised for QF. The first two failures of the Y488 bulkhead were excised at the time they were repaired. Figure 3 shows the fracture surface produced by the first Y488 bulkhead failure. The shiny surfaces located at the lower and side edges are fatigue cracks. The largest, on the right hand side, caused the final fracture to occur. It is clear that this is not an isolated fatigue crack, but one of many. This is characteristic of the bulkhead material, which was etched prior to the IVD coating procedure. The etching covers the surface with very small pits, which in addition to aiding the adhesion of the protective coating, also provide a multitude of initiation sites for cracking. The preliminary results from QF have shown that the significant cracks have initiated from etch pits formed during the IVD coating process.

All crack indications found so far have been in locations where cracking has been found on previous fatigue tests. It may be hypothesised that since the etch pits cover almost all of the structure and that cracks initiate very early in the structure’s service life, then these pits will result in a uniform population of growing cracks at all areas of high stress. Assuming that the distribution of etch sizes is equal in all areas, it follows that the most highly stressed areas are likely to grow cracks from etch pits most quickly, which means they will be detected or cause failure prior to any service induced damage unless this damage is severe or also introduced very early in the service life. This is supported by the experience on the first centre barrel, where the nine cracking sites found so far consist mainly of four sites mirrored on both sides. It also supports the consistency in cracking sites between fatigue test articles. The findings so far are inconsistent with concerns about widespread fatigue damage in the form of random cracking throughout the critical structure, because cracking has only been found in discrete locations of high stress.

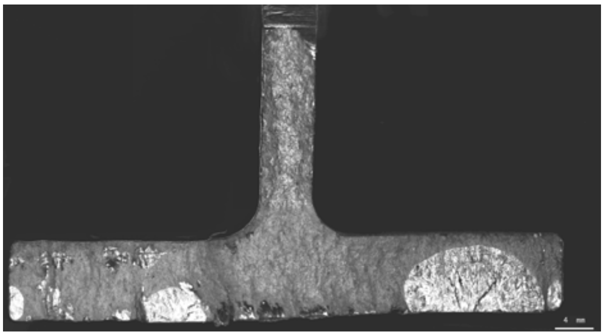

Figure 3: The fracture surface produced by the first Y488 bulkhead failure of CF-18 CB

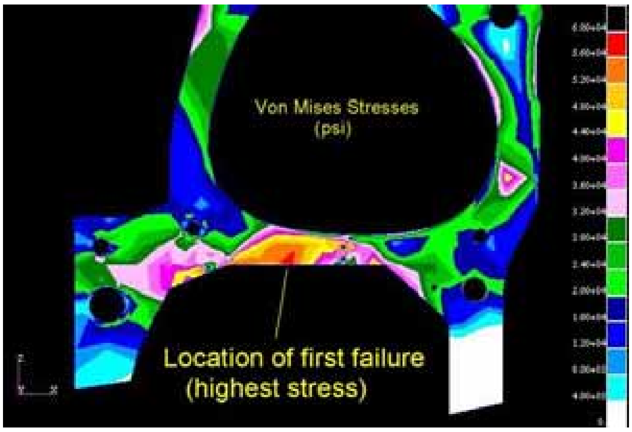

Figure 4: Y488 bulkhead stress distribution

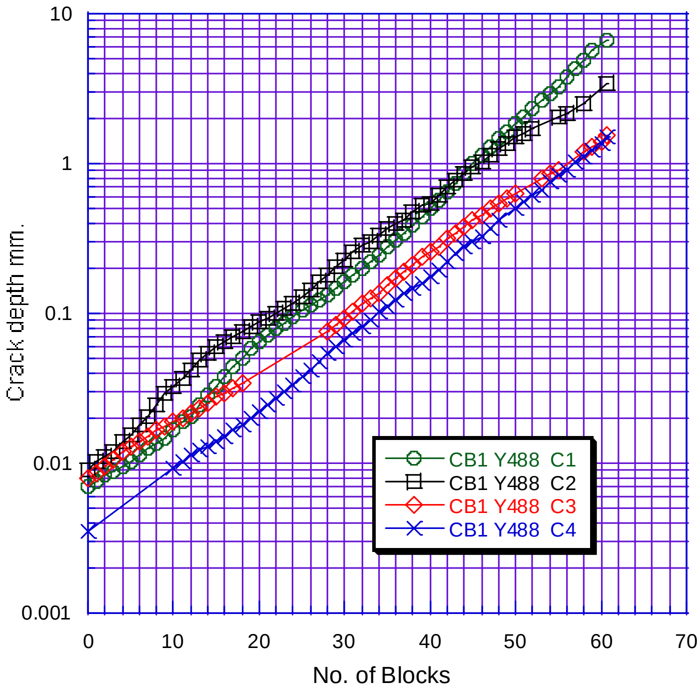

Figure 5: Crack growth curves for the four largest fatigue cracks at the first Y488 bulkhead failure of CF-18 CB. The curves were derived from QF of the fracture surface.

So far no cracking from mechanical damage or corrosion has been found. From a corrosion standpoint this was not surprising since there was none detected during inspection. The next CB tested in the FINAL program is from an ex-US Navy aircraft that has corrosion evident at several locations. This test article should enhance understanding of the significance of corrosion to the fatigue life of the F/A-18 CB. The mechanical damage on the first test article appeared severe, but as yet no evidence has been found to support any connection between significant cracking and mechanical damage.

6. CONCLUSION

DSTO are currently undertaking teardown inspections of ex-service F/A-18 centre barrels to support RAAF deliberations concerning a number of planned modifications to critical structure, including the complete replacement of the fracture critical centre barrel. It is hoped that a discrete modification package will allow the RAAF to operate the F/A-18 to its planned withdrawal date, with the minimum number of centre barrel replacements. As the size of cracking in ex-service centre barrels is expected to be below the threshold of current NDI, DSTO are fatigue cycling them to grow the existing cracks to a size where they may be more easily found.

A simple rig has been built to apply wing root bending moment to the centre barrels, which are being fatigue cycled with the mini-FALSTAFF spectrum. This fatigue cycling of the first centre barrel in the program revealed nine cracking locations that were not detectable when it was retired from service. It is currently being torn down to find more cracks.

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