DSTO Testing in Support of the Sustainability of the Hornet's Structural Integrity as part of the SRP

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As tactical military aircraft age, and in particular enter into the last third of their life, sustainment issues become much more important. The expense of structural refurbishment and the cost required to maintain the aircraft's capability can become prohibitive at a time when the RAAF's attention is usually focused on new capability, so ways must be found to maintain the current capability while minimising or reducing costs whilst still maintaining an acceptable level of risk from structural failure. To this end, DSTO is undertaking a series of structural integrity tests aimed at reducing the cost of maintaining the RAAF F/A-18 A/B Hornet fleet to the required planned withdrawal date.

These tests cover, among others, three major areas of the aircraft: the Centre Barrel (CB) that acts as the wing attachment structure, the outer wings including attached missile launchers, and the horizontal stabilators. While aspects of the CB test program (Flaw IdeNtification through the Application of Loading: FINAL) is well documented and has already provided significant savings, work continues on related aspects of the CB's fatigue life. The outer wing program (Hornet Outer Wing StAtic Test: HOWSAT) concentrates on reducing the costs of outer wing inspections and the costs of launcher replacements (LAU-7 lifE Extension Program: LEEP). Finally, the horizontal stabilators and other flight control surface (Canadian/Australian Flight control surface Evaluation: CAFÉ) collaborative program with the Canadians is aimed at reducing the rejection rate of control surfaces due to service damage so as to allow currently rejected items to return to service and existing in-service items to remain in-service longer. This paper presents a brief description of each of these test programs and summarises the gains that have been or are likely to be achieved. This work is aimed at satisfying the intent of Defence's Strategic Reform Program (SRP) whilst ensuring the safe operation of the aircraft is not compromised.

Keywords: F/A-18 Hornet, FINAL, CAFÉ, HOWSAT, LEEP, Centre Barrel, Testing, Crack Growth, Safe Life Extension.

Introduction

The F/A-18A/B Hornet was originally designed to a safe life of 6,000 airframe hours (AFHRS) under United States Navy (USN) usage. The Original Equipment Manufacturer (OEM) conducted a number of full-scale fatigue tests (FSFTs) to substantiate this life. This substantiation was the basis for the original verification and acceptance of the F/A-18A/B for the Royal Australian Air Force (RAAF).

To account for the longer term implications of varying usage and configuration to that assumed in the OEM certification test, the International Follow-On Structural Test Project (IFOSTP) was instigated by the RAAF and Canadian Forces (CF) [2]. This involved further FSFTs of the F/A-18A/B to verify the aircraft's fatigue life for the RAAF and CF structural configuration and operational usage. IFOSTP consisted of three major FSFTs: the centre fuselage test (FT55) and wing test (FT245), both performed in Canada; and the aft fuselage/empennage test (FT46) performed in Australia at the Defence Science and Technology Organisation (DSTO). IFOSTP testing was conducted to a representative RAAF and CF usage spectrum and demonstrated that (amongst other findings) the RAAF fleet would require a mid-life structural upgrade of the centre fuselage (particularly the part of the centre barrel (CB) to which the wings are attached) to reach a 6,000 AFHRS service life. The inner wings were found to be full-life, apart from a small number of areas that could be inspected; the forward fuselage was considered to be full life and the empennage was found to be life limited in some areas although these could also be inspected [3].

When deciding upon a course of action to address potential structural deficiencies or fatigue life limitations it is necessary to consider:

- Replacement verses repair;
- Local industry capability and logistics;
- Adequacy and difficulty of inspections;
- Adequacy and fidelity of extant lifing policy;
- Impact on aircraft availability; and
- Cost and return on investment.

To help in these deliberations DSTO supported by Directorate General Technical Airworthiness (DGTA) and Defence Materiel Organisation (DMO) have embarked on a series of additional tests aimed at reducing the cost burden of F/A-18 A/B operations and to improve the aircraft's service availability.

This paper presents a brief description of these test programs and summarises the gains that have been or are likely to be achieved. This work is aimed at satisfying the intent of Defence's Strategic Reform Program (SRP) whilst ensuring the safe operation of the aircraft is not compromised.

FINAL

The most significant aspect of the mid-life structural upgrade to the F/A-18 A/B was the CB replacement program. The CB is comprised of the three wing attachment bulkheads, and is the core load bearing structure in the aircraft as it reacts the wing and landing loads into the fuselage. A Centre Barrel Replacement (CBR) program was considered more cost effective than an alternative suite of discreet modifications to the CB due to the restricted access within the CB assembly. This CBR process required the original CB to be removed (at approximately its safe-life as determined through IFOSTP) and replaced by a new CB effectively "zero-timing" this part of the aircraft. The process itself takes about one year to complete. Additionally, CB replacement was preceded by a relatively small number of discreet modifications to allow the replacement to be carried out at a latter date. The number of aircraft undergoing CBR was determined from fleet usage predictions and planned withdrawal date.

Because of the lack of data from high life fleet aircraft at the time, a number of risks existed in implementing the discreet modification program as part of the CB life improvement. The risks included:

- The influence of possible in-service defects including mechanical damage and corrosion, with the possibility of a shorter than expected life being found in some areas of the CBs as a result of these types of in-service damages.
- Uncertainty about the appropriate scope of the modifications, their calculated fatigue lives, their impact on surrounding areas and the optimum time for their introduction; and
- The potential for new fatigue critical locations not previously seen in other F/A-18 A/B FSFTs to occur in the fleet.

The teardown and inspection of ex-service CBs was agreed to be a method of reducing the risks involved in the discreet modification program. Since the USN and CF had embarked on their own CBR programs before the RAAF, retired CBs were made available to DSTO for examination and testing from these sources.

The average size of the largest cracks present on ex-service CBs at retirement are expected to be less than 1 mm [4]. This is below the threshold of current practical Non-Destructive Inspection (NDI) methods, meaning that it is difficult to gain service data from ex-service CBs in their as-removed-from service condition. To overcome this obstacle, the Flaw IdeNtification through the Application of Loading (FINAL) program was initiated [5]. This ongoing program involves the application of representative Wing Root Bending Moment (WRBM) fatigue loads to ex-service CBs in a test rig. The fatigue cycling has been shown to grow existing flaws or cracks to a size where they may be readily detected under laboratory conditions. After fatigue cycling of each CB has been completed, a destructive teardown including disassembly, thorough inspection and Quantitative Fractography (QF) is performed. The data generated have addressed the following aims of FINAL:

- The determination of any in-service aircraft CB damage not accounted for in the FSFT program, including mechanical damage and corrosion that may have resulted from the service environment;
- Provided a more complete picture of the types of defects or degradation that lead to cracking in the fleet;
- Ensured that the decisions on the CBR program were based on as much relevant information about the structural integrity of the in-service CBs as possible; and
- Provided data that enhanced the current risk and reliability method deliberations with regard to the F/A-18 aircraft (e.g. see [4]).

Fatigue cycling of CBs

The ex-service CBs are cycled in the test rig shown in Figure 1 prior to teardown.

The rig was designed to simulate WRBM 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 at the wing attachment lugs. The WRBM produced by the actuators is transferred as a couple at the wing attachment lugs. The CBs are rotated by 90 degrees to allow them 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 each CB.

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 a bulkhead has failed by switching off the actuators attached to the failed bulkhead. As a result, each bulkhead is cycled until failure, maximising the amount of growth of existing flaws, thus increasing the chances of finding the maximum number of cracks.

A modified version of the mini-FALSTAFF (Fighter Aircraft Loading STAndard For Fatigue evaluation) sequence was generally applied to the test articles. The mini-FALSTAFF sequence is a truncated version of FALSTAFF, which was developed to represent the standard load history at the wing root of a fighter aircraft [7]. The sequence is equivalent to 200 flights of a standard fighter at the time of its development and was normalised by dividing each load by the maximum in the sequence. The FINAL fatigue sequence also had some of the mini-FALSTAFF flights rearranged to make it easier to interpret during QF. This was confirmed by a coupon testing program. To the latter CBs, the FT55 wing root bending moment sequence was applied.

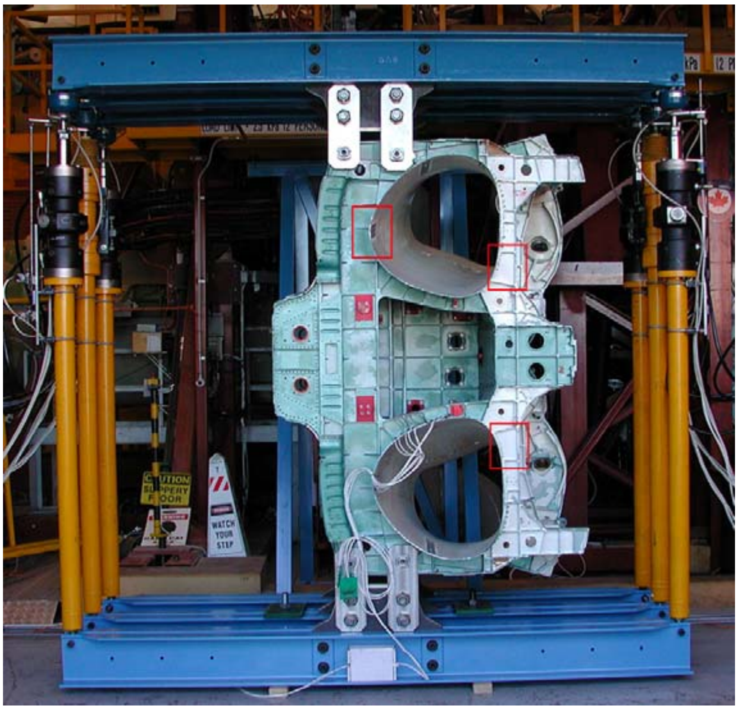

Figure 1 An F/A-18 Hornet CB mounted in the FINAL rig. The locations where the Y488 bulkhead of the first CB tested failed have been highlighted in red.

Instrumentation is applied to each test article to assess the distribution of load between the three bulkheads and to compare the applied loads to previous F/A-18 FSFTs.

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.

At the time of writing 16 CB had been tested at DSTO [6]. Many of the failures have been investigated and a wealth of information of direct relevance to the RAAF has been produced. A good deal of this information has been used to aid in the setting of new safe life limits (SLL) using the methods set out in the next Section.

Fatigue Crack Growth Lifing Philosophy

For highly stressed structures like combat aircraft the period of crack nucleation or initiation is normally an insignificant fraction of the total life [8], thus, there are only three aspects that influence fatigue life:

(a) The initial flaw or starting discontinuity size;
(b) fatigue crack growth rate; and
(c) critical crack size.

In many cases FT55 provided information on the initial flaw size and fatigue crack growth rates for locations where QF could be performed. To this was added the information gathered during the QF of the FINAL cracks as well as many other coupon cracks grown with the spectra of interest and with stress levels typical of the critical areas of the CB. The QF from all these tests showed that the form of the crack growth was typically exponential in nature, resulting in near to straight curves when plotted on a log crack size versus linear time scale plot (for example see [8]).

However, FT55 did not provide information on the critical crack sizes for damaged locations as the conservative nature of the test meant that any suspected cracks were repaired to avert potential failure, thereby changing the local configuration of the test article at these repair times. To address this unavoidable short coming, and in addition to the outcomes noted in the previous Section, FINAL has been used to determine the critical crack size of specific locations by: demonstrating the critical crack size through Residual Strength (RS) testing; or, growing cracks to failure (or to a large enough size) where the resultant QF data and analysis can be used to calculate the critical crack size under an RS load, and then the FT55 QF data can be extrapolated to this crack size using the exponential model.

In other cases where FT55 locations had no QF data, an initial flaw size of 0.01 mm (0.0004 inch) was assumed, since this value has been found to be a good representative size for the starting size of average cracks in CB bulkheads [9]. The pseudo critical crack size of these was conservatively estimated, typically by using a depth equivalent to the amount of material removed during the FT55 modification that removed the suspected crack. Due to the demonstrated behaviour of cracks at the same locations on FINAL CBs, the FT55 growth was modelled as exponential between the assumed initial flaw size and the estimated end size.

For some locations, the deficiency in the FT55 QF data was supplemented by in-service crack growth data that were determined by the QF, from suitable ex-RAAF CBs tested in the FINAL program [10].

Results

This safe-life reassessment resulted in a minimum life increase of 10% which led to a reduction of the number of required CB replacements, thus producing a saving of AU$400 million and a significant increase in aircraft availability.

CAFÉ

The Hornet's horizontal stabilators (composed of carbon fibre skins over an aluminium honeycomb core) are subject to in-service damage. Often this damage has been found to be marginally beyond current aircraft Structural Repair Manual (SRM) limits resulting in the retirement and replacement of these expensive items. A collaborative program with the Canadians (Canadian/Australian Flight control surface Evaluation: CAFÉ) is aimed at reducing the rejection rate of these control surfaces due to service damage and should allow currently rejected items to return to service and existing in-service items to remain in-service longer. As a result, it is expected that there will be a significant saving to the through life cost of these items.

In this program delamination damage beyond SRM limits will be induced into relevant areas of the horizontal stabilator (see Figure 2) and loads equivalent to a factored design limit load applied in a test rig in an attempt to demonstrate the structural integrity of the damaged stabilator. The testing will involve a number of ex-service stabilators with the bulk of this testing occurring in Canada. Means of inducing the desired damage sizes have also been developed by the Canadians. In addition to the static strength considerations, skin debonds have the potential to reduce the stiffness of the component to the point where flutter margins may be reduced. To address this concern DSTO is conducting Ground Vibration Testing (GVT) of pre- and post-damaged stabilators in order to assess any potential change in stiffness which might impact flutter boundary envelopes. The GVT set-up is shown in Figure 3.

It is expected that the damage limits will be expanded and that considerable savings in RAAF fleet maintenance costs will be realised in return for a small initial investment.

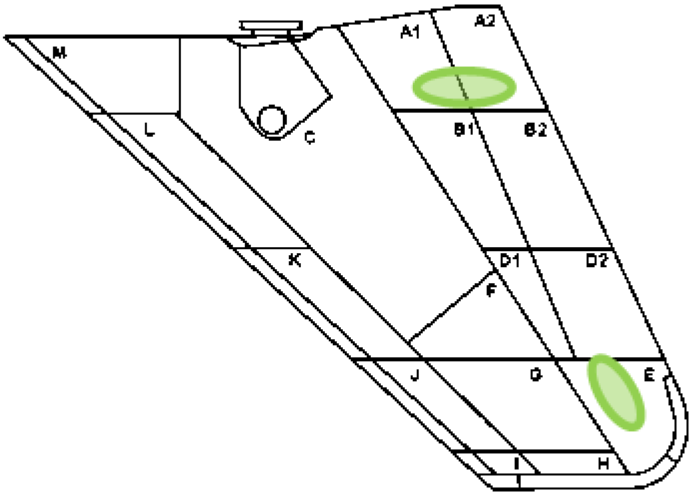

Figure 2: Typical horizontal stabilator test damage zones

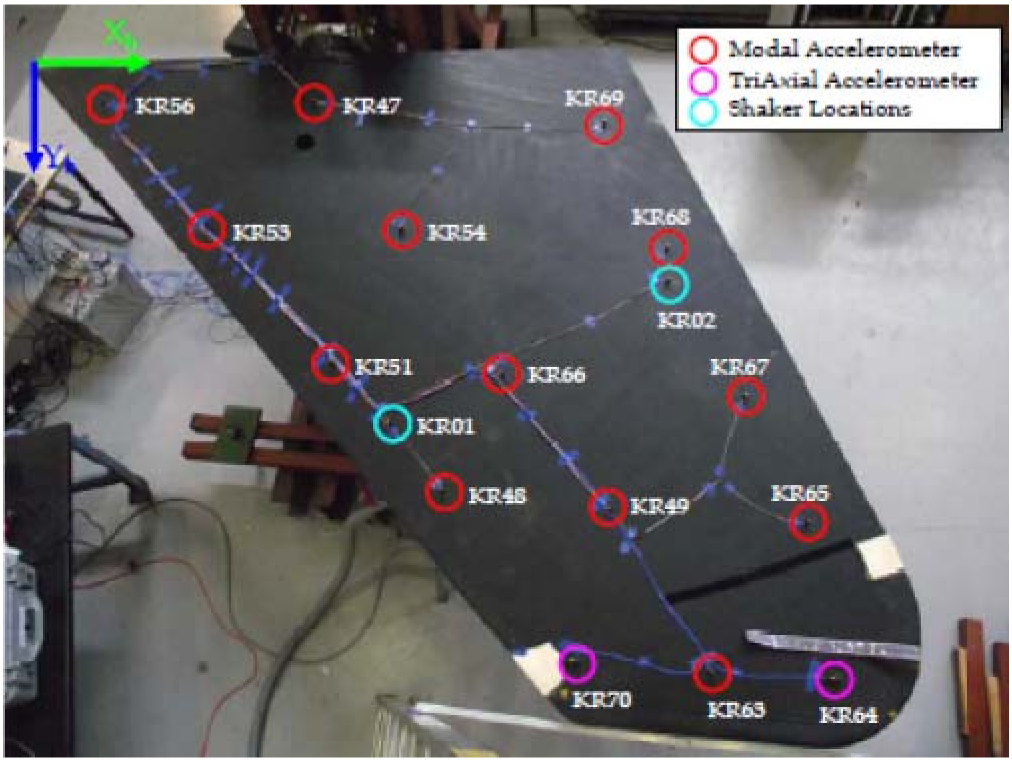

Figure 3 Top view of instrumented horizontal stabilator at DSTO

LEEP

The LAU-7A launcher is used on the F/A-18 A/B to carry ASRAAM missiles on the wingtip weapon stations. Fatigue cracking has commonly occurred at relatively low flight hours in the guide rail flanges adjacent to the forward hanger position (see Figure 4 and Figure 5) of the launcher housing. These have traditionally been addressed through replacement of the housing. The LAU-7 lifE Extension Program (LEEP) was established to develop a cost effective repair/modification procedure that could be approved for service, and would extend the useful life of the housings.

The repair chosen for development was an optimised shape rework procedure [12] involving cutting a profile designed to lower the stresses in the critical location and, for cracked housings, cut out the cracking to leave a similar optimised shape. As part of the evaluation of this re-work, a fatigue test program was devised to assess the effectiveness of the rework and the associated considerations. This testing was based on sectioning used rails into coupons (see Figure 6), and testing with representative loading.

The cracking generated in the test program was shown to be representative of that detected in service, thus providing confidence that the same test arrangement could be used to assess the effectiveness of the re-profiled launcher. The results show that a doubling of baseline life can be achieved through the re-profiling of previously unserviceable cracked housings. This could represent significant replacement cost savings for the RAAF. The same concept is currently being developed for the re-profiling of new housings, where an even greater life increase is envisaged This could represent significant replacement cost savings for the RAAF and the same technique has also been shown to recover previously unserviceable housings by using the same re-profiling to remove existing cracks.

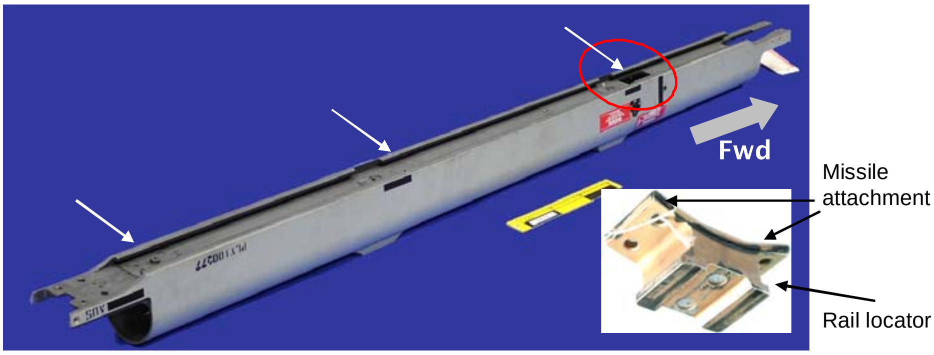

Figure 4   A LAU-7/A missile launcher housing showing the locations of the three missile hangers when a missile is fitted (white arrows). The area of concern is circled and a view of a forward hanger is shown in the inset.

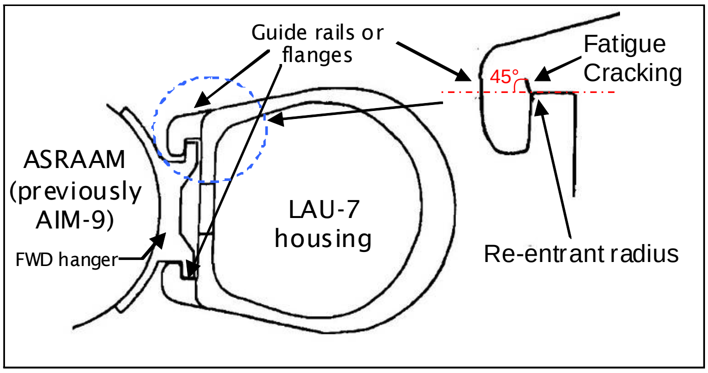

Figure 5   Schematic cross section of LAU-7/A launcher housing with a missile fitted, at the forward hanger position showing typical features. The critical location, where fleet cracking occurs is indicated in the expanded view of the upper rail, shown to the right.

Figure 6 Test section from a LAU-7 in a test machine.

HOWSAT

The IFOSTP FT245 wing test was successfully used to develop through life management strategies for nearly all of the critical structural components in the inner wing (IW). However, in the case of the outer wing (OW), difficulties have arisen when relating the FSFT result to fleet usage, primarily due to the highly variable buffet loading environment the assembly is routinely exposed to. Since the OW has a higher ratio of buffet to manoeuvre loading than the IW, test interpretation of the OW required overly conservative assumptions, which if applied would result in a through life management program that would be difficult and costly to implement. Additionally, damage modes other than fatigue have been identified as being the possible drivers in limiting the life of these components, and these need to be addressed in the final management plan for the OW.

Hence, there still remains a requirement to certify the structural life of the OW to the RAAF configuration, role and environment. The resultant management strategy must enable safe and efficient operation of the OW through to fleet retirement.

Since a detailed inspection of the interior of the OW requires wing skin removal, a Safety-By-Inspection (SBI) Through Life Management Strategy (TLMS) alone is undesirable as the time required to remove the skin would adversely impact aircraft availability. Hence, the Hornet Outer Wing StAtic Test (HOWSAT) program [11] was initiated to develop a safe TLMS that does not require skin removal and direct internal inspection. Another consideration is that at this stage in the fleet life, with a planned aircraft retirement of 2020, a follow-on component fatigue test is not likely to be feasible due to the complexity and duration of the test and subsequent timeframe available to implement the resultant maintenance strategy.

Assessing the available worldwide condition data for the OW was the first step in selecting an appropriate certification approach. Since a number of countries operating the F/A-18A/B have service life targets that are more ambitious than the RAAF, they have set up OW refurbishment lines. The results from the inspections carried out during these servicings, has supplied a large amount of condition data that covers both the internal and external components. A review of the condition data for the OW from both the RAAF and USN fleets indicated that corrosion and Stress Corrosion Cracking (SCC), not fatigue, has been the primary degradation mechanism in this assembly. The implication of this finding is that further FSFT would not be useful, because it would not be able to reproduce the corrosion and SCC related degradation that is likely to define the economic and structural life of the OW.

Therefore, a static test program that aims to investigate the level of load path redundancy, and by extension validate a 'fail safe' management strategy, was found to be the most appropriate approach to underpin the certification of the OW. This decision was based on both the findings from the condition data assessment and the RS test of the Hornet A/B wing (both the IW and OW), conducted after the FT245 fatigue test, which indicated that there is a significant positive margin in static strength[1]. Although the FT245 wing survived the applied 1.5 DLL, it was later found that the absence of adequate buffet information (at the time of the testing) suggested that loading on the wing tip had been insufficient to demonstrate that 1.5 DLL (buffet plus manoeuvre load equivalent) had actually been achieved for the OW. Nevertheless, the inherent strength and damage tolerance of the IW, which is attributed primarily to the thick carbon-epoxy composite wing planks enclosing the top and bottom of the wing box suggests that the OW structural design and composition
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[1] The wing assembly survived without unacceptable deformation the application of 1.5 DLL after 3.1 lifetimes of fatigue testing had been completed and the lower cap of the front spar was severed [2].

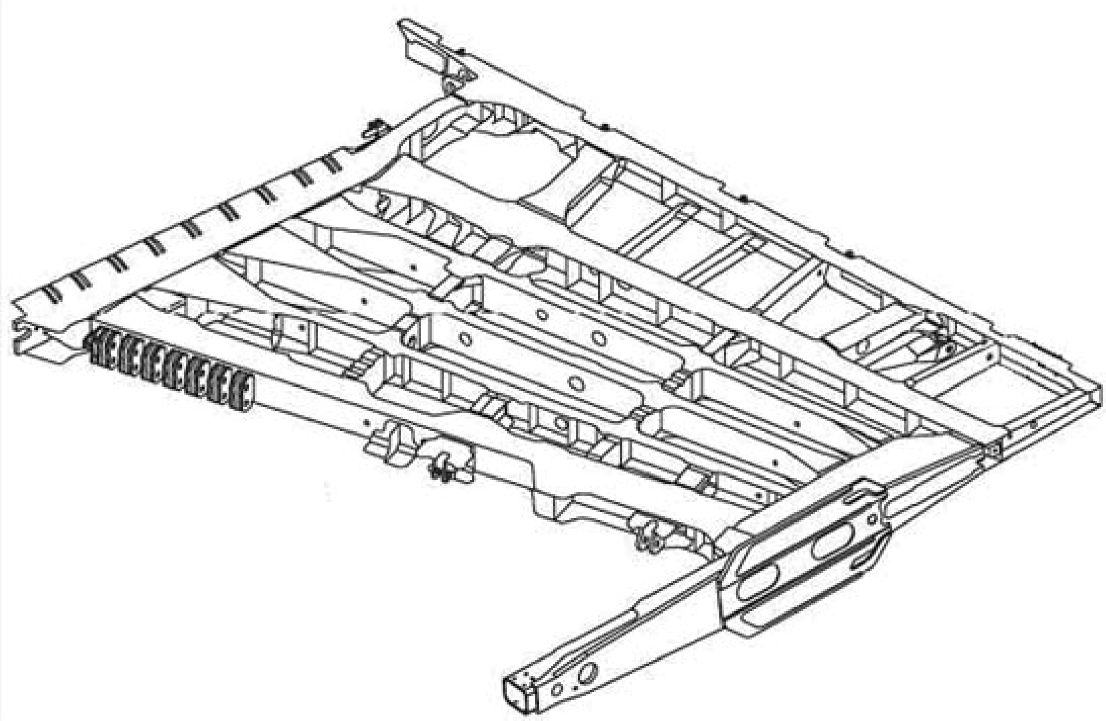

Figure 7), being similar to that of the IW, will have comparable margins on durability, strength and structural redundancy to meet the higher loads with considerably more damage included. Hence, the aim of this static test program is to demonstrate the fail safe capability of the OW torque box assembly with significant representative damage to either clear it for full life, or implement inspections designed only to detect gross cracking of the internal structure, thereby assuring the structural integrity of the F/A-18A/B OW until planned withdrawal date. The test article will also be used to validate planned inspection procedures. A schematic of the HOWSAT loading arrangement is shown in Figure 8.

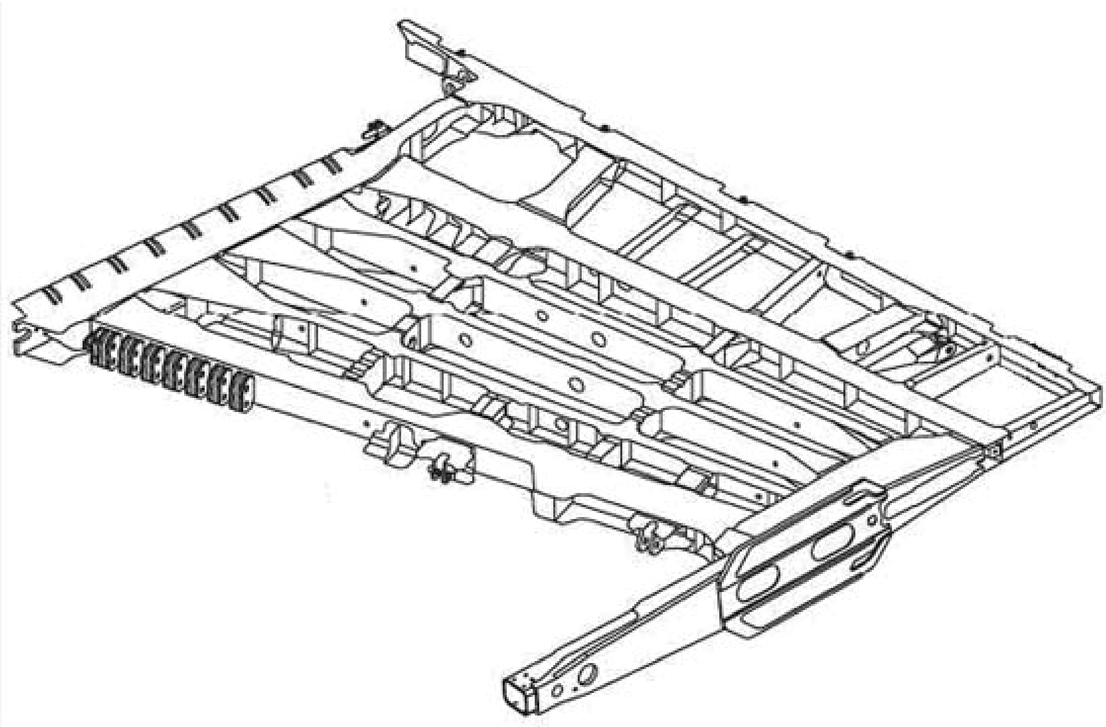

Figure 7 F/A-18 Outer wing internal structural layout

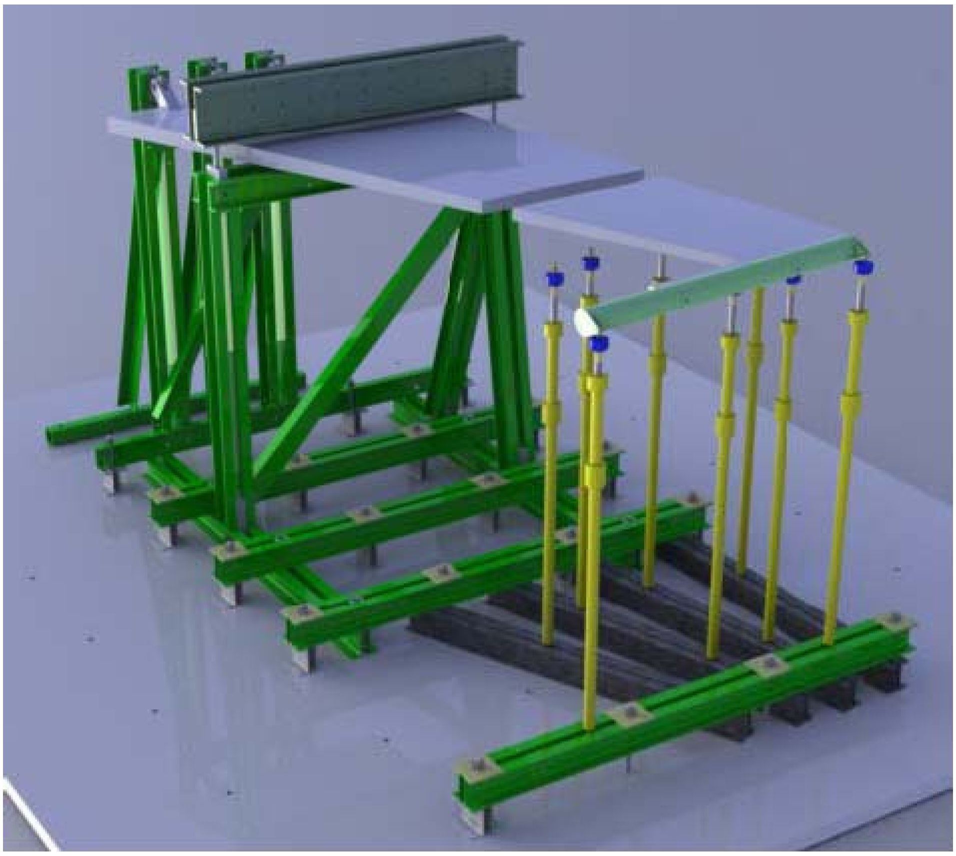

Figure 8 Schematic of the HOWSAT loading arrangement

Through this OW testing it is expected that considerable savings and increased availability will be achieved when compared to an inspection and refurbishment program that would have involved wing cover removal and the repair of minor damage.

Conclusion

A series of structural integrity tests have been initiated by DSTO, DGTA and DMO (supported by the CF and USN) in an attempt to reduce sustainment costs in the latter years of RAAF Hornet operations. These tests cover, among others, three major areas of the aircraft: the Centre Barrel (CB) that acts as the wing attachment structure, the outer wings and the attached missile launchers, and the horizontal stabilators. This paper presented a brief description of each of these test programs and summarised the savings to the RAAF that have been or are likely to be achieved. This work is aimed at satisfying the intent of Defence's Strategic Reform Program whilst ensuring the safe operation of the aircraft is not compromised.

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