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SKORAŠNJA ISPITIVANJA NA ZAMOR REALNIH SKLOPOVA F/A-18 U AUSTRALIJI

RECENT AUSTRALIAN FULL-SCALE F/A-18 FATIGUE TESTS

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- defects (materials)
- buffet loadings

Izvod

Poslednjih godina Australija je uključena u brojne programe ispitivanja na zamor realnih sklopova radi podrške integritetu konstrukcija aviona F/A-18 Hornet tokom eksploatacijskog veka flote Kraljevskih australijskih vazduhoplovnih snaga (RAAF). Uočeno je rano, u toku prijemnih ispitivanja, da verifikaciona ispitivanja proizvođača teško mogu da pokriju mnogo oštrije i drugačije eksploatacijske uslove RAAF. Isti stav su imale i Kanadske snage (CF). S obzirom na sličnu filozofiju upravljanja integritetom konstrukcija u obe zemlje, dve strane su ocenile da se saradnjom može postići velika korist. Posebno, kako se u obe zemlje smatra da je suštinska osnova za upravljanje integritetom zamorno ispitivanje reprezentativnim CF/RAAF opterećenjem, prihvaćen je Međunarodni projekt dodatnih ispitivanja konstrukcija (IFOSTP). Nadalje, zbog odsustva eksploatacijskih oštećenja (npr. korozija, mehanička oštećenja) pri ovim laboratorijskim ispitivanjima, smatralo se da je tumačenje njihovih uticaja rizično. Da bi tumačenje ovih uticaja bilo ispravno i da bi se smanjio rizik od slepog prihvatanja rezultata ograničenog obima ispitivanja, glavni okviri centralnog dela trupa, kome je istekao eksploatacijski vek, ispitani su na zamor i izvedena je detaljna inspekcija eksploatacijskih oštećenja. Posle toga su izvedena dodatna ispitivanja podkomponenti kroz program smanjenja broja opravki aviona u toku eksploatacije, radi dostizanja planiranog veka i utvrđivanja delova aviona koji više ne ispunjavaju početne projektne zahteve zbog izmena u toku eksploatacije. Neka od ovih ispitivanja su prikazana.

U ovom radu su istaknute australijske komponente IFOSTP, unapređen postupak inspekcije konstrukcija povučenih iz eksploatacije i nekoliko ispitivanja podkomponenti nakon inspekcije. Objašnjene su neke inovacije i posledice ovog programa. One mogu biti primenjive u budućim programima integriteta avionskih konstrukcija.

Abstract

Over recent years Australia has been involved in a number of full-scale fatigue testing programmes in support of the through-life structural integrity of the Royal Australian Air Force (RAAF) F/A-18 Hornet fleet. It was recognised early in the acquisition cycle that the certification testing conducted by the manufacturer would be unlikely to cover the typically more severe and diverse RAAF operations. The Canadian Forces (CF) also shared this position. Given similar aircraft structural integrity management philosophies, both parties foresaw that major benefits could be realised through collaboration. In particular, as the basis for both countries' structural integrity management, fatigue testing under representative loading CF/RAAF was considered as essential, thus the International Follow-On Structural Test Project (IFOSTP) was born. Subsequently, the lack of in-service induced degradation (e.g. corrosion, mechanical damage) in these laboratory tests was identified as a risk for their interpretation. To address these interpretation issues and to reduce the risk of blindly accepting the results of limited testing, fatigue life expired ex-service centre fuselage bulkheads were fatigue cycled and torn down to inspect for in-service degradation. After that, additional sub-component tests were carried out as part of a programme to reduce the numbers of repairs the aircraft required during service to meet its planned withdrawal date and to address regions of the aircraft that no longer meet the original design requirements due to in-service modifications. Some of these tests are described.

This paper emphasises the Australian components of IFOSTP, the enhanced teardown of ex-service structure and several sub-component tests born from the teardown testing. Several of the innovations and consequences of this work programme are highlighted. These may be applicable to future aircraft structural integrity programmes.

UVOD

MekDonal Daglas (Boing) (izvorni proizvođač opreme – OEM) isporučio je Kanadskim snagama (CF) i Kraljevskim australijskim vazduhoplovnim snagama (RAAF) 210 aviona F/A-18 koji su isporučeni od 1982. do 1990. godine.

INTRODUCTION

To the Canadian Forces (CF) and the Royal Australian Air Force (RAAF), 210 F/A-18 aircraft were purchased by McDonnell Douglas (Boeing), (Original Equipment Manufacturer – OEM), with deliveries from 1982 till 1990.

U obe zemlje se avioni koriste na sličan način, različit od načina korišćenja u američkoj mornarici (USN). Verifikaciona ispitivanja za USN su izvedena na osnovu operacija sa nosača aviona, sa spektrom definisanim načinom upotrebe u USN, koji je za najveći broj delova primarne strukture značajno blaži u poređenju sa spektrom RAAF i CF. Sem toga, postoje značajne razlike u konfiguraciji CF/RAAF flota i opitnog uzorka korišćenog za verifikaciona ispitivanja. Ovo je dovelo do problema u određivanju eksploatacijskog veka aviona. Kako je filozofija upravljanja integritetom konstrukcije aviona (ASI) slična, zasnovana na Britanskom standardu odbrane 00-970, /1/, obe strane su sagledale velike prednosti koje se mogu postići saradnjom u zajedničkom programu ispitivanja na zamor realnih sklopova, koja bi se izvodila sa reprezentativnim CF/RAAF opterećenjem. Program je poznat kao Međunarodni projekt dodatnih ispitivanja konstrukcija (IFOSTP), a rezultati su baza za upravljanje integritetom ASI za avione F/A-18 u obe zemlje. Ovaj projekt visoke tehnike podstakao je brojna ispitivanja na zamor realnih sklopova. Mnoga od njih su bila moguća samo zbog prirode saradnje u IFOSTP, /2/. Uvedene su značajne inovacije:

– prva primena spektra sa redosledom opterećenja dobijenim direktno iz upotrebe aviona sa digitalnim komandnim sistemom pri različitim zakonima upravljanja i u slobodnom manevru;
– razvoj metodologije parametarske formulacije opterećenja (PLF) koja omogućuje tačno određivanje opterećenja glavnih sekcija iz podataka leta za svaki manevar u velikom spektru i reprodukciju raspodele opterećenja u vremenu primenom podataka dobijenih pri korišćenju aviona;
– razvoj metode raspodele opterećenja za ispitivanje krila, koja uzima u obzir uticaj velikih komandnih površina i optimiziranu raspodelu, kao i klasično prihvaćenu raspodelu po tetivi i razmahu;
– prva uspešna primena sinhronizovanih manevarskih i dinamičkih opterećenja, tipičnih za uslove leta, koja deluju na komponente pri ispitivanju kompletnog aviona;
– razvoj jedinstvenog pneumatskog sistema za uvođenje manevarskih opterećenja (meka opruga) sa tačnim i brzim odzivom kontrolera;
– projekt i razvoj komandnog sistema za ispitivanje repnih površina (FT46), koji omogućuje upravljanje sa 67 različitih aktuatora (pneumatskih, elektromagnetskih, hidrauličkih), od kojih su mnogi kanali sa značajnim međudejstvom;
– primena komandnog i akvizicionog sistema pri ispitivanju krila (FT-245) sa novim načinom provere greške u krajnjim tačkama segmenata opterećenja i načinom prikazivanja, uključujući i sofisticirani on-lajn trend monitoring;
– unapređena primena lepljenih kompozitnih zakrpa za opravke u području alata pri razvoju projekta, kao i za moguće opravke visoko opterećenih komponenti složenog geometrijskog oblika sa prslinom;
– unapređenje kvantitativne fraktografije (QF) koja, za poznate lokalne napone, može tačno da predvidi vreme do loma komponente iz ograničenih podataka o rastu prsline;
– primena nove tehnologije i baza podataka za memorisanje, pretraživanje i katalogizaciju zamornih ispitivanja.

Time su dobijeni pogodni alati za upravljanje flotom.

Both countries operate the aircraft in similar roles that are different from its role in the United States Navy (USN). The USN certification test was performed for carrier based operations, with a USN specified design usage spectrum that is significantly less severe for most primary structural elements, compared to that of the RAAF and CF. Additionally, there were significant configuration differences between CF/RAAF fleets and the certification test article. These issues led to concerns over the determination of the useful life of the airframe. Given their similar aircraft structural integrity (ASI) management philosophies, based on the UK defence standard 00-970, /1/, both parties saw that major benefits could be realised through collaboration in a joint programme of full-scale fatigue testing conducted under representative CF/RAAF loading. This is known as the International Follow-On Structural Test Project (IFOSTP) and the results became the basis for F/A-18 ASI management in both countries. This highly technical project fostered many initiatives for full-scale fatigue testing. Many of these tests were only feasible due to the collaborative nature of IFOSTP, /2/. The significant innovations achieved included:

– 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 Parametric Loads Formulation (PLF) methodologies that allowed accurate prediction of major section loads for each flight manoeuvre in a very large spectrum and the recreation of load distributions on a continuous time base using operational flight data;
– development of load distribution methods for the wing test that accounted for large control surface effects and optimised chordwise as well as the traditional spanwise distributions;
– the first successful simultaneous application of coordinated dynamic and manoeuvre loads typical for flight conditions on multiple components of a full aircraft test structure;
– development of a unique pneumatic manoeuvre loading system (soft spring) with accurate and fast response controllers;
– design and development of a control system on the empennage test (FT46) capable to control 67 different actuators (pneumatic, electromagnetic, hydraulic) with many channels and significant actuator interaction (dependency);
– implementation, on the wing test (FT-245), of a control and data acquisition system with new end point error checking and notification processes including sophisticated online 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 of geometrically complex components;
– advancement of Quantitative Fractography (QF) that allowed, knowing local stresses, its use to accurately predict component time to failure from limited crack growth data;
– application of evolving technology and use of databases to store, retrieve and catalogue the rests of fatigue testing.

This has led to several useful fleet management tools.

Posle analize rezultata prvih ispitivanja IFOSTP bilo je jasno da je vek u nekim slučajevima ispod zahtevanog. Ovo je uočeno na sekciji centralnog dela trupa, gde je zahtevana sanacija konstrukcije lokalnom opravkom i/ili po programu zamene podstrukture centralnog dela trupa (CBR) u toku veka aviona. Iako je ispitivanjem utvrđen vek, ipak postoji izvestan rizik od ad hok modifikacija izvedenih zbog pojave problema tokom veka flote, jer izvršena ispitivanja ne obuhvataju oštećenja u eksploataciji (npr. korozija, mehanička oštećenja). Ovo je bilo moguće utvrditi rastavljanjem podstrukture centralnog dela trupa (CB) povučenih iz eksploatacije. Zamorni vek povučenih glavnih okvira (gotovo kompletna podstruktura) je dobijen od USN i CF, i nedavno iz RAAF programa zamene CB. Ove podstrukture su dodatno ispitane na zamor i rastavljene za inspekciju oštećenja u eksploataciji. Ovaj program je nazvan *Otkrivanje prslina pod dejstvom opterećenja* (FINAL). Takav program se normalno ne izvodi pri zamornom ispitivanju realnih sklopova, iako je u ovom slučaju interesantan zbog dostupnih korišćenih CB, kao i predviđenog rizika od nekih nepoznatih faktora koji utiču na interpretaciju zamornog veka. Program FINAL je opisan i neki rezultati su diskutovani.

Sledeći prvobitni koncept smanjenja rizika FINAL programa, podaci ispitivanja na zamor pre rastavljanja i dodatnih ispitivanja podkomponenti, omogućili su da se smanji broj opravki aviona u eksploataciji, zahtevanih radi dostizanja planiranog datuma povlačenja iz upotrebe. Ova su ispitivanja ukazala na sekcije aviona koje ne ispunjavaju originalne projektne zahteve zbog izmena u eksploataciji i sekcije sa kratkim vekom zbog opravki (neizbežnih u to vreme zbog nesigurnosti u pogledu rasta prslina) izvedenih tokom ispitivanja na zamor realnih sklopova sa prslinama manjim od kritične. I neka od kasnijih ispitivanja su opisana u radu.

MEĐUNARODNI PROJEKT DODATNIH ISPITIVANJA KONSTRUKCIJA

Analiza početne upotrebe F/A-18 u RAAF pokazala je da se zamorna oštećenja razvijaju brže nego što je pri projektovanju predviđeno. U stvari, utvrđeno je da se prosečno može ostvariti samo dve trećine početno zahtevanog veka aviona bez dodatnih verifikacionih ispitivanja. To je imalo velike eksploatacijske i ekonomske posledice.

Kod proizvođača je na konstrukciji aviona izvedeno više ispitivanja na zamor, ali je ocenjeno da ona nisu dovoljno reprezentativna iz sledećih razloga:

– i kod CF i kod RAAF se način upotrebe bitno razlikuje od pretpostavljenog pri projektovanju;

– značajne su razlike između konfiguracija OEM opitnog uzorka i aviona CF/RAAF;

– mnoge rekonstruisane komponente su uvedene samo na osnovu analize;

– pristup USN verifikacionom ispitivanju, uz primenu oštrog spektra izvedenog iz tri najnepovoljnija „slučaja u letu (PITS)“ i sa faktorom rasipanja dva, nije u skladu sa politikom zahteva plovidbenosti CF i RAAF;

– kod proizvođača je opterećenje u ispitivanju zamora zadnjeg dela trupa od baftinga trupa i repa kvazistatičko;

– proizvođač nije uzeo opterećenja od baftinga spoljnjeg dela krila, krilca i zakrilca u ispitivanju na zamor krila;

After analysis the results of first tests in IFOSTP it was clear that the life of some items was below the required. These locations were found in the centre fuselage region requiring structural refurbishment by discreet repair and/or a centre barrel replacement (CBR) programme in the aircraft's life. Having established lives by test, there was still a small risk of ad hoc modifications being required due to problems arising during the fleet life since the tests lacked in-service induced degradation (e.g. corrosion, mechanical damage). It became possible to address this risk by the teardown of ex-service centre barrels (CB). Fatigue lives of expired centre fuselage bulkheads (almost complete centre barrels) were available from USN and CF, and recently from the RAAF CB replacement programme. These centre barrels were further fatigue cycled and torn down to inspect for in-service degradation. This programme is called Flaw IdeNtification through the Application of Loads (FINAL). Such programme is not usually included in a full-scale fatigue testing, although in this case is attractive due to the available used CBs, along with the foreseen risk of several unknown factors affecting interpreted fatigue lives. The FINAL programme is described and some results discussed.

Subsequent to the original FINAL risk reduction concept, the data from fatigue testing prior to the teardowns and additional sub-component testing has allowed a reduction in the repair numbers of the aircraft required in service to meet its planned withdrawal date. These tests revealed the aircraft regions that do not meet the original design requirements due to in-service modifications and areas of short lives dictated by repairs (unavoidable at the time due to uncertainties of crack growth) carried out during the full-scale fatigue tests at crack sizes well below the critical size. Some of further tests are also described in this paper.

INTERNATIONAL FOLLOW-ON STRUCTURAL TEST PROJECT

Analysis of initial usage of the F/A-18 in RAAF service revealed that the aircraft were accumulating fatigue damage faster than predicted by the design. In fact, it was found that on average, only two thirds of the initial required aircraft life can be achieved without additional certification testing. This had immense operational and economic implications.

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 were significantly different to that assumed during design;

– configuration differences between OEMs test articles and CF/RAAF aircraft are significant;

– many redesigned components were used based on analysis only;

– 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 manufacturer's fatigue aft fuselage testing included aft fuselage and empennage buffeting by quasi-static loading;

– the manufacturer's wing fatigue testing did not include buffeting of the outer wing, aileron and trailing edge flap;

– dozvoljena oštećenja i sigurnost od otkaza (kao i preostala čvrstoća) nisu razmatrani pri ispitivanju kod proizvođača.

Osnova IFOSTP je da reprezentativno ispitivanje omogućuje mnogo ekonomičniji vek, održavanje i opravke, izbegavajući konzervativno tumačenje ranijih ispitivanja.

IFOSTP uključuje tri ispitivanja na zamor realnih sklopova i prateća ispitivanja pojedinih komponenti. Ispitivanja centralnog dela trupa (FT55) i krila (FT245) su izvedena u Kanadi, a ispitivanja zadnjeg dela trupa i repova (FT46), kao i dva pojedinačna ispitivanja okvira centralnog dela trupa (FT488/1 i FT488/2), su izvedena u Australiji. U obe zemlje su izvedena brojna dopunska ispitivanja uzoraka po posebnom programu, kao što je saopšteno, na primer u /3/.

Spektri opterećenja su kompromis dve flote i smatraju se realističnim i tipičnim za njihov način eksploatacije. Kao podršku tim ispitivanjima u obe zemlje je izveden niz obimnih probnih letova, /4/. Ovi podaci, sa podacima snimljenim u letu aviona flote, numeričkom analizom dinamike fluida i podacima iz aerotunelskih ispitivanja, korišćeni su za definisanje spektara i raspodela opterećenja.

Usaglašeni ciljevi ovih ispitivanja su bili:
– odrediti ekonomični vek, i u tom procesu, siguran vek primarne strukture izložene reprezentativnom CF/RAAF spektru opterećenja;
– dobiti, gde je moguće, podatke o rastu prsline za podršku upravljanju prema sigurnosti na osnovu inspekcija;
– overiti modifikacije i opravke, i
– sačiniti inženjersku bazu podataka za upravljanje ciklusom veka sve do povlačenja iz eksploatacije.

Ispitivanja okvira za vezu krilo-trup centralnog dela trupa

Kod aviona F/A-18 opterećenja krila se prenosi na CB u trup preko tri glavna strukturna elementa, okvira Y453, Y470.5 i Y488 (sl. 1). Ovi okviri su kritični u pogledu loma i lom bilo kojeg od njih može dovesti do gubitka aviona. Oni su izrađeni od legure aluminijuma 7050-T7451.

Okvir Y488 je polomljen više puta pri OEM ispitivanju trupa na zamor, zbog čega je više puta rekonstruisan i uvedeni su poboljšani tretmani kritičnih područja u pogledu zamora (povećana otpornost na zamor).

Pre početka tri IFOSTP ispitivanja, kao prirodni razvoj OEM ispitivanja na zamor, dva okvira Y488 su ispitana na zamor u Organizaciji za odbrambenu nauku i tehnologiju (DSTO) u Australiji, radi provere uspešnosti uvedenih modifikacija. Ovo je bilo zahtevano jer su opravke okvira u eksploataciji bile različite od onih u OEM ispitivanju.

Da bi se ispitale rekonstrukcije i poboljšanja Y488 okvira, OEM je izveo nekoliko pojedinačnih ispitivanja okvira Y488 na zamor, koja su konačno pokazala marginalnu saglasnost sa zahtevima USN. Ova ispitivanja su izvedena sa USN projektnim spektrom, bez primene postupaka za poboljšanje kritičnih površina u pogledu zamora mlazom staklenih kuglica. Svi kanadski i polovina RAAF aviona su sa ugrađenim originalnim okvirima Y488 koji ne ispunjavaju zahteve, pa su okviri modifikovani u eksploataciji. To znači da može da dođe do značajnog rasta zamornih prslina u kritičnim zonama pre primene ove modifikacije u floti. Da bi se ovo ispitalo, DSTO je izveo zamorna ispitivanja originalnog okvira Y488 i modifikovao ga u fazi ispitivanja koja odgovara vremenu modifikacije izvedene u floti.

– damage tolerance and fail-safety (and residual strength too) had not been considered in the manufacturer's testing.

The basis of IFOSTP is that a representative test would allow more cost effective living, maintenance and repair, avoiding conservative interpretations of previous tests.

IFOSTP consisted of three major full-scale fatigue tests, and supporting stand-alone component tests. The centre fuselage test (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. Both countries also carried out many supporting coupon test programmes, as reported, for example in /3/.

The test spectra were a compromise between the two fleets and considered realistic and typical of their in-service usage. In support of these tests, both countries conducted a series of comprehensive flight trials, /4/. 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 spectra and load distributions.

The agreed objectives of the programme 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.

Stand-alone centre fuselage wing carry-through bulkhead tests

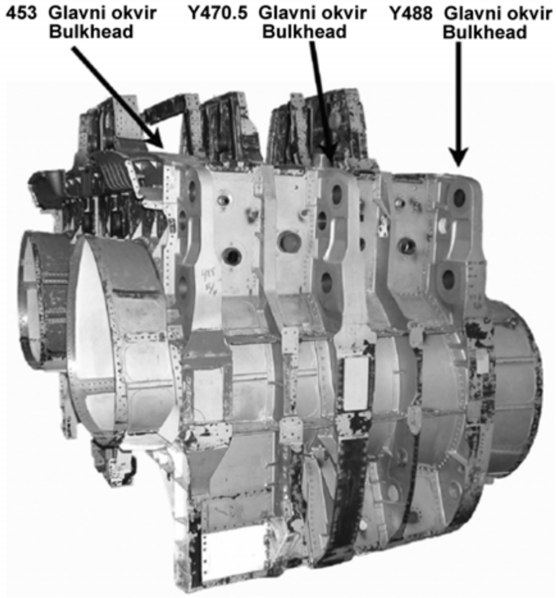
The F/A-18 CB carries wing loads into the fuselage by its three main structural elements, the Y453, Y470.5 and Y488 bulkheads (Fig. 1). These bulkheads are fracture critical and loss of structural integrity in any of them may cause the loss of the aircraft. They are made from 7050-T7451 aluminium alloy.

The Y488 bulkhead failed several times during the OEM full-scale fatigue test, which led to it being redesigned several times with the inclusion of fatigue enhancing treatments (improving fatigue resistance) to critical areas.

Prior to the start the three IFOSTP tests, as a natural progress in OEM fatigue testing, two Y488 stand alone bulkhead fatigue tests were performed at the Defence Science and Technology Organisation (DSTO), Australia, to cheque the effectiveness of modifications. This was required since in service bulkhead repairs differ from that in OEM test.

To test the redesigns and enhancements of Y488 bulkhead, the OEM carried out several Y488 stand-alone bulkhead fatigue tests, which finally indicated marginal compliance with USN requirements. These tests were performed by USN design spectrum, without the fatigue enhancement treatment, glass bead peening of the critical area. All the Canadian and half the RAAF aircrafts had been built with the original Y488 bulkhead shape that had not met the requirements, so the bulkheads were modified in service. For that a lot of fatigue crack growth could occur in the critical area prior to the in-fleet modification applied. To cheque this, DSTO performed a Y488 stand-alone bulkhead fatigue test with pre-modification bulkhead, modified during the test at the time corresponding to the fleet modification time.

Projektni spektar USN je korišćen da se simulira poslednje pojedinačno OEM ispitivanje na zamor okvira Y488. Uređaj DSTO za pojedinačno ispitivanje na zamor okvira Y488 sa postavljenim uzorkom je prikazan na sl. 2.



Slika 1. Podstruktura centralnog dela trupa povučenog iz CF, ispitana u programu FINAL, sa tri glavna okvira za vezu krilo-trup
Figure 1. A central barrel of ex-CF used in the FINAL programme with the three main bulkheads of attached wings.

Prvim DSTO pojedinačnim ispitivanjem na zamor Y488 (FT488/1) je ostvaren cilj, jer je pokazalo da predloženo kašnjenje prerade okvira u floti ne smanjuje zamorni vek, kako je nađeno ranije OEM ispitivanjem. Vek ispitanog okvira je sličan veku iz poslednjeg OEM ispitivanja, a lom se javlja u sličnom zoni, pa su ova dva ispitivanja saglasna.

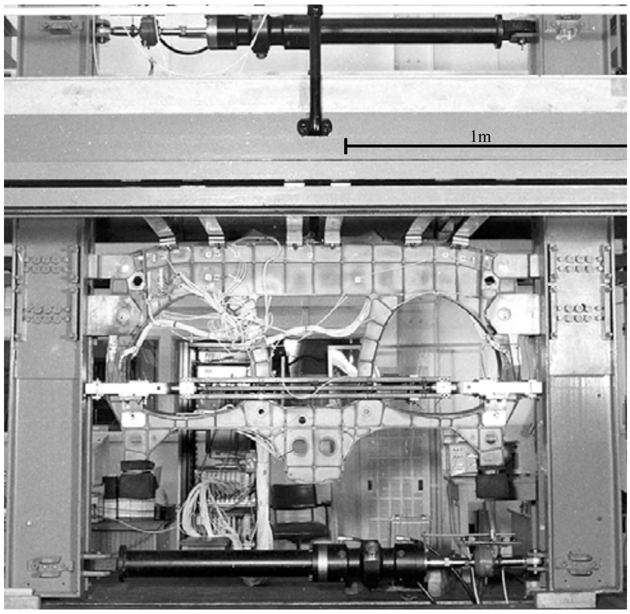
Analiza je pokazala da je lom krenuo iz prsline nastale na plitkom radijusu, za razliku od rupa za vezne elemente koje su, na ranijim lovcima i drugim civilnim i vojnim avionima najvažniji izvor zamornih prslina, /5/. Izgleda da je to rezultat prikladnog projektovanja i preventivnih mera u pogledu zamora kao što su presovani sklopovi, hladno kovanje ivice otvora, utiskivanje čaura u otvor i proširivanje otvora za vezne elemente na hladno u kritičnom području.

Ovaj oblik prslina na avionu F/A-18 je preovlađujući na čitavom trupu.

Drugo DSTO pojedinačno ispitivanje na zamor okvira Y488 (FT488/2) je izvršeno u istom uređaju kao i prvo. Modifikovani okvir, čije su kritične površine ojačane mlazom staklenih kuglica, ispitan je sa oštrijim spektrom FT55, tipičnim za letove CF i RAAF.

Ovo ispitivanje je pokazalo da modifikovano kritično područje okvira ima adekvatan vek sa spektrom FT55, iako oštećenje na površini obrađenoj mlazom staklenih kuglica (ovde zbog odstranjenog tankog površinskog sloja za lepljenje mernih traka) može da prouzrokuje neodgovarajući vek, što zahteva veću brigu o oštećenjima u eksploataciji i kontrolu kvaliteta procesa izlaganja mlazu staklenih kuglica (poslednji primer u ovom članku). Ovaj je nalaz takođe primenjen na opitni uzorak FT55 da bi se izbegla pojava nereprezentativnih otkaza.

The USN design spectrum was used to simulate the last of the OEM Y488 stand-alone bulkhead fatigue tests. The DSTO Y488 stand-alone bulkhead fatigue test rig with one of the test pieces positioned is shown in Fig. 2.



Slika 2. Uređaj za ispitivanje na zamor okvira Y488 sa postavljenim uzorkom. Opterećenje se uvodi gornjim i donjim aktuatorom
Figure 2. Y488 stand- alone bulkhead fatigue test rig with an article fitted. Loading is involved via upper and lower actuators.

By the first DSTO Y488 fatigue test (FT488/1) its goal is achieved, showing that the proposed delay in the fleet bulkhead rework would not reduce the fatigue life, as found by the previous OEM testing. The life of the bulkhead tested was similar to that of the last OEM tests and it failed in a similar area, confirming consistency between the tests.

The analysis has shown that the fracture initiated from a crack induced in a shallow radius as distinct from fastener holes that were, in previous fighter and other civil and military aircrafts, the most significant fatigue cracking source, /5/. This could be the result of efficient design and the use of fatigue preventive measures, such as interference fit fasteners, cold coining around holes, holes force mate bushings and fastener hole cold expansion in critical area.

This cracking type of F/A-18 aircraft is prevalent in the entire fuselage.

The second DSTO Y488 stand-alone bulkhead fatigue test (FT488/2) was performed in the same rig as the first one. The test was conducted for the modified bulkhead with glass bead peened critical areas, when loaded with the more severe FT55 test spectrum, typical of CF and RAAF flying.

This test revealed that the modified critical region of the bulkhead appeared to have adequate life with the FT55 spectrum, although damage to the peened surface (here as the result of a small amount of surface material removed for strain gauges application) could result in an inadequate fatigue life, thus raising concerns about in-service damage and quality control of the peening process (the final example in this paper). This finding was also applied to the FT55 test piece to mitigate against non-representative failure.

Svako od ovih ispitivanja je izvedeno do loma, i svaka nađena reprezentativna zamorna prslina je ispitana pomoću QF da bi se odredila brzina rasta prsline, oštrina lokalnog napona i vrsta i priroda diskontinuiteta iz kojih je prslina nastala.

ISPITIVANJE CENTRALNOG DELA TRUPA FT55

Razvoj spektra

Svi avioni F/A-18 su opremljeni sistemom zapisa podataka signala održavanja (MSDRS) i sistemom digitalnog upravljanja letom (DFCS). Sistem MSDRS je razvijen radi praćenja eksploatacije iz aspekta zamora, beleženja incidenata u letu, podataka o radu motora i održavanju. Uređaj se koristi za prikupljanje podataka o opterećenju u spektru i za praćenje svakog aviona, da se zbirno oštećenje poveže sa spektrom IFOSTP ispitivanja opitnih uzoraka.

Kanadski spektar za centralni deo trupa/krilo je definisan na bazi manevra i PITS primenom programa za identifikaciju manevra, /4/. Ovaj program prvo eliminiše sve periode neaktivnog letenja određivanjem segmenata vremena kada je brzina valjanja aviona blizu nule, napadni ugao (AOA) manji od 10° i normalno ubrzanje oko 1. Svi ostali segmenti vremena su utvrđeni ili kao standardni manevar (skretanje, propinjanje, poniranje, vađenje iz poniranja ili valjanje) ili kao nestandardni manevar. To je postignuto merenjem „g“ opsega, proračunom uglova u toku valjanja i beleženjem smera valjanja i sekvenci brzina obrtanja i „g“ pikova i udolina, a zatim poređenjem ovih podataka sa prethodno definisanim karakteristikama manevra. Rezultat je redosled simulaciju manevara pri ispitivanju centralnog dela trupa.

Proces identifikacije manevara rezultirao je ogromnim brojem pojedinačnih manevara. Prvobitna namera je bila da se grupišu manevri primenom definisanih parametara leta i granicama zakona upravljanja, pa bi bila razumna pretpostavka da su opterećenja za sve manevre u grupi ili konstantna ili se mogu jednostavno ekstrapolirati. Opterećenja se tada u svakoj tački promene reprezentativnog manevra u grupi proračunavaju kombinujući MSDRS i izmerene letne podatke, podatke modela numeričke dinamike fluida (CFD) i podatke iz aerotunela.

Zbog neprikladnog alata analize za predviđanje opterećenja u režimima velikih napadnih uglova (AOA), moraju se više koristiti opterećenja izmerena u letu. U Kanadi je razvijena empirijska metoda parametarske formulacije opterećenja (PLF). Metoda PLF se zasniva na poznavanju dejstva aerodinamičkog opterećenja i analizi podataka opterećenja izmerenih u letu, koja daje opterećenje u funkciji parametara leta, otklona komandnih površina i nekih deformacija, /6/. Kako je proces brz i MSDRS beleži deformacije i parametre leta u svakoj tački veće promene smera na mernoj traci i „g“, može je proračunati opterećenje za spektar centralnog dela trupa u tim tačkama. Jedini izuzetak su simetrični slučajevi velikog momenta uvijanja krila i malog momenta savijanja krila u korenu, kada se pik momenta uvijanja ne poklapa sa zabeleženim deformacijama.

Na osnovu poređenja oštećenja, nađeno je da su za spektar IFOSTP ispitivanja jedino značajna opterećenja na zemlji, sletanje i ciklusi održavanja glavnog stajnog trapa, /7/.

Each test was cycled until fracture, and each of the representative fatigue cracks found was examined by QF to establish the crack growth rate, the severity of the local stress, and the type and nature of discontinuities from which the fatigue crack initiated.

CENTRE FUSELAGE TEST FT55

Spectrum development

All F/A-18 aircraft are fitted with a Maintenance Signal Data Recording System (MSDRS) and a Digital Flight Control System (DFCS). The MSDRS was developed to provide fatigue usage, flight incident records, engine usage data and maintenance data. This device was used to collect data for the derivation of test spectrum loads and to monitor each aircraft to identify the damage accumulated compared to the spectrum finally applied to the IFOSTP test articles.

The Canadian centre fuselage/wing spectrum is defined in terms of manoeuvre and PITS using a manoeuvre identification programme, /4/. This programme first eliminated all periods of inactive flying by identifying time slices of the roll rate near zero, the angle of attack (AOA) was below 10° and the normal acceleration about 1. All other time slices were identified as either a standard manoeuvre (a turn, pull, push, rolling pull or roll) or a non-standard manoeuvre. This was achieved by testing for “g” ranges, calculating roll-through angles and noting roll directions and the sequence of roll rate and “g” peaks and valleys, and then comparing the observed data against pre-defined manoeuvre characteristics. The end result was an ordered list of manoeuvres to be simulated on the centre fuselage test.

The manoeuvre identification process resulted in a very large number of discrete manoeuvres. The original intent was to group these manoeuvres using defined flight parameters and control law boundaries where it would be reasonable to assume that the loads for all manoeuvres within each group were either constant or could be simply extrapolated. The loads at each turning point of a representative manoeuvre within a group would then be calculated combining the MSDRS and measured flight data, Computational Fluid Dynamics (CFD) models and wind tunnel data.

Because of the inadequacies of the analysis tools for predicting loads in high AOA regimes, increasing use had to be made of flight-measured loads. An empirical Parametric Loads Formulation (PLF) method was developed by the Canadians. The PLF method was based on knowledge of the aerodynamic loading actions and an analysis of the flight loads data that gave the loads as a function of flight parameters, control surface deflections and some strains, /6/. Since the process is rapid and MSDRS records strains and flight parameters at every significant turning point of the strain gauges and “g”, the option existed of calculating loads in considered points for centre fuselage spectrum. The only exception was for some symmetric, high wing torque, low wing root bending moment cases when the torque peak is not quite coincident with any strain trigger.

Based on damage comparison is found that for IFOSTP test spectrum only important are ground based loads, landing events and main landing gear maintenance cycling, /7/.

Ispitivanje

Uređaj za ispitivanje centralnog dela trupa sa postavljenim uzorkom dat je na sl. 3. Uzorak sa oko 700 sati naleta uzet je iz CF flote. Za uvođenje opterećenja i držanje aviona primenjeno je ukupno 64 hidraulička aktuatora, od kojih su dva za uvlačenje/izvlačenje glavnog stajnog trapa i šest za statičke reakcije oslonaca. Za svaki slučaj u spektru, opterećenje aktuatora je optimizirano za najbolje slaganje sa proračunskim opterećenjem preseka. Transverzalna sila, momenti savijanja i uvijanja u korenu krila, i momenti savijanja trupa u vertikalnoj ravni su podešeni na tačnost od 1,5% zadate deformacije.

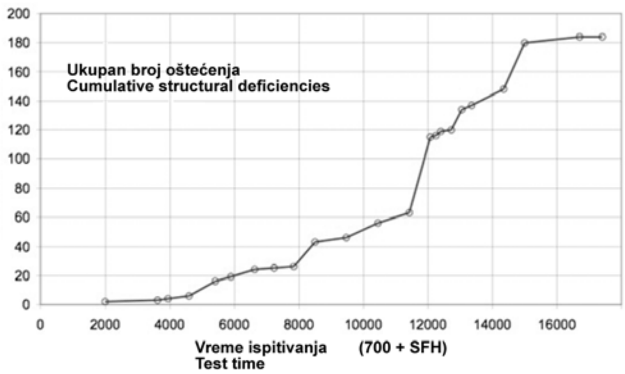
Testing

The centre fuselage test rig is shown in Fig. 3, with the sample in place. The test piece, of about 700 hours of service life, was taken from the CF fleet. A total of 64 hydraulic actuators, the two main landing gear retract actuators and six static reaction points were used to load and restrain the aircraft. For each of the spectrum load conditions, actuator loads past an optimisation process to best match the calculated loads of the test section. Typically, wing root shear, bending moments and torque and fuselage vertical bending moments were matched to 1.5% of target strains.

Slika 3. CF-18 IFOSTP ispitivanje na zamor centralnog dela trupa (FT55) u prirodnoj veličini u laboratoriji Bombardir (sada L3)
Figure 3. CF-18 IFOSTP Centre Fuselage Full Scale Fatigue Test (FT55) at Bombardier Aerospace Defence Services (now L3).

Ispitivanje je završeno posle ostvarenih 17.335 sati naleta (od kojih 700 sati naleta u eksploataciji). Izvršeno je ispitivanje preostale čvrstoće i uzorak je rastavljen zbog inspekcije. Akumulirana oštećenja strukture u funkciji sati ispitivanja data su na sl. 4. Zabeleženo je ukupno 184 oštećenja. Pedeset dva su nađena u inspekciji na 12 000 sati naleta u spektru (SFH), a 32 posle 15.100 SFH, /8/.

Active cycling was finished when the specimen accumulated 17,335 test hours (of which 700 hrs were service flight hours). Residual strength testing was performed and the article was torn-down. Accumulated structural deficiencies vs. test hours are given in Fig. 4. A total of 184 deficiencies were recorded. Fifty-two were found at the 12,000 spectrum flight hours (SFH) and 32 after 15,100 SFH, /8/.



Slika 4. Ukupan broj oštećenja u FT55 u funkciji sati naleta
Figure 4. Summary of FT55 deficiencies vs. flight hours.

Radi ostvarenja ciljeva projekta definisane su opravke prema zahtevima plovidbenosti i uvedene kada je to bilo moguće. Kao rezultat, preko 35 opravki ili modifikacija iz FT55 je uzeto za razvoj modifikacija u programu produženja konstrukcijskog veka flote CF-18. Slično je RAAF razvio program sanacije konstrukcije na osnovu dobijenih rezultata, uvodeći iste opravke i modifikacije. Ispitivanja su pokazala visok stepen tačnosti i kvalitet i trećina oštećenja u ispitivanju centralnog dela trupa je utvrđeno u CF ili u RAAF floti.

To fulfil project objectives, airworthy repairs were developed and installed whenever possible. As a result, over 35 repairs or modifications from FT55 were used in development of modifications in the Fleet Structural Life Extension Programme CF-18. Similarly, the RAAF developed a structural refurbishment programme based on the results obtained, following the same repairs and modifications. The test results have proven to be of high fidelity and quality and about one-third of the identified centre fuselage fatigue test failures have been found on CF or RAAF fleet aircrafts.

Ovo ispitivanje je pokazalo da je, za neke avione iz flote, projektovani siguran vek CB nedovoljan da se dostigne planirano povlačenje. Postalo je jasno da je najekonomičniji način za ostvarenje planiranog datuma povlačenja flote CF i RAAF usvojiti da siguran vek CB bude između 0,72 i 0,85, umesto određenog veka na zamor 1,0. Vrednost između ova dva broja kada treba da se zamene CB, ima vrlo veliki uticaj, naročito na troškove i operativnost lovaca RAAF. To je dovelo do koncepta programa detaljne inspekcije konstrukcije posle istrošenog zamornog veka, kao pomoć u određivanju stepena rizika pri izboru najdužeg perioda do zamene CB za RAAF (oko 0,85). Ovaj program se kasnije razvio u FINAL program, razmatran dalje u ovom radu.

Na kraju FT55, izvedeno je ispitivanje preostale čvrstoće (RST). Načinjen je pregled merodavnih opterećenja flote. Usvojeno je da opterećenje za ispitivanje RST treba da bude 1,2 puta veće od proseka maksimalnog opterećenja svakog aviona u floti u preostalom veku eksploatacije. Ovo ispitivanje je pokazalo da, iako opitni uzorak ima mnogo prslina, on ima dovoljnu čvrstoću da podnese opterećenje 1,2 puta veće od graničnog projektnog opterećenja u mnogim slučajevima. Ovaj podatak se može iskoristiti kao pomoć u donošenju odluke o integritetu konstrukcije aviona pri kraju veka. To je bilo posebno korisno u zonama sa prslinama, koje pri ispitivanjima nisu bile dovoljno opterećene da bi se jasno odredio status do planiranog datuma povlačenja. Ovo ispitivanje je ostavilo otvorenom mogućnost mnogo jasnijeg definisanja veka za zahtevani nivo sigurnosti pomoću analize prsline i bolje definicije veličine prsline za RST. Zbog toga se QF merenje brzine rasta prsline ispitivanjem površine preloma uvek smatra važnim delom inspekcije opitnog uzorka u IFOSTP, i brojne prsline koje su se pojavile pri FT55 su analizirane korišćenjem QF.

ISPITIVANJE KRILA FT245

Posebno ispitivanje krila je zahtevalo razvoj detaljnijeg spektra opterećenja veće tačnosti u poređenju sa opterećenjem krila pri ispitivanju centralnog dela trupa FT55, gde je bilo važno samo opterećenje u korenu krila.

Razvoj spektra

Za utvrđivanje spektra opterećenja krila su primenjeni i ispitivanje je izvedeno sa istim MSDRS blokovima podataka, samo je izbor segmenata opterećenja baziran na promeni smera opterećenja krila, a ne centralnog dela trupa. Ustanovljeno je da je uticaj dinamičkog opterećenja spoljnjeg dela krila, pretkrilca i zakrilca značajan sa aspekta oštećenja, pa su i ova opterećenja uključena u spektar.

Utvrđivanje raspodele opterećenja krila u manevru je složeno zbog komandnog sistema aviona, koji omogućuje varijacije zakona upravljanja po brzini i visini. Ova situacija i velike komandne površine na krilu traže analizu raspodele opterećenja. Da bi se definisala manevarska i dinamička opterećenja, RAAF je izveo dodatna ispitivanja u letu.

Ista empirijska PLF metoda kao u ispitivanju trupa primenjena je i za ispitivanje krila, a dobija se opterećenje glavnih sekcija u funkciji parametara leta i otklona komandnih površina. Kako predviđanje PLF važi za 10 Hz, spektar opterećenja pre skraćenja sadrži milione segmenata manevra.

This test has showed that the designed safe-life of the CB is insufficient to meet planned withdrawal for some fleet aircrafts. It became clear that the most cost effective way for the CF and RAAF fleets to reach planned withdrawal date was to accept safe life of aircraft CBs at between 0.72 and 0.85 instead designated fatigue life of 1.0. The point between these two numbers that this CB replacement should occur has a significant effect, particularly on the cost and capability of the RAAF's fighter arm. This led to the concept of fatigue life-expended teardown programme aiding to quantify the risk involved in selecting a late (nearer 0.85) CB replacement time for the RAAF. This programme has later been developed to FINAL programme discussed later on in this paper.

At the end of the FT55 test a residual strength test (RST) was completed. A review of respective fleet loads was made. It was determined that the applied RST demonstration load would be 1.2 times the average of the maximum load experienced by each fleet aircraft in its remaining service life. This test indicated that, although the test article had many cracks, it still had sufficient strength to withstand 1.2 times the design limit load for a number of load cases. This information can be used to aid decision on the structural integrity of the aircraft as it approaches the end of its life. It was particularly valuable in the cracked areas which had not received sufficient loading in the tests to clear them through to planned withdrawal date. This testing left open the possibility of more clearly defining the life to the required level of safety through analysis of the cracking and better definition of the RST crack sizes. Thus QF measuring the rate of crack growth by examining the cracks surface was always considered as an important part of the final teardown of the test articles in IFOSTP, and many of the cracks generated in FT55 have been analysed using QF.

WING TEST FT245

A separate wing test required a highly developed load spectrum with greater fidelity in application compared to the test loads for the wings attached to the centre fuselage FT55 where wing root loading was the focus.

Spectrum development

The derivation of the wing spectrum and loads was carried out by using the same MSDRS data blocks, only the interface loads for the load lines selection for the test were based on the wing load reversals rather than those of the centre fuselage. Dynamic loading of the outer wing and of the leading and trailing edge flaps was found to be damaging; and the wing test spectrum included also these loads.

The derivation of the wing manoeuvre load distributions was complex due to aircraft control system that allows variation of the control laws with speed and altitude. This situation and large control surface on the wing required the load distribution analysis. To find both manoeuvre and dynamic loads derivations, next RAAF flight tests were flown.

The same empirical PLF method used for the fuselage test is applied to the wing test, providing the major section loads vs. flight parameters and control surface deflections. Since PLF method predicts loads at 10 Hz, the loads spectrum contains millions of lines before truncation.

Sem toga, uključenim opterećenjima od baftinga dodat je manevarskim opterećenjima veliki broj ciklusa niskih amplituda. Ova opterećenja baftinga su određena karakterizacijom iskazanom napadnim uglom (AOA) i dinamičkim pritiskom (Q) i na osnovu prikupljenih podataka o segmentima vremena u letu pri odgovarajućim slučajevima opterećenja krila za svaki par AOA/Q. Filtriranjem na 2 Hz su podaci o opterećenju od baftinga iz ispitivanja u letu razdvojeni od podataka manevra. Kao rezultat ova dva izvora opterećenja generisana je velika istorija (8 000 000 linija) i morala je da se skrati. Normalno, ovaj proces je uključio proračun naponske istorije kritičnih lokacija na bazi uvedenog opterećenja, praćen analizom i ispitivanjem malih uzoraka, da bi se izbacili ciklusi koji ne izazivaju oštećenja, /9/.

Posle nekoliko iteracija skraćivanja, sirovi spektar ima oko 154 500 pojedinačnih raspodela opterećenja. Zbog ograničenja u sistemu uvođenja opterećenja i potrebnog vremena da se optimizuju i provere opterećenja aktuatora za toliko slučajeva, uveden je binarni proces svođenja pojedinačnih uslova na ispod 50.000, /10/. Ovi segmenti se koriste za proračun opterećenja aktuatora za ispitivanje krila.

Ispitivanje

Izgled krila i alata za ispitivanje u Kanadskom nacionalnom savetu za istraživanje (NRC) je dat na sl. 5. Osnovni predmet ispitivanja su kesoni spoljnjeg i unutrašnjeg desnog polukrila povučeni iz eksploatacije. Da bi se obezbedilo pravilno uvođenje opterećenja u konstrukciju, sva opterećenja, sem direktnog opterećenja površine krila, uvedena su preko uzorka (povučeni USN trup), uključivši komandne površine i pilone, reprezentativne za F/A-18 konstrukciju.

Opterećenje je uvedeno preko 63 servo-hidraulička aktuatora: 10 na trupu, 12 na tri podvesna nosača, 6 na segmentu levog polukrila, 2 horizontalna i 33 vertikalna na desnom polukrilu i komandnim površinama.

Additionally, aerodynamic buffet loads were included, adding large numbers of low amplitude cycles to the manoeuvre loads. These loads were addressed by characterising the buffet in terms of Angle-of-Attack (AOA) and dynamic pressure (Q) and collecting time segments of flight test data for relevant wing loads in each of the AOA/Q bins. The flight test buffet data were separated from the manoeuvre data by filtering at 2 Hz. As a result of these two load sources, an exceedingly large load history (8,000,000 lines) was generated and had to be truncated. Typically, this process involved the calculation of a stress history at a critical location based on the applied loads followed by both analytical and coupon studies to eliminate non-damaging cycles, /9/.

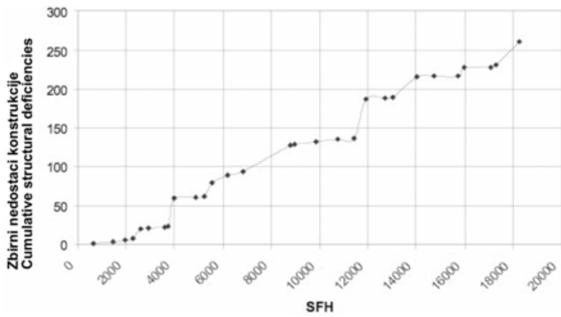
After several truncation iterations involved, the raw spectrum had about 154,500 unique load conditions. Because of control system limitations and the time required to optimise and check the actuator loads for so many load conditions, a binning process was used to reduce the number of unique load conditions bellow 50,000, /10/. These load lines were then used to calculate the actuator loads for the test wing.

Testing

The view of the wing test structure at National Research Council of Canada (NRC) is shown in Fig. 5. The primary test article was an ex-service right hand inner and outer wing box. To ensure that loads were properly introduced into this structure, all loading other than direct loads on the wing surfaces was introduced through representative structure (ex-service USN fuselage), including all control surfaces and pylons, which are representative F/A-18 structure.

Loads were introduced via 63 servo-hydraulic actuators: 10 on the fuselage, 12 on three sets of stores, 6 on left stub wing, 2 horizontal and 33 vertical on right wing and control surfaces.

Slika 5. IFOSTP ispitivanje krila (FT245) u Kanadskom nac. savetu za istraž. (NRC)
Figure 5. IFOSTP Wing Test (FT245) at Nat. Research Council of Canada (NRC).



Slika 6. Zbirni nedostaci konstrukcije FT245 zavisno od SFH
Figure 6. Summary of FT245 structural deficiencies vs. SFH.

Rezultati ispitivanja krila

Oštećenja uneta pri ispitivanju konstrukcije (više od 260 velikih) u funkciji vremena ispitivanja data su na sl. 6. Uzroci više od 75% utvrđenih oštećenja na FT245 su bili:
– Prsline.
– Pomeranje čaure.
– Čaure koje su plastično deformisane ili su prekomerno pohabane.
– Ovalizirane rupe.
– Slomljeni ili razlabavljeni vezni elementi.

Wing Test Results

Accumulation of structural test deficiencies (more than 260 major) vs. test hours is given in Fig. 6. Over 75% of the deficiencies detected on FT245 making damage were:
– Cracks.
– Bushing migrations.
– Bushings exceeding elongation limits or were found worn beyond limits.
– Elongated holes.
– Broken or loose fasteners.

Polovina otkrivenih oštećenja je na čaurama.

Najveća oštećenja pri ispitivanju na zamor su na:

– zadnjem delu punog rebra korena krila: 4000 SFH;
– unutrašnjem pretkrilcu, spoljni zglob: 8800 SFH;
– prednjoj ramenjači sa desne strane (RHS), modifikovanoj na 4000 SFH, prslina na 12000 SFH, prslina sa leve strane na 7000 SFH + 3000 USN sati;
– spoljnjem pretkrilcu, spoljni zglob: 17000 SFH;
– mnogi vezni elementi labavi i dotegnuti na 12000 SFH.

U prvom delu veka (6000 SFH) najviše grešaka je bilo na čaurama (56 od 105) (pomerena čaura, prekoračeno granično izduženje).

Mnoga otkrivena oštećenja na opitnom uzorku su nađena i na avionima u floti. Oštećenja na prednjoj ramenjači, koja su zahtevala modifikaciju na oko 4.000 SFH u FT245, odgovaraju oštećenjima na avionima u flotama RAAF i CF.

ISPITIVANJE ZADNJEG DELA TRUPA FT46

F/A-18 je lovački/jurišni avion velike manevarske moći, svestran, visokih performansi. Izduženi deo napadne ivice unutrašnjeg dela krila (LEX) daje trupu i unutrašnjem delu krila uzgon koji omogućuje postizanje napadnog ugla većeg od 60°. Dvostruki vertikalni rep, blago nagnut prema spolja, koristi visoku energiju vrtloga koje stvara LEX, obezbeđujući dobru uzdužnu stabilnost u uslovima velikog napadnog ugla (sl. 7). Nažalost, pri AOA od 10° ovi vrtlozi se odvajaju, javlja se bafting strukture, pobuđujući rezonantnu frekvenciju repa visokog nivoa ubrzanja, sa pratećim visokim naponima u glavnim strukturnim delovima. Problem je bio veliki, pa je proizvođač morao da ojača vezu dodatnim elementima radi veće čvrstoće u korenu repa, i da ugradnjom usmerivača graničnog sloja na LEX smanji lepršanje.

Postoji interakcija između kvazistatičkog manevarskog opterećenja i visokofrekventnog opterećenja od baftinga u odnosu na oštećenja od zamora.

Opšti uticaj je da se bafting javlja pri visokim srednjim opterećenjima i povećava njegov doprinos zamornom oštećenju. Ova pojava je dobro proučena i OEM je pokušao da uvede reprezentativno opterećenje (tj. korektan srednji napon plus bafting) pri ispitivanju na zamor zadnjeg dela trupa. Izvedena su posebna dinamička ispitivanja repa, samo je dinamičko opterećenje uvedeno na gornju polovinu repa. Ali, opterećenja nisu bila realna u pogledu frekvencije i broja ciklusa, već su to računska rezultujuća opterećenja za normalne brzine kvazistatičkog ispitivanja zamora. Primarni cilj utvrđivanja FT46 opterećenja je bio da se osigura da je dinamički odgovor opitnog uzorka što je moguće bliži ponašanju aviona u letu. Da bi se to postiglo potreban je sistem za uvođenje manevarskog opterećenja koji ne utiče bitno na dinamičke karakteristike konstrukcije. Ispitivanja

One half of detected damages were at bushings.

Major damages during the fatigue test was found at:

– Aft wing root closure rib: 4000 SFH.
– Inboard leading edge flap, outboard hinge: 8800 SFH.
– Front spar, RHS modified at 4000 SFH, crack found at 12000 SFH, LHS crack at 7000 SFH + 3000 USN hrs.
– Outboard leading edge flap, outboard hinge: 17000 SFH.
– Many fasteners backing off and re-torqued at 12000 SFH.

In the first lifetime (6000 SFH) most defects (56 out of 105) were bushing related (bushings migrated, exceed elongation limits).

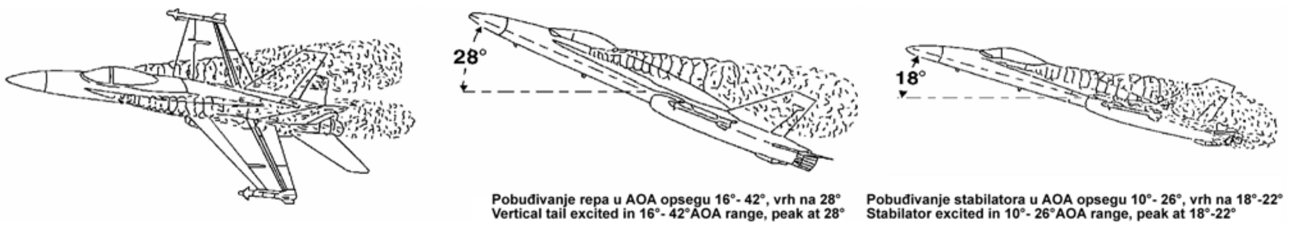
Many of the defects detected on the test article have also been found on fleet aircraft. The front spar defects that necessitated a modification at about 4000 SFH on FT245 correlate to defects detected on RAAF and CF fleet aircraft.

AFT FUSELAGE TEST FT46

The F/A-18 is fighter/attack aircraft extremely manoeuvrable, versatile, high performance. The inner wing Leading Edge Extension (LEX) provides fuselage and inner wing lift enabling it to achieve AOA above 60°. 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 (Fig. 7). Unfortunately, at AOA 10° these vortices break down, buffeting the structure and exciting the resonant frequencies of the empennage of high acceleration levels that result in high stress levels in key structural components. The problem was severe, and manufacturer increased fin attachments strength by fitting additional cleats at the tails base, and fitted aerodynamic fences to leading edge extensions 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, increasing their contribution to fatigue damage. This phenomenon is well understood and the OEM attempted to apply representative (i.e. correct mean stress 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 realistic in terms of frequency and count but as calculated resultant loads at the normal quasi-static fatigue test rates. The primary objective of the FT46 loading development process was to ensure that the test article was loaded such that its dynamic response matched that of an aircraft in flight. To accomplish this, a manoeuvre loading system was required that would not significantly affect the dynamic characteris



Slika 7. Bafting repa pri visokim AOA
Figure 7. Empennage buffet at high AOA.

su izvedena sa spektrima koji odgovaraju uslovima upotrebe pre i posle ugradnje usmerivača graničnog sloja LEX.

Realne modalne vibracije su generisane na korektnim frekvencijama i uvedene kada i odgovarajuće manevarsko opterećenje, /11-16/. RAAF i DSTO su ušli u veliki program razvoja uređaja za ispitivanje i jedinstvenog sistema za uvođenje opterećenja, sekvence opterećenja od manevra i baftinga, i, što je takođe važno, sistema upravljanja. Nova konstrukcija aviona (bez krila, prednjeg dela trupa i opreme) je naručena za ispitivanje.

Sistem za ispitivanje

Sistem za ispitivanje je razvijen tokom petogodišnjeg razvojnog programa, uz upotrebu ST01, ranije statički ispitanog centralnog i zadnjeg dela trupa, dobijenog od USN. Dostupnost ovog opitnog uzorka je bila presudna, jer je omogućila razvoj sistema za uvođenje opterećenja i upravljanje bez rizika po opitni uzorak FT46.

Srce sistema za uvođenje opterećenja je specijalni pneumatski aktuator mekog dejstva (sl. 8), koji ima krutost sličnu mekoj opruzi i malu masu. Primenom ovog sistema uvedena je raspodela manevarskog opterećenja bez uticaja na efektivnu krutost repa. Istovremeno, elektromagnetni pobuđivači (šejkeri) (sl. 8) uvode dinamičko opterećenje, a aktivni komandni sistem oslanjanja održava skoro nulto pomeranje zone repa da bi se smanjili zahtevi hoda šejkera pri visokom manevarskom opterećenju. Tako je značajan broj dinamičkih ciklusa eksploatacijskog veka aviona ekonomično primenjen na opitni uzorak u realnom vremenu.

Istovremeni rad vazdušnih opruga i hidrauličkih aktuatora u zatvorenoj petlji je uspešno razvijen. Kontroler, razvijen u DSTO, pokriva 65 međuzavisnih kanala opterećenja, tako da je manevarskim opterećenjem upravljano u okviru 2% zahtevanog opterećenja spektra, a oblik signala i frekvencija glavnih komandnih površina su odstupali oko ±5% od veličina merenih u letu. Uređaj za ispitivanje FT46 se vidi na sl. 9. Nekoliko naspramnih vazdušnih opruga je korišćeno na svakoj komandnoj površini da se dobije opterećenje u dva pravca. Potisak i inercijalne sile motora, aerodinamički otpor repova i bočna opterećenja trupa uvedeni su u realnom vremenu.

Promenljivost udarnog opterećenja

Opterećenje od baftinga stabilizatora F/A-18 je po prirodi složeno, nelinearno i kvazi-slučajno. Različiti odgovori aviona u istim uslovima leta, ili različiti odgovori raznih aviona u istim uslovima leta su mogući.

Položaj odvajanja vrtloga ima značajan uticaj na raspodelu pritiska na neokvašenoj površini F/A-18. Osim AOA i Q, brojni faktori mogu uticati na položaj „tačke odvajanja vrtloga", kao što su bočno klizanje i struja vazduha oko uvodnika motora i površinske nepravilnosti.

Pre odvajanja struje, vrtlozi imaju velike periferne brzine rotacije, usled čega se stvara jak potpritisak, i otud uzgon aviona na gornjoj površini.

Od tačke odvajanja vrtloga niz struju obimna brzina rotacije opada, pa se smanjuje i mogućnost stvaranja uzgona. Položaj odvajanja vrtloga može uticati na opterećenje repa.

Sem povećanog rasipanja zbog visokocikličnog zamora, nesigurnost zbog opterećenja od baftinga će dodatno pove

tics of the structure. Spectra representing usage both before and after the addition of the LEX fence were tested.

Actual modal vibrations were generated at the correct frequencies and simultaneously applied with the corresponding manoeuvre loading, /11-16/. The RAAF and DSTO entered into major programmes to develop the test rig and unique loading system, the test loading sequence of manoeuvre and buffet loads, and equally important, the control systems. A new airframe (less wings, forward fuselage and auxiliaries) was purchased for the test.

Test System

The test system was developed during a five-year development programme utilising ST01, an early centre/aft static test fuselage provided by the USN. The availability of this test article was crucial to the development programme, 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 (Fig. 8) of soft spring-like stiffness and low mass. Using this system, distributed manoeuvre loads were applied without affecting the effective stiffness of the empennage components. Concurrently, electromagnetic shakers (Fig. 8) applied 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 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 covered 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 about ±5% of those measured in flight. The FT46 test arrangement is shown in Fig. 9. 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.

Buffet load variability

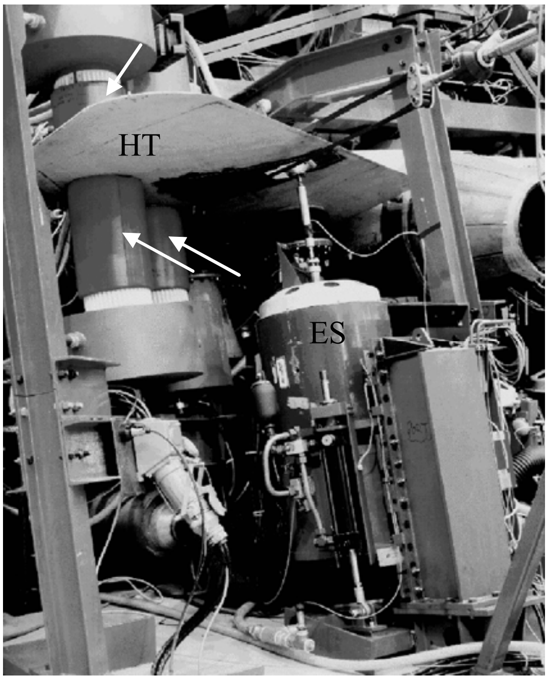
Buffet loading on the F/A-18 empennage is in nature complex, non-linear and quasi-random. Individual aircraft response to the same flight conditions or response variation of specific aircraft to the same flight conditions is possible.

The position of vortex burst have a significant effect on pressure distribution of the leeward side of F/A-18. In addition to AOA and Q, many factors can influence the location of the “burst point”, such as sideslip and engine inlet flow and surface irregularities.

Prior to bursting, the vortices produce high swirl velocity causing high suction pressures and therefore lift of the aircraft over the surface.

Downstream of the burst point, the swirl velocity of the vortices is reduced and also is its lift generating potential. For that burst position can affect empennage loading.

In addition to the increase in scatter associated with high cycle fatigue, the variability due to buffet loading will further ćati faktor rasipanja primenjen na ispitani vek, /17/. Zaključeno je da ispitivanje FT46 ne može da traje dovoljno dugo da pokrije sve moguće varijacije opterećenja i dinamičkog odgovora aviona u floti, pa sprovođenje ispitivanja na bazi verifikovanja sigurnog veka za većinu repova nije bilo praktično. Za dopunu ispitivanja analiza prslina primenom QF, kombinovana sa ispitivanjem na zamor jedne od kritičnih komponenti, uz ispitivanja manjih uzoraka i FE analize, omogućili su korektno određivanje veka za većinu kritičnih struktura.



Slika 8. Pneumatski aktuatori (strelice) i elektromagnetni šejker (ES), postavljeni na horizontalni rep (HT)
Figure 8. Rolling Sleeve Airbags (arrows) and Electromagnetic Shaker (ES) in place on the Horizontal Tail (HT).

Rezultati ispitivanja zadnjeg dela trupa

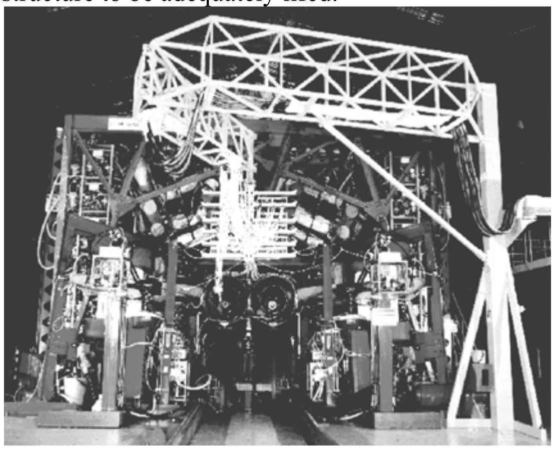
Ispitivanje sa Pre-LEX spektrom izvršeno je sa 1270 SFH. Ono je praćeno nizom modifikacija na opitnom uzorku i na uređaju za ispitivanje pre faze Post-LEX spektra. Na kraju ispitivanja, zbog ekonomičnosti, opitni uzorak je akumulirao ukupno 23 090 SFH, /18/. Akumulacija oštećenja strukture u funkciji vremena ispitivanja data je na sl. 10. Više od polovine uočenih velikih oštećenja, 75 od ukupno 148, nastala su u prvih 6000 SFH. Najviše ranih oštećenja je bilo na vezi vertikalnog repa sa delovima okvira. Mnogi od ovih okvira su imali prsline koje su ostavljene da rastu u toku ispitivanja, ali pre 18 000 SFH bile su potrebne opravke u skladu sa zahtevima plovidbenosti. Dva važna otkaza u FT46 su bila na zadnjem najopterećenijem okviru (Y598), koji je morao da se zameni na 17 374 SFH, i ozbiljan otkaz oba lonžerona dorsala na 20 997 SFH, /19/.

Više sličnih oštećenja je uočeno na avionima flote. Neka oštećenja delova trupa su saglasna sa ispitivanjima.

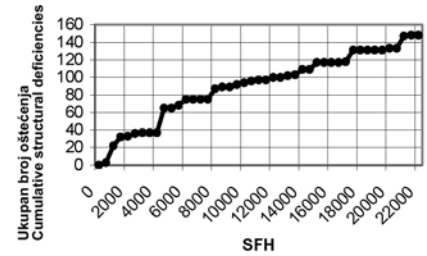
Ispitivanje preostale čvrstoće zadnjeg dela trupa

Zahtevi za RST su u CF i RAAF definisani kao dopuna ispitivanju na zamor. Zbog starosti flote uzeti su podaci iz eksploatacije da se utvrdi maksimalno opterećenje koje može

increase the scatter factor applied to test lives, /17/. It was concluded that FT46 could not be cycled for long enough to cover the potentially large variation in loading and dynamic response in fleet aircraft and thus the test demonstrated safe life based management, for most of the aft empennage was not practical. To supplement the testing, further analysis of the cracking using QF, combined with a stand-alone fatigue test of one of the critical components, associated coupon test programmes and FE studies allowed most of the critical structure to be adequately lifed.



Slika 9. Uređaj za ispitivanje FT46 (pogled s leđa) sa postavljenim opitnim uzorkom
Figure 9. The FT46 test rig (rear view) with presented test article positioned in place.



Slika 10. Zbirna oštećenja u FT46 u funkciji vremena ispitivanja
Figure 10. Summary of FT46 total deficiencies vs. test time

Aft Fuselage Results

Testing ran for 1270 SFH of the Pre-LEX spectrum. This was followed by a series of modifications to the test article and test rig before the Post-LEX spectrum phase. At the cycling end due to economy the article had accumulated a total of 23,090 SFH, /18/. Accumulation of structural test deficiencies vs. test hours is given in Fig. 10. More than one half, 75 of total 148 observed major deficiencies occurred in the first 6000 SFH. Most of the early deficiencies were at vertical tail attachments to the stub frames. Many of these frames had cracks that were left to grow during testing but needed airworthy class repairs before 18,000 SFH. Two important failures on FT46 were that of the aft most support frame (at Y598), which had to be replaced at 17,374 SFH and severed failure of both dorsal longerons at 20,997 SFH, /19/.

Several similar defects have been observed on fleet aircrafts. Some stub deficiencies correlate well with the test.

Aft fuselage residual strength testing

The CF and RAAF defined an RST requirement at the completion of fatigue cycling. Due to the maturity of the fleets, operational data were used to assess the maximum delovati na svaku konstrukcijsku komponentu u veku flote. Na osnovu tih podataka, definisani su odgovarajući slučajevi opterećenja da se dokaže preostala čvrstoća opitnih uzoraka na kraju zamornog ispitivanja. Priroda ovih ispitivanja zahtevala je različite pristupe ispitivanju preostale čvrstoće centralnog dela trupa/krila i zadnjeg dela trupa.

Kako su F/A-18 u floti RAAF već dostigli polovinu od planiranih 6000 sati veka u vreme RST ispitivanja FT46, odlučeno je da osnova RST bude 3000 sati preostalog veka za slučajeve opterećenja koji zbog baftinga padaju izvan projektne anvelope opterećenja. Za komponente FT46, podaci o prekoračenju post-LEX opterećenja iz spektra ispitivanja za svaku važniju komponentu su ekstrapolirani primenom raspodele Gumbela za predviđanje najvećeg očekivanog opterećenja za ukupni vek aviona (6000 sati) i za preostali vek (3000 sati). Gumbelova raspodela daje prihvatljivo slaganje za ekstremne vrednosti razmatranih opterećenja. Nađeno je da je odnos najvećeg uvedenog i opterećenja predviđenog za 6000 sati približno 1,2. Kako je faktor 1,2 načelno dat specifikacijom za korišćenje pri RST, faktor 1 za 6000 sati je ocenjen kao prihvatljiv za FT46 RST za slučajeve opterećenja u kojima bafting uzrokuje opterećenje na zamor izvan početnih projektnih slučajeva.

RST je uspešno izveden i opitni uzorak je rastavljen da se otkriju do tada neidentifikovane prsline. Sve važne prsline su istraživane pomoću QF. Posebno su za QF analizu bile interesantne zone u kojima su inicirane prsline. Analiza QF, uz program ispitivanja manjih uzoraka (kako je ranije rečeno), u nekim slučajevima omogućuje ekstrapolaciju veka iznad broja sati ispitivanja uzorka.

FINAL – ISPITIVANJE POVUČENOG TRUPA

U uvodu naveden Program zamene podstrukture centralnog dela trupa (CBR) je zahtevan za analizu grupe oštećenja objašnjenih u ovom području u ispitivanju FT55. Sopstveni programi CBR u USN i CF su već bili započeti.

Isto tako je i RAAF planirao uvođenje takvog programa, ali je traženi obim programa kasnio zbog problema dostupnosti aviona. Zbog toga je morala da se razmotri alternativna strategija smanjenja CBR programa.

Jedna strategija je bila da se izvede niz modifikacija na kritičnim lokacijama u kasnoj fazi veka F/A-18 radi produženja veka nekih aviona flote, tako da oni mogu da postignu planirani datum povlačenje bez CBR. Ovo je uglavnom zasnovano na iskustvu sa ranijim vekom flote i rezultatima ispitivanja na zamor uključujući IFOSTP.

Zbog nedostatka podataka iz dužeg veka aviona flote, postoje brojni rizici u ovom programu, koji su odnose na:
– oštećenja u eksploataciji (mehanička oštećenja i korozija);
– moguće više zamornih oštećenja (oštećenja u kritičnim zonama, neutvrđena ranije u F/A-18 ispitivanju zamora), i
– moguće neuspešne opravke.

Rastavljanje i inspekcija CB povučenih iz upotrebe su se potvrdili kao metoda smanjenja rizika unetog opravkama. Kako su USN i CF u tom trenutku preduzeli CBR programe, brojni trupovi povučenih aviona su bili dostupni. Nažalost, očekivano je da prosečna veličina najveće postojeće prsline u njima bude manja od 1 mm, /20/. To je danas ispod praga osetljivosti metoda ispitivanja bez razaranja (NDI),

loads likely to be encountered by each structural component in the life of the fleet. Based on this data, appropriate load cases were developed to demonstrate residual strength of the test articles at the end of fatigue cycling. The nature of the tests required different approaches to RST for the centre fuselage/wing tests and the aft fuselage test.

Since the RAAF F/A-18 fleet had already completed half of its planned 6000 hour life at the time of the RST testing of FT46, it was decided to base RST on the 3000 hours of life remaining for those load cases which fell outside the design envelope due to the buffet. 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 (6000 hours) and the aircraft's remaining life (3000 hours), respectively. The Gumbel distribution gives an acceptable fit for extreme values of the type being assessed here. It was found that the ratio between the highest loads applied and predicted in 6000 hours is about 1.2. As the 1.2 factor is commonly specified for use in RSTs, the factor 1 in 6,000 hours load case was considered acceptable for the FT46 RST in load cases where the buffet had produced fatigue loading outside original design cases.

The RST was successfully completed and the test article was torn down to detect yet unidentified cracks. All the important cracks have been investigated by QF. Of particular interest for QF analysis are areas in which cracks initiated. The QF analysis along with coupon test programme (as mentioned above) has in some instances allowed life extrapolation beyond the hours applied to the test article.

FINAL – USED CENTRE BARREL TESTS

In the Introduction noted Centre Barrel Replacement (CBR) programme was required to address a group of deficiencies highlighted in this region by FT55. The USN and CF have already commenced their own CBR programmes.

The RAAF have also planned to implement such a programme but required scope for programme delaying due to aircrafts availability issues. For that, alternative strategies to minimise the CBR programme had to be considered.

One strategy was to perform a series of modifications at critical locations late in the life of the F/A-18 to extend the life of some aircrafts in the fleet so that they may achieve planned withdrawal date without CBR. These actions were based mainly on experience from the early life of the fleet and the results of the fatigue tests including IFOSTP.

Because of the lack of data from high life fleet aircraft, a number of risks existed in this programme, connected with:
– in-service defects (i.e. mechanical damage and corrosion);
– potential widespread fatigue damage (new fatigue in critical locations not found before in F/A-18 fatigue tests), and
– potentially ineffective repairs.

The teardown and inspection of ex-service centre barrels was highlighted as a method of reducing by repairs involved risks. Because the USN and CF were currently undertaking CBR programmes, many of ex-service centre barrels were available. Unfortunately the size of the average largest cracks present in them are expected to be bellow 1 mm, /20/. This is bellow the threshold of current Non-Destructive što znači da je bilo teško dobiti eksploatacijske podatke za povučene CB u stanju prilikom preuzimanja. Da bi se prevazišla ta prepreka, iniciran je FINAL program u kome je za ove CB pri ispitivanju uvedeno reprezentativno opterećenje od momenta savijanja u korenu krila (WRBM). Ispitivanje na zamor je proširilo postojeće prsline do veličina koje, posle zamaranja, mogu da se otkriju nakon rastavljanja u laboratorijskim uslovima, što uključuje detaljnu inspekciju i QF nađenih prslina. Podaci dobijeni u FINAL se koriste da:

– se utvrdi da li avioni u eksploataciji imaju oštećenja CB neobuhvaćena IFOSTP programom zamornog ispitivanja, uključujući mehanička oštećenja i koroziju u eksploataciji;
– se dobije detaljna slika o vrstama grešaka ili degradacija iz kojih se iniciraju prsline u floti;
– se osigura da buduće odluke o programu CBR budu zasnovane na što merodavnijim podacima o integritetu konstrukcije CB u eksploataciji;
– se ponovo provere neke lokacije koje ograničavaju vek, posebno uticajem kritičnih dužina prslina CB na RST;
– se dobiju podaci na osnovu kojih će se poboljšati postojeće metode rizika i pouzdanosti, koje se koriste u analizi veka na zamor aviona F/A-18, /20/.

Ispitivanje na zamor centralnog dela trupa

Iz eksploatacije povučeni CB su pre rastavljanja ispitani na zamor u jednom od dva uređaja (sl. 11). Uređaj je projektovan da simulira opterećenje krila na uškama veze krilo-trup. Parovi aktuatora uvode ista opterećenja suprotnog smera na krajevima greda, spojenim na stranama svakog okvira. Aktuatori prenose kao spreg WRBM na uške veze krilo-trup. Rotacija CB za 90° im omogućava oslanjanje na jedan set greda. Uređaj se sam podešava tako da gornje i donje grede uvode iste, a suprotno usmerene momente savijanja na naspramnim stranama svakog CB.

Svakim aktuatorom se upravlja posebno, tako da na svaki okvir deluje srazmerni moment savijanja. Opterećenje CB se može podesiti tako da simulira raspodelu u letu. Svaki okvir se zamara do otkaza, uz rast prsline iz početne greške, pa je moguće utvrditi najveći broj prslina; ispitivanje se može nastaviti isključivanjem aktuatora tog okvira.

Za ispitivanje opitnih uzoraka je primenjen modifikovani spektar mini-FALSTAFF (Standardizovano opterećenje na zamor borbenih aviona). Mini-FALSTAFF spektar je u stvari skraćena verzija FALSTAFF, koji predstavlja standardizovanu istoriju opterećenja u korenu krila borbenog aviona, /21/. Normalizovani mini-FALSTAFF spektar je generisan primenom softvera Genesis 4 Fatigue, razvijenog u Nacionalnoj vazduhoplovnoj laboratoriji (NLR), /22/.

Sekvenca primenjena u FINAL uključuje neke od mini-FALSTAFF sekvenci, preuređene za lakšu interpretaciju QF, što je potvrđeno programom ispitivanja malih uzoraka.

Nivo opterećenja za sekvencu primenjenu na čitav CB je izveden množenjem normalizovane sekvence sa najvećim WRBM pri ispitivanju IFOSTP centralnog dela trupa (FT55). Deo WRBM uveden u svaki okvir je određen na osnovu horizontalnih sila u uškama za projektne slučajeve opterećenja, /23/. Deo ukupno uvedenog WRBM za svaki okvir, kako je uslovljeno horizontalnim silama u uškama, je korišćen za skaliranje opterećenja svakog okvira.

Inspection (NDI) methods, meaning that it was difficult to gain service data from ex-service CBs in their as removed condition. To overcome this obstacle, the FINAL programme was initiated where the application of representative Wing Root Bending Moment (WRBM) fatigue loads to the ex-service CBs in test rigs was carried out. The fatigue cycling extended existing flaws to a size where they could be detected under laboratory conditions during a post cycling teardown that included a thorough inspection and the QF of crack found. The data from FINAL is used to:

– determine if in-service aircraft contain CB damage not accounted for in the IFOSTP fatigue test programme, including mechanical damage and corrosion from service;
– provide a detailed picture of the types of defects or degradation that lead to cracking in the fleet;
– ensure that future decisions on the CBR programme are based on as much relevant information about the structural integrity of the in-service CB as possible;
– re-assess some of the life limiting locations, particularly related to the RST critical crack sizes in the CB;
– provide data that will enhance current risk and reliability methods applied in the analysis of F/A-18 aircraft fatigue lives, /20/.

Fatigue cycling of centre barrels

The ex-service CBs were cycled in one of two test rigs (Fig. 11), prior to teardown. The rig 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 CBs are rotated by 90° 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, enabling to proportion the bending moment for each bulkhead. This allows to adopt the loading of the CB to match in-flight distribution. Each bulkhead is cycled till failure, with growth of existing flaws, enabling to find maximum number of flaws; cycling can be continued switching off actuators of failed bulkhead.

A modified version of the mini-FALSTAFF (Fighter Aircraft Loading STAndard For Fatigue evaluation) sequence is applied to the test articles. The mini-FALSTAFF sequence is a truncated version of FALSTAFF, which represents the standard load history at the wing root of a fighter aircraft, /21/. A normalised mini-FALSTAFF sequence was generated using the National Aerospace Laboratory (NLR) developed software Genesis 4 Fatigue, /22/.

The FINAL fatigue sequence included some of the mini-FALSTAFF flights rearranged to make it easier to interpret QF, as confirmed by a coupon testing programme.

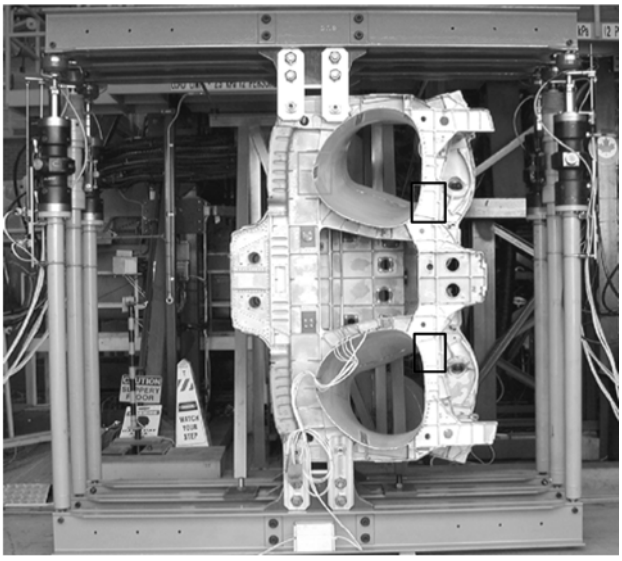
The load level for the sequence applied to the whole CB was derived multiplying the normalised sequence by the peak IFOSTP centre-fuselage (FT55) WRBM. The WRBM applied to each bulkhead was then determined from the horizontal lug loads at the design load cases, /23/. The proportion of the total WRBM applied to each bulkhead, as inferred by the horizontal lug loads, was used to scale the loads applied to each bulkhead.

Svi opitni uzorci su instrumentirani da se utvrdi raspodela opterećenja na tri okvira i uporede uvedena opterećenja sa prethodnim ispitivanjem na zamor F/A-18.

Uređaj ne uvodi opterećenja CB od sletanja. Sledstveno tome, oštećenja u zoni gde u eksploatacijskom opterećenju dominira opterećenje sletanja, verovatno neće bitno rasti pri ovom ispitivanju. Utvrđeno je da opterećenja pri sletanju nisu kritična za australijsku F/A-18 flotu.

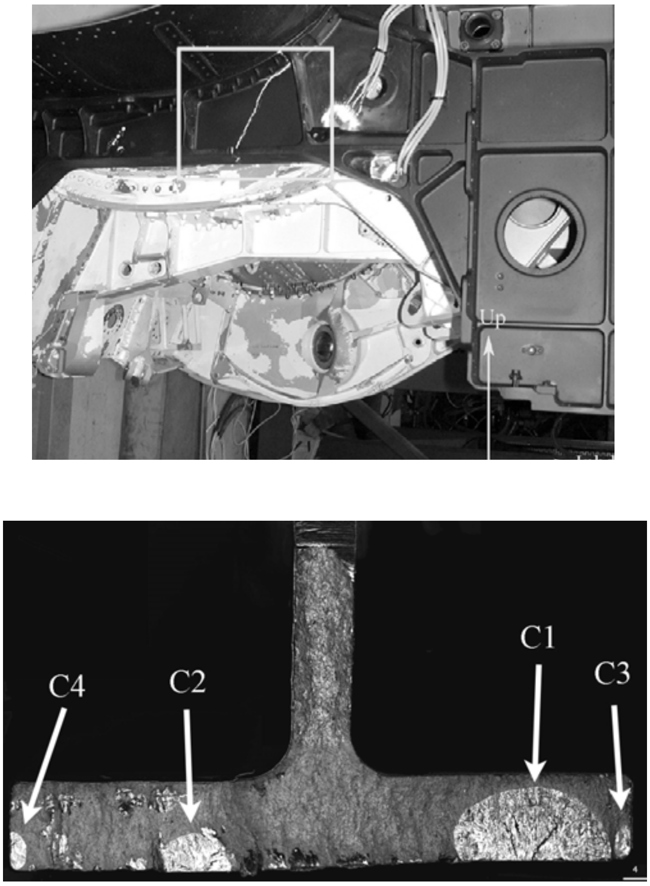
Instrumentation was applied to each test article to assess the distribution of load between the three bulkheads and to compare the applied loads to previous F/A-18 fatigue tests.

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 grow significantly by the fatigue cycling process. Landing loads have not been identified as being critical to the Australian F/A-18 fleet.



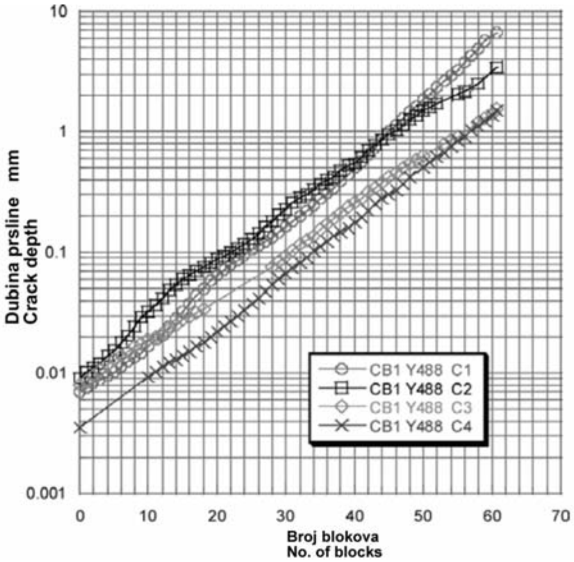
Slika 11. Jedan F/A-18 CB postavljen na uređaj FINAL. Položaji otkaza oplate Y488 u prvom ispitivanju CB su uokvireni

Figure 11. An F/A-18 CB mounted in the FINAL rig. Boxes indicate locations of the Y488 bulkhead failures in first CB test.



Slika 12. Lokacija prvog otkaza prvog CB na donjem pojasu okvira Y488. Prsline C1–C4 su ispitane pomoću QF

Figure 12. Location of the first failure of the first CB at the Y488 bulkhead's lower flange. Cracks C1–C4 examined by QF.



Slika 13. Krive rasta prsline za četiri najveće zamorne prsline sa sl. 12. Krive su izvedene na osnovu QF površine preloma

Figure 13. Crack growth curves for the four largest fatigue cracks from Fig. 12. The curves were derived from fracture surface QF.

Rezultati ispitivanja programa FINAL

Od do sada ispitanih na zamor i rastavljanih deset CB, prva dva su prikazana u radu, /24/. Ovi CB aviona su dobijeni iz flote CF (1), USN (7) i RAAF (2). U vreme njihovog povlačenja avioni su imali između 3500 i 6200 sati naleta. Do otkaza je došlo na deset odvojenih lokacija na tri okvira (kao grupe) tokom ispitivanja na zamor. Lokacije na kojima je prvi okvir CB Y488 otkazao označene su na sl. 12. Na

Test results of FINAL programme

Fatigue cycling and teardown of ten CBs has been completed, the first two are reported in /24/. The CBs came from CF (1), USN (7) and RAAF (2). The CBs had flown between 3500 hours and 6200 hours at the time of their removal. Failures have occurred at ten distinct locations in the three bulkheads (as a group) during fatigue cycling. Locations where the first CB's Y488 bulkhead failed are highlighted in Fig. 12.

ovom okviru Y488 su bila tri otkaza, jer je on opravljen (kao i većina ostalih okvira Y488) da bi se nastavila ispitivanja radi otkrivanja više prslina posle prvog otkaza.

QF je izvedena na površini preloma svakog otkaza i na mnogim od prslina koje su naknadno otkrivene pri inspekciji. Analiza prikazuje oko 80 ispitanih područja sa prslinama i više od 350 prslina merenih da se odredi kriva rasta prsline.

Primera radi, prvi otkaz koji se javio na prvom CB bio je posledica zamorne prsline na donjoj površini donjeg pojasa okvira Y488. Četiri zamorne prsline, analizirane pomoću QF, vide se na površini preloma i njihove krive rasta prsline date su na sl. 13.

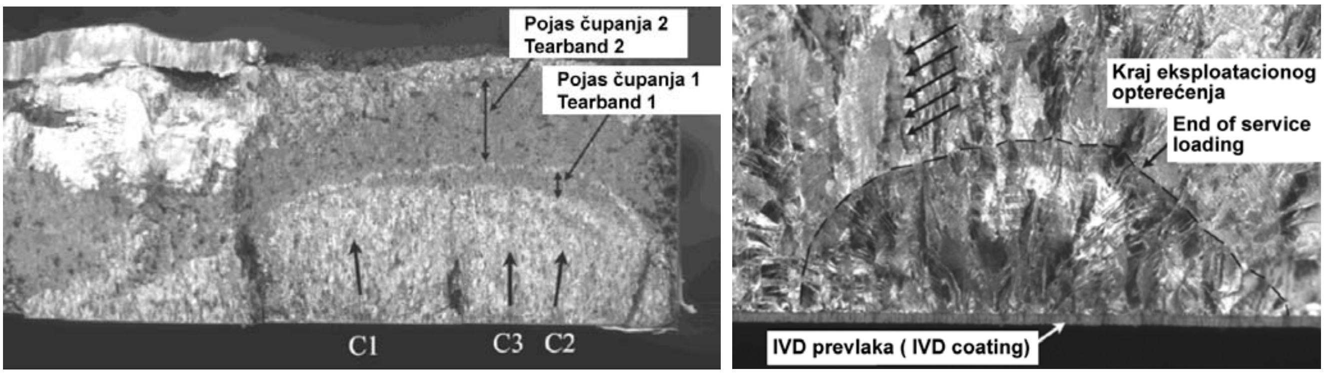
Takođe je u većini slučajeva na površini preloma bilo moguće odrediti početak blokova opterećenja FINAL i oceniti rast prsline u eksploataciji. Ustanovljeno je da su dubine prslina na kraju eksploatacije bile manje od 0,1 mm, sem kod nekih prslina, npr. prsline pri jednom od otkaza okvira Y470.5 drugog CB. U slučaju okvira Y470.5, najveća dubina prsline na kraju eksploatacije bila je oko 1 mm. Prslina koja je izazvala otkaz okvira Y470.5 prikazana je na sl. 14. Tri sub-prsline, koje su se spojile u glavnu prslinu, ispitane su pomoću QF. Uvećani pogled na jednu od tri sub-prsline prikazan je na sl. 14. Jasno se vidi područje rasta pod eksploatacijskim opterećenjem. Krive rasta prslina, merene za tri sub-prsline (sl. 14), su pokazale da je veličina prslina na početku bloka opterećenja bila od 0,4 do 0,9 mm. Ove prsline su se javile u području u kojem nije izvedena propisana obrada mlazom kuglica u eksploataciji. To je dovelo do značajnog rasta eksploatacijskih prslina, praćenog ranim otkazom ovog okvira u ispitivanju FINAL (posle dvadeset blokova, sl. 15). Ove prsline nisu reprezentativne za očekivane uslove dugog eksploatacijskog veka do povlačenja aviona u području obrade mlazom kuglica, jer se pokazalo da ova obrada, kada je dobro i u pravo vreme izvedena, značajno usporava rani rast prsline.

There were three failures in this Y488 bulkhead since its repair (as well as most of the other Y488 bulkheads) to allow further cycling to reveal more flaws after the first failure.

QF has been completed on the fracture surfaces of each failure and on many of the cracks that were post festum revealed during the teardowns. The analysis presented includes about 80 cracked regions examined and over 350 cracks measured to produce crack growth curves.

By way of example, the first failure to occur on the first CB was caused by fatigue crack in the lower surface of the Y488 bulkhead lower flange. Four fatigue cracks analyzed by QF are visible at the fracture surface, and for them obtained crack growth curves are given in Fig. 13.

It has also been possible in most cases to identify the start of FINAL block loading on the fracture surface and thus estimate the service crack growth. It was found that the crack depths at the end of service were less than 0.1 mm, except few cracks, e.g. the cracks at the site of one of the Y470.5 bulkhead failures in the second CB. In the case of Y470.5 bulkhead largest crack depth at the end of service was about 1 mm. The crack that caused Y470.5 bulkhead to fail is shown in Fig. 14. Three of the sub-cracks joined to form main crack were examined with QF. A closer view of one of these sub-cracks is shown in Fig. 14. The region of growth caused by service loading is clearly visible. Crack growth curves measured for the three sub-cracks (Fig. 14), indicate that cracksizes at the start of block loading were from 0.4 mm to 0.9 mm. This cracking occurred in a region where prescribed in-service shot peening had not been completed. This resulted in significant service crack growth, followed by early failure of this bulkhead in fatigue cycling FINAL (after twenty blocks, Fig. 15). This cracking was not representative for the expected condition of high service life teardown aircraft where this area has been shot peened, since the peening, performed correctly and timely has been shown to greatly retard early crack growth.



Slika 14. (Levo) Prslina koja je izazvala otkaz okvira Y470.5 druge CB. Označeni su počeci sub-prslina, istraživani pomoću QF. Strelice iznad početaka pokazuju pravac merenja rasta prsline.
(Desno) Na uvećanom izgledu početka C1 tamno područje je rast prsline u eksploataciji. Označen je kraj eksploatacijskog opterećenja i početak FINAL bloka opterećenja, sa linijama razvoja reprezentativnim za FINAL blok opterećenja (strelice).
Figure 14. (Left) The crack causing failure of the second CB's Y470.5 bulkhead. The origins of the sub-cracks investigated by QF are labelled. The arrows above these origins indicate the directions of crack growth measurements.
(Right) At closer view of C1 origin the darker region is service crack growth. The end of service and the start of FINAL block loadings are highlighted, with progression lines, representative of FINAL block loading (arrows).

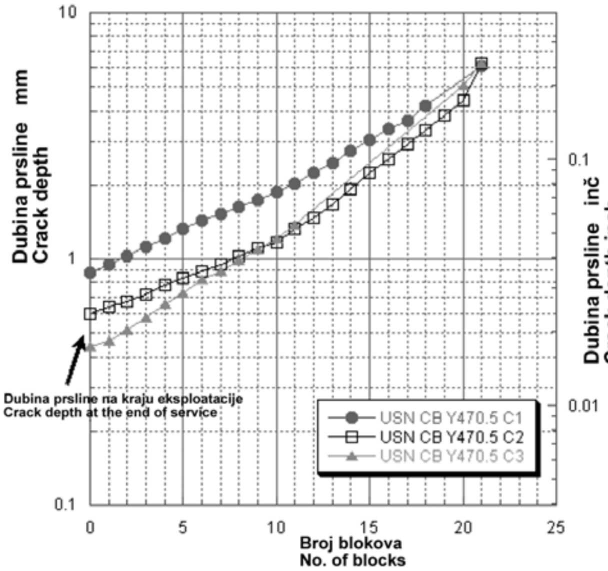
Načelno međutim, rezultati QF su potvrdili da je teško otkriti prsline na kraju eksploatacije bez obimnog i složenog ispitivanja razaranjem. Takođe je interesantno uočiti da

Generally however, the QF results confirm that it would be difficult to find cracks at the end of service without a comprehensive and complex destructive examination. It is je rast prsline u log skali približno prava linija u funkciji veka, pojava koja je kod rasta velikog broja zamornih prslina uobičajena za konstrukcije borbenih aviona pri simuliranom eksploatacijskom opterećenju, /25/.

Sve najznačajnije prsline, koje su bile uzrok loma, identifikovane su u ranijim ispitivanjima na zamor, a samo nekoliko novih lokacija sa prslinama je otkriveno. Ovo potvrđuje konzistentnost nalaženja novih zona sa prslinama u opitnim uzorcima. Značajne prsline, koje su dovele do otkaza, bile su na mestima visokih lokalnih napona u CB sa mnoštvom prslina. Do sada nisu nađene prsline od mehaničkih oštećenja (sem u otvorima za vezne elemente) ili korozije u eksploataciji, iako su se korozijske prsline javljale posle skidanja CB sa aviona i u zonama gde ostale opravke nisu bile izvedene ili nisu izvedene korektno, /26/.

also to note that the crack growth appears to be an approximate straight line on a log crack depth vs. life curve, an observation generally found for many fatigue cracks grown in fighter structure loaded with service like loads, /25/.

The most significant cracks causing the failures have all been identified on previous fatigue tests, and only some new crack locations have been found now. This supports the consistency in new cracking sites found between fatigue test articles. The locations where significant cracking have led to failure have been in high stress discrete locations of widespread cracking in the CBs. So far no cracking from mechanical damage (except fastener holes) or service corrosion occurred, although corrosion cracks are found after the CBs removal from the aircraft, and in areas where repairs had been performed properly, /26/.



Slika 15. Krive rasta prsline izvedene pomoću QF za sub-prsline na prslini otkaza okvira Y470.5 druge CB
Figure 15. Crack growth curves derived with QF for the sub-cracks at the crack failed the second CB's Y470.5 bulkhead.

ISPITIVAJE POJEDINAČNIH KOMPONENTI

Na velikim sekcijama konstrukcije, dostupnim posle ispitivanja, mogle su se naći zone u kojima je opravka bila potrebna, ali za koje je iskustvo pokazalo da se ta opravka ne mora izvesti ili da je vreme za njeno izvođenje ograničeno.

Neke od ovih zona su bile u vezi sa CB i dodate su im veštačke prsline, ili su isečene iz okvira na kraju FINAL ispitivanja i ispitivane pojedinačno. Jedna od tih zona je opisana u daljem tekstu. (Y488 vezni pojas).

Sem toga, neki delovi aviona u floti su bili modifikovani izvan granica propisanih u Priručniku za opravku konstrukcije (SRM). Neki od njih nisu bili uključeni u tri IFOSTP ispitivanja i ostali su relativno neoštećeni na kraju ovih ispitivanja. To je omogućilo da se oni ispitaju u sada postojećoj konfiguraciji u floti, uz potrebno odobrenje s obzirom na zamor do planiranog datuma povlačenja (PWD), ili da se, po sistemu sigurnost na osnovu inspekcije, uključe u ASI program za F/A-18. Jedno od ovih ispitivanja komponenti je opisano (ispitivanje zgloba krmila pravca).

Vezni pojas okvira Y488

Analizirana su dva otvora na veznom pojasu okvira Y488 na mestu veze lonžerona sa okvirom. Na tim otvorima su se

DISCRETE COMPONENT TESTING

With large sections of structure available after the testing it was possible to find the areas of required repair indicated, but the experience had shown that this repair may not be required or the induction time was found to be restrictive.

Some of these locations were associated with the CB and they had either artificial flaws added or were cut from the bulkheads after FINAL testing and tested as stand-alone. One of them is described here (Y488 mould-line flange).

In addition, some components in the fleet had been modified beyond the limits imposed by the Structural Repair Manual (SRM). Some of them had not been directly part of the three IFOSTP tests and they remained relatively damage free at the end of these tests. This gave an opportunity to test them in now existed configuration in the fleet so that appropriate fatigue clearance to the Planned Withdrawal Date (PWD) or a safety-by-inspection regime could be incorporated in the ASI programme for the F/A-18. One of these component tests is described (Rudder hinge test).

Y488 mould-line flange

Two holes in the mould-line flange of the Y488 bulkhead that attach the drag longerons to the bulkhead were of javljale prsline u svim ispitivanjima na zamor, ali nikad nisu bile uzrok loma okvira. Za opravku ovih otvora definisana je modifikacija koja se sastoji u razvrtanju radi povećanja prečnika veznih elemenata, ali se pojavila dilema kada treba izvršiti opravku i koji uticaj opravka može imati na budući vek u toj zoni, jer je u toj zoni primenjen tretman radi povećanja otpornosti na zamor. U otvore su utisnute čaure. Da bi se rešio ovaj problem odlučeno je da se izvrši ispitivanje ovog dela okvira Y488, kako bi se odredila otpornost na zamor ovih otvora sa utisnutim čaurama uz prisustvo značajnih oštećenja. Da bi se odredile kritične veličine prsline radi određivanja stvarnog veka na zamor ovih otvora, korišćeni su podaci sa RST vrednostima, koji su već bili sakupljeni iz različitih ispitivanja.

Iz okvira Y488, sa sedmog ispitanog CB, isečen je deo spoljnog pojasa sa leve strane okvira Y488. Prsline su u otvorima detektovane pomoću NDI, ali su one smatrane suviše malim za svrhu ovog ispitivanja. Prethodno ispitivanje zamornih prslina na ovim otvorima je pokazalo da je tipičan njihov brzi rast u početku, a da se zatim usporava, kako se približavaju zoni oko utisnutih čaura. Utvrđeno je da je rast kroz područje pritisnih zaostalih napona, nastalih utiskivanjem čaura, vrlo spor, ali ni jedna od ovih prslina nije bila dovoljno dugo opterećivana tokom bilo kog ispitivanja CB, da bi se proverio njihov preostali vek kada prslina prođe zonu zaostalih napona. Bilo je teško pri analizi uzeti u obzir zaostale napone, tako da je ispitivanje ove zone omogućilo značajne prednosti prilikom utvrđivanja kritične veličine prsline, kojom treba da se ispune zahtevi RST ove zone i na taj način potvrdi koliko je usporavanje rasta prsline.

Da se utvrdi kritična veličina prsline pri RST opterećenju, izvedeni su zarezi na spoljnjoj ivici udubljenja oko utisnutih čaura na jednoj strani svakog otvora, dok su prirodne prsline ostavljene na drugoj strani. Ovaj deo okvira je zatim ispitivan na zamor savijanjem u tri tačke (sl. 16) da se odredi kritična veličina prslina koje nastaju iz otvora. Ciljno za ovo ispitivanje je bilo RST opterećenje na otvoru za vezu lonžerona. Kriterijum RST je bio ispunjen dostizanjem veličine 1,32 × maksimalno izduženje, mereno na lokalnoj mernoj traci pri FT55. Sekvenca, koja se sastoji od deset ciklusa do RST opterećenja, 675 kN, zatim 200 ciklusa opterećenja od 50% RST, 338 kN, je ponavljana dok se uzorak nije slomio pri odnosu R = 0,1, tako da je rast prsline praćen na površini preloma. Kako je prslina ulazila u zonu zaostalih napona, unetih hladnim utiskivanjem čaure, razmak strija se smanjivao (sl. 16). Epruveta se slomila na veznom pojasu okvira posle 4770 ponavljanja spektra, kada je RST opterećenje ponovljeno 4770 puta.

Ovo ispitivanje je ponovljeno na više komponenti isečenih iz različitih CB dok se lom nije pojavio na odgovarajućoj lokaciji. Time je utvrđena kritična veličina prsline RST i bilo je moguće koristiti izmereni rast prsline (najnepovoljniji slučaj) da se odredi siguran vek u toj zoni.

Ustanovljeno je da, ako je utiskivanje čaure bilo dobro, što se pokazalo u svim slučajevima ispitivanja okvira, siguran vek te zone je dovoljan da se dostigne PWD, bilo da je predložena modifikacija sprovedena ili ne.

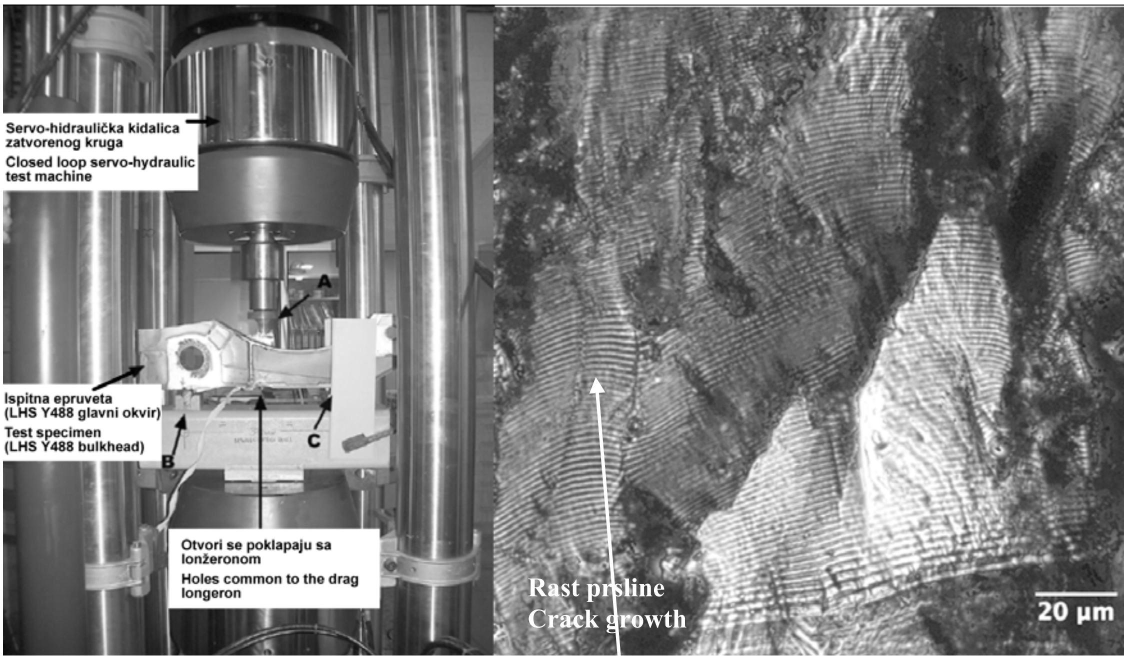
concern. These holes had cracking in all the fatigue tests but never caused the bulkhead to fail. A repair modification had been defined for these holes, consisting of an oversize, but there was some concern about of implementation time of the repair and what effect the repair can have on the next life of this location since it had a fatigue enhancing treatment applied to it. The holes were ring pad coined. To address these concerns, it was decided to perform discreet testing of this part of the Y488 bulkhead to determine the fatigue resistance of these holes in the ring pad coined condition with substantial damage present. To determine the critical crack size, the crack growth data that had already been gathered from the various tests was used with the RST value to establish the true fatigue lives of these holes.

A section of the Y488 bulkhead's LHS outboard flange was cut from the Y488 bulkhead from the seventh CB tested. Cracks were detected in the holes by NDI, but these were considered too small for the purposes of this testing. Previous examination of fatigue cracking from these holes found that the cracks typically grew quickly initially and then slowed as they approached the ring pad coined dents. Growth through the region of compressive residual stress created by these dents was found to be very slow, but none of these cracks had been loaded for a sufficiently long time during any of the CB's tested to prove their remaining life had the cracks progressed beyond the residual stress region. It was difficult to account for the residual stresses by analysis, so the testing of this region offered considerable advantages for the establishment of a critical crack size that would meet the RST requirements of this location and to confirm the extent of the retardation of crack growth.

To establish the critical crack size under RST loading, saw cuts to the out edge of the ring pad coined dents were inserted on one side of each hole while the natural cracks were left on the other sides. This part of the bulkhead was then cycled in a three-point bending test (Fig. 16) to determine the critical size of cracks emanating from the holes. The target load for this test was the RST load at the drag longeron hole. The RST criterion was matched by reaching 1.32 × maximum strain recorded on FT55 by local gauge. A repeating sequence consisting ten cycles up to RST load, 675 kN, followed by 200 cycles of 50% RST load, 338 kN, applied till the specimen failed at ratio R = 0.1 enabled to track the crack growth on the fracture surface. Since the crack is progressing into the residual stress region produced by the cold coining, the striation spacing was initially reduced (Fig. 16). The specimen broke at the mould line flange after 477 spectrum repeats, when RST load had been applied for 4770 times.

This testing was repeated on several components cut from different CBs until failure occurred at the appropriate location. This established a RST critical crack size and it was possible to use the crack growth measured (worst case) to estimate the safe life of this location.

It was found that if the ring pad coining was effective, which was the case for all bulkheads tested, then the safe life of this region was sufficient for it to reach the PWD both with or without the proposed oversizing modification.



Slika 16. Izgled postavke ispitivanja savijanjem u 3 tačke (levo). Rast prsline na površini preloma pod RST opterećenjem, nastalog iz zamorne prsline tokom FINAL ispitivanja (desno).
Figure 16. A view of the 3-point bending test set-up (left). Crack growth on a fracture surface under the RST loading, from a fatigue crack produced during FINAL (right).

Ispitivanje oslonca krmila pravca

Dva oslonca aktuatora krmila pravca, koji predstavljaju drugo i treće povećanje dimenzije otvora (specijalu) na uškama oslonca aktuatora, ispitani su na zamor na servo-hidrauličkoj kidalici da se dobiju podaci za podršku upravljanja zamorom ovih konfiguracija, koja ne postoje u OEM Priručniku za opravke konstrukcija (SRM). Oslonac aktuatora krmila pravca je u vertikalnom repu F/A-18, a izrađen je ručnim kovanjem legure AA7075-T7352. Vertikalni rep na F/A-18 je zamenljiv, tako da su na avionu isti oslonci leve (LHS) i desne strane (RHS), a nisu slika u ogledalu, pa su sa FT46 postojala dva opitna uzorka.

Opterećenja od aktuatora krmila pravca prima uška na zadnjem kraju oslonca. Ova uška je prikazana na sl. 17. Ona ima običan sferni ležaj i njena zadnja površina je u proizvodnji obrađena mlazom čeličnih kuglica, sa namerom da se bitno poboljša zamorni vek u ovoj zoni, kritičnoj zbog održavanja. Ponekad je potrebno demontirati ležaj iz uške i nekad se u ovakvim slučajevima otvor rupe ošteti ili izađe iz granične tolerancije prečnika, pa je potrebno proširiti otvor na sledeću veću meru. Ove opravke na veću meru se izvode u skladu sa F/A-18 SRM procedurom. Kada oštećenje otvora uške prevazilazi opseg prve specijale, potrebna je opravka drugom specijalom i u nekoliko slučajeva je morala da bude izvedena i opravka trećom specijalom zbog problema sa alatima za opravku.

U 2003. je shvaćeno da druga i treća specijala za opravku nisu podržane ispitivanjem na zamor, kao ni statičkim ispitivanjem čvrstoće, niti analizom. Zbog toga su ove opravke obustavljene.

Urađena je analiza radi ocene integriteta uške sa drugom i trećom specijalom, koja je nagovestila da uške nemaju dovoljni vek i da ih je potrebno zameniti pre PWD, ili bar uvesti više inspekcija sa kraćim intervalima. Da bi se rešilo

Rudder hinge testing

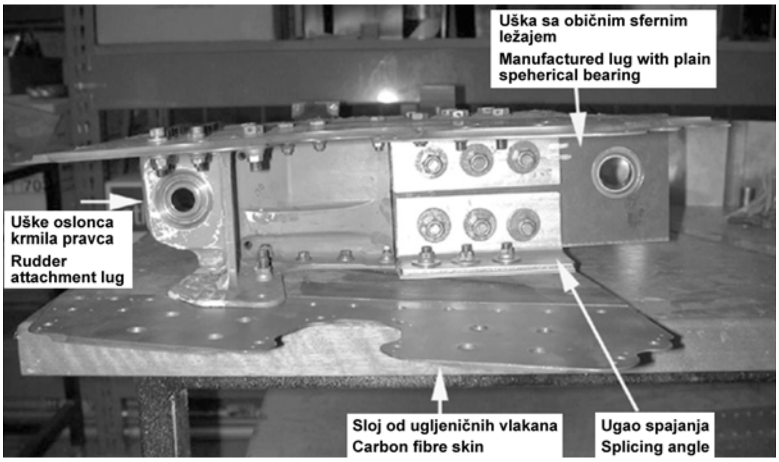
Two rudder actuator fittings, representing the 2nd and 3rd oversizes of the actuator attachment lugs were fatigue tested in a servo-hydraulic test machine to provide data to support fatigue management of these configurations that were not addressed in the OEM Structure Repair Manual (SRM). The rudder actuator fitting is located in the F/A-18 vertical tail and is made from an AA7075-T7352 alloy hand forging. Vertical tails on the F/A-18 are replaceable with fittings identical on the left (LHS) and the right hand side (RHS) of the aircraft and not mirror image of one another, so two test articles were available from the FT46.

The loads from the rudder actuator are reacted through a lug at the aft end of the fitting. The lug is shown in Fig. 17. It contains a plain-spherical bearing and its aft face is steel shot-peened in production, which is intended to significantly improve the fatigue life at this maintenance critical location. Occasionally there is a need to remove a bearing from the lug and on some of these occasions the bore of the hole is damaged or found to be outside of the blueprint diameter tolerance requiring an oversizing of the hole. These oversize repairs are performed in accordance with the F/A-18 SRM procedure. When the damage in the lug hole exceeds the scope of the first repair, a second repair is necessary and in several cases a third oversize repair has been performed due to repair tooling problems.

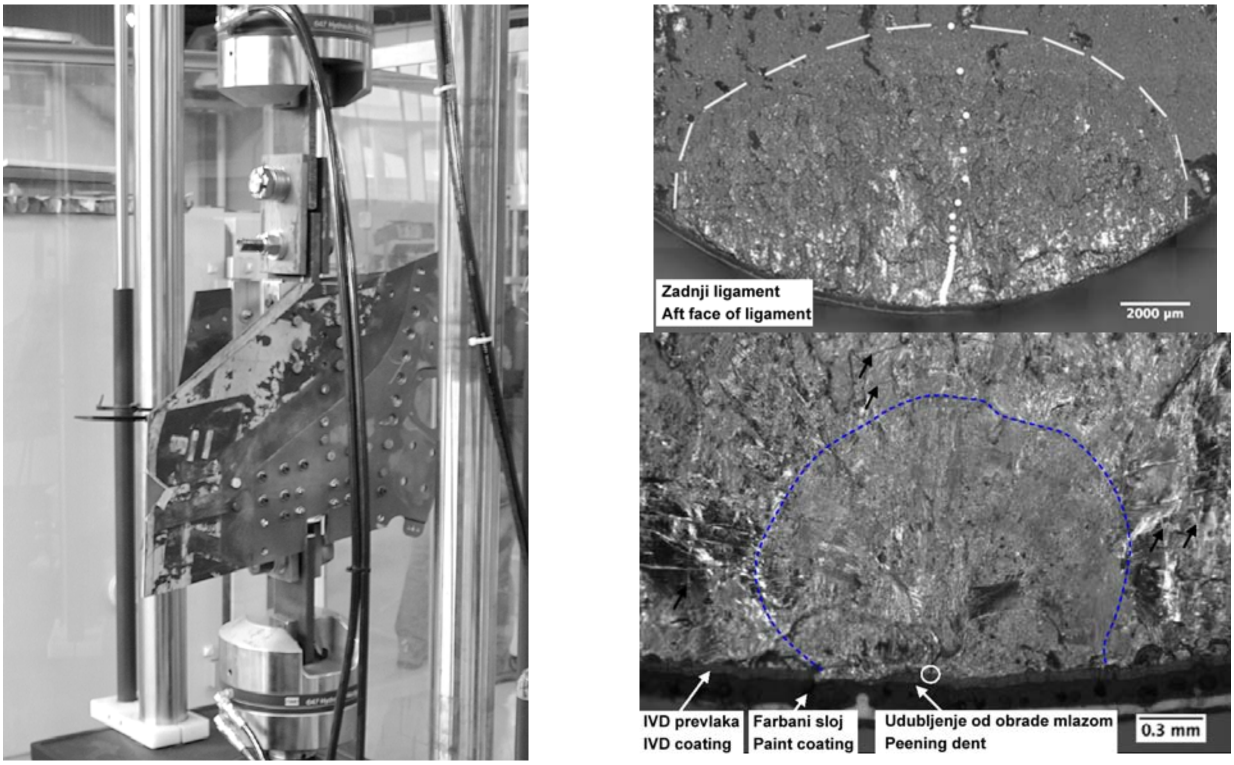
In 2003 it was recognised that the 2nd and 3rd oversize repair configurations had not been supported by fatigue or static strength test data or analysis. These repairs were subsequently ceased.

To address the structural integrity of the 2nd and 3rd oversized lugs analysis was performed, suggesting that the life of lugs is insufficient and they should be replaced prior to the PWD, or at least a number of inspections at short ovo pitanje, izvedena su ispitivanja na zamor i statička ispitivanja sa parom oslonaca koji su imali ušku sa drugom i trećom specijalom. Ovi oslonci su uzeti sa opitnog uzorka FT46. Podaci o rastu prsline, dobijeni zamornim ispitivanjem, izvedeni iz QF, su korišćeni da se, prema DEFSTAN 00-970, odrede novi sigurni vek i intervali inspekcija radi potvrde o sigurnosti oslonaca sa drugom i trećom specijalom, ispravna NDI i odgovarajući NDI intervali.

intervals would be required. For that, fatigue and static tests were performed on a pair of fittings of the 2nd and 3rd oversized lugs. The fittings were available from the FT46 test article. Crack growth data from the fatigue tests, derived by QF were used to establish new safe life and inspection intervals following DEFSTAN 00-970 allowing confirmation of the safety of 2nd and 3rd oversized fittings, the proper NDI and the appropriate NDI interval.



Slika 17. Bočni izgled oslonca u položaju za ispitivanje
Figure 17. Side view of a fitting in the test configuration.



Slika 18. Epruveta druge prekomere (specijale) na 100 kN servo-hidrauličkoj kidalici (levo). Zamorna prslina na zadnjem ligamentu uške. Bele tačke pokazuju ponavljanje blokova (desno gore). Oblik male prsline (desno dole).
Figure 18. The 2nd oversize specimen in the 100 KN servo-hydraulic test machine (left). The fatigue crack in the lug aft ligament. The white dots indicate the repeats in the blocks (right up). The shape of the small crack (right down).

Pripremljena su dva opitna uzorka, jedan sa drugom, a jedan sa trećom specijalom. Da bi se ostvarilo korektno uvođenje opterećenja u oslonac, iskorišćena je konstrukcija FT46 i ispitivanje je izvršeno OEM projektnim spektrom na

Two test articles were prepared; one with the 2nd oversize and one with the 3rd oversize. They used the structure from the FT46 to gain the correct load transfer into the fitting, and were tested with the OEM design spectrum in a servo-hidrauličkoj kidalici, primenom samo zateznog dela spektra opterećenja, jer je FEM pokazala da samo tim delom može da se izazove lom dve kritične lokacije. Uređaj za ispitivanje je prikazan na sl. 18. Usporeni rast zamorne prsline na površini je tipičan u prisustvu zaostalog napona koji je nastao obradom površine mlazom kuglica (sl. 18).

Uška sa drugom specijalom se slomila pri ispitivanju na zamor na zadnjem ligamentu (u pravcu dejstva sile). Prelomna površina se vidi na sl. 18. Statičko ispitivanje je izvedeno na istom uzorku i lom na bočnom ligamentu je otkrio drugu zamornu prslinu. Ovo ispitivanje je pokazalo da, čak iako je zadnji ligament napukao, preostala čvrstoća je značajna. Uška sa trećom specijalom je slomljena na bočnom ligamentu pri zamornom ispitivanju. Njen zadnji ligament je ispitan razaranjem i nađene su brojne zamorne prsline dubine ispod 2 mm.

Prsline otkrivene u ispitivanju su istražene pomoću QF. Krive rasta prsline su konstruisane na osnovu lokacija markera opterećenja u spektru. Utvrđeno je da kvalitet obrade mlazom kuglica zadnjeg ligamenta uške ima značajan usporavajući uticaj na rast prsline, što dovodi do različitog ponašanja dve uške. Zato je zadnji ligament uške sa drugom specijalom slomljen pri ispitivanju na zamor, a uška sa trećom specijalom nije. To je jedan od problema obrade mlazom kuglica radi poboljšanja otpornosti na zamor legura aluminijuma.

Podaci o rastu prslina su korišćeni za analizu sigurnog veka, izvedeni prema DEFSTAN 00-970. Prvi korak u analizi je da se generišu geometrijske sredine veka za prsline zadnjeg ligamenta i bočnog ligamenta. Ispitivanja dva veka su izvedena za svaku lokaciju prsline, za konfiguracije sa drugom i trećom specijalom, iako se javio samo po jedan zamorni lom u svakoj od njih. Rezultati dodatnih ispitivanja su izvedeni podešavanjem prikazanog rasta prslina za različite napone uške tih konfiguracija sa drugom i trećom specijalom, množenjem prikladnim faktorom rasipanja.

Koristeći podatke o vremenu uvođenja modifikacija prekomera u flotu, utvrđeno je da je ukupni sigurni vek, koji odgovara planu rada i konfiguracijama proširenih otvora, znatno iznad RAAF zahtevanog veka za F/A-18. Zbog toga je preporučeno da se modifikovanim uškama aviona upravlja na osnovu strategije sigurnog veka.

Nažalost, postoji faktor koji unosi komplikacije; RAAF je obznanio da su u nekim slučajevima u floti F/A-18 mehanička oštećenja zadnjeg ligamenta uške popravljena prevlakom. Iz rasta ovih prslina u prvom ispitivanju zaključeno je da ovi radovi mogu da podrazumevaju postojanje prethodnih zaostalih napona. Sem toga, ako ne postoje zaostali naponi, nastali obradom mlazom, sigurni vek uške je znatno smanjen. Zbog toga je preporučena primena zaštitnih prevlaka na zadnjoj površini svih uški aktuatora krmila pravca da bi se sprečila dalja mehanička oštećenja i nanošenje prevlaka, a potrebno je da se sve površine sa prevlakama obrade mlazom keramičkih kuglica da se povrate osobine usporavanja rasta prslina unete prvobitnom obradom mlazom.

Ali, kako u floti postoje uške sa prevlakom, koje još nisu obrađene mlazom, postoji opasnost da obrada mlazom keramičkih kuglica u budućnosti neće dati rezultat, jer su prsline

servo-hydraulic test machine using only the tension part of the loading spectrum since this part of the loading would cause failure of the two critical locations identified by FEM. The test setup is shown in Fig. 18. The retarded fatigue crack growth at the surface is typical in the presence of residual stresses produced by surface peening (Fig. 18).

The 2nd oversize fitting fractured during the fatigue test through aft ligament (in the force direction). The fracture surface is shown in Fig. 18. A static test was conducted on this sample and fracture at the side ligament revealed another fatigue crack. This test indicated that even with the aft ligament failed, there was considerable residual strength. The 3rd oversize fitting fractured through side ligament in fatigue test. Its aft ligament was destructively inspected and many of fatigue cracks, deep below 0.2 mm, were detected.

The cracks revealed by the testing were examined using QF. Crack growth curves were derived from the locations of marker loads placed in the test spectrum. It was found that the quality of peening of the lug aft ligament had a significant retarding effect on crack growth, causing the difference in the two fittings behaviour. For that the aft ligament of the 2nd oversize lug fractured in fatigue test while the 3rd oversize lug did not. This is one of the problems when using peening as a fatigue enhancement method on aluminium alloys.

The crack growth data was used in a safe life analysis, performed according to DEFSTAN 00-970. The first step of the analysis is to generate geometric mean lives for aft ligament cracks and side ligament cracks. Two test lives were generated for each cracking location for both the 2nd and 3rd oversize configurations, even though only one fatigue failure occurred in each of them. The additional test results were derived by adjusting the demonstrated crack growth for stress differences between the 2nd and 3rd configuration lugs, multiplying them by proper scatter factors.

Using information about the implementation time of the oversize modifications in the fleet, it was determined that the total safe life, that is the safe life in blue print and oversize configurations, was well above the RAAF F/A-18's required life. It was therefore recommended to manage the modified fittings on these aircraft under a safe life strategy.

Unfortunately, there was a complicating factor; the RAAF advised that in some cases in the F/A-18 fleet mechanical damage to the aft ligament of the fitting's lug has been removed by blending. From the crack growth in the first test was concluded that these actions may have compromised the original residual stresses. Furthermore, without present peening stresses, the safe life of fitting would be significantly reduced. For that, the application of protective media to the aft face of all rudder actuator fitting lugs was recommended to prevent further mechanical damage and blending, and all blended areas should be ceramic bead peened to restore crack retarding properties of the original peening.

But, because blended lugs not yet been peened already exist in the fleet, there is a danger that any ceramic bead peening in the future will be ineffective, since cracks may be already extended beyond the peening depth. For this već mogle da se prošire preko dubine očvršćavanja ovom obradom. Zato je strategija upravljanja vekom ovih uški određena kao da obrade mlazom nema.

Ova strategija upravljanja zamorom preporučuje kontrolu vrtložnim strujama visoke učestanosti zadnjeg ligamenta uške u intervalima opšte opravke. Zbog nepostojanja podataka o rastu zamornih prslina za uške obrađene mlazom keramičkih kuglica, preporučeno je da se područja sa prevlakom, obrađena mlazom odmah posle nanošenja prevlake, prekontrolišu u isto vreme.

ZAKLJUČAK

Ispitivanja IFOSTP praćena dodatnim istraživanjima i inženjerskom aktivnosti proizvela su visoko kvalitetne informacije o integritetu konstrukcija, koje su bile podloga za definisanje aktivnosti pri sanaciji konstrukcija, kako u floti RAAF, tako i u floti CF, što je omogućilo da svaka od flota ostvari odgovarajuće termine za povlačenje iz eksploatacije. Ove informacije su utvrdile vek sa granicama i omogućile tačnu procenu cene sanacije konstrukcija. Dok drugi faktori takođe utiču na procenu, da li sistem naoružanja treba ranije zameniti, informacije IFOSTP su zauzvrat pomogle da se donese valjana odluka o investiranju u F/A-18.

Rezultati IFOSTP su doneli dosad nepostojeće informacije koje daju menadžerima flote mogućnost da odrede cenu i efektivno oblikuju programe upravljanja vekom aviona zajedno sa pratećom infrastrukturom. Posebno, ovi programi ispitivanja su omogućili da se u obe zemlje promene osnove verifikacionih ispitivanja za avione. Iako se još koriste informacije koje su dobijene na osnovu prvobitnog OEM sertifikacionog ispitivanja, IFOSTP ispitivanja su kamen temeljac za upravljanje integritetom konstrukcija F/A-18 u RAAF i u CF. Posebno:

– IFOSTP je potvrdio da je siguran vek centralnog dela trupa, po zahtevima upotrebe u CF/RAAF i zahtevima plovidbenosti, bio oko dve trećine veka specificiranog u OEM. Što je još važnije, IFOSTP je identifikovao ranije nepoznate lokacije sklone pojavi prslina.

– Za održavanje flote duže od dve trećine sigurnog veka zahteva se niz inspekcija, modifikacija i opravki. One su bile primenjene na opitnim uzorcima radi ocene uspešnosti. U više slučajeva one su primenjene dovoljno rano, što je omogućilo da se te opravke verifikuju ispitivanjem.

– Jasan put upravljanja flotom i za to odgovarajući troškovi za sledećih 15 godina su rezultirali iz IFOSTP. Obe zemlje (uz neke razlike) su razvile ekonomične programe sanacije konstrukcija na sredini veka, kojima se smanjuje uticaj na operativnu raspoloživost flote. Sem toga, modifikacije konstrukcija se mogu izvesti u koordinaciji sa programom planiranih usavršavanja avionike na avionima. Takođe je utvrđeno da je moguće očekivati zahtev da se zamene brojni centralni delovi trupa. To je omogućilo razmatranje nabavke i zamene CB znatno pre vremena koje se zahteva za uvođenje u flotu.

Kao prirodni razvoj iz tri glavna IFOSTP ispitivanja razvijena je grupa ispitivanja FINAL i pridruženih ispitivanja komponenti. Rezultati ovih ispitivanja upućuju na razmišljanje u RAAF da li je broj planiranih modifikacija kritičnih konstrukcija, uključujući potpunu zamenu u pogledu

reason, a fatigue life management strategy was determined for these fittings based on no effective peening.

This fatigue management strategy recommended high frequency eddy current inspection of the aft ligament of the fitting lug at major overhaul intervals. Because of the absence of fatigue crack growth data for the fitting lug with ceramic bead peening applied, it was also recommended that blended areas that are immediately peened after blending, should also be inspected at this time.

CONCLUSION

The IFOSTP tests and associated research and engineering activities have generated high quality structural integrity information which has been pivotal in defining major structural refurbishment activities in both RAAF and CF fleets, that will 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 helped 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 programmes along with the associated infrastructures. Specifically, the testing programmes have allowed both countries to change the basis of certification for the aircraft. 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. In particular:

– 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 have been incorporated into the test article for performance assessment. In some cases, they were applied so early for repairs to be certified through testing.

– A clear path for fleet management and its associated costs for the next 15 years has resulted from IFOSTP. Both countries (with some differences) developed cost effective mid-life structural refurbishment programmes, minimizing the impact on the operational availability of fleets. In addition, the structural modifications can be co-ordinated with the avionics upgrade programmes planned for the aircraft. Furthermore, it was determined that replacements of a number of centre fuselage would be required. This has allowed a centre barrel acquisition and replacement trial well in advance of the required fleet induction time.

As a natural progression from the three main IFOSTP tests, the FINAL group of tests and the associated component tests were developed. Results from these tests suggest that RAAF deliberations concerning a number of planned modifications to critical structure, including the complete loma kritičnih CB, vredan podrške, tako da pojedinačne modifikacije u paketu omoguće RAAF da koristi F/A-18 do planiranog termina povlačenja sa najmanjim brojem zamena CB.

Do sada je svaki ispitani CB otkazao na deset lokacija tokom ispitivanja na zamor. Lokacije otkaza i pojava drugih značajnih prslina u ovim CB izgleda da su saglasni sa onim što je utvrđeno u ranijim ispitivanjima FT55.

Druga ispitivanja na zamor važnih konstrukcija su izvedena kao podrška F/A-18, koristeći komponente dobijene posle različitih ispitivanja. Ova ispitivanja su pokazala da je utvrđeni vek bilo teško oceniti na osnovu analize, obično zbog mera za poboljšanje u pogledu zamora primenjenih u OEM. Rezultat ovih ispitivanja je bolje razumevanje mogućih problema prslina.

replacement of the fracture critical CB is supportable such 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.

Thus far, each CB tested has failed in ten locations during fatigue cycling. Locations of failures and other significant cracking appear to be consistent across these CBs when compared to the previous FT55 test.

Other fatigue tests on structure of interest have been carried out in support of the F/A-18 using components left over from various testing. These tests have demonstrated lives that were difficult to assess by analysis, usually due to fatigue enhancing measures that were implemented by the OEM. As a result of these tests, better understanding of the likely cracking problems was determined.

ZAHVALNOST

Autori izražavaju svoju zahvalnost što je značajan uspeh IFOSTP ostvaren zahvaljujući inovacijama, posvećenosti i profesionalizmu, doprinosom brojnih učesnika iz sledećih organizacija:

– Kraljevske australijske vazduhoplovne snage;
– Kanadske snage;
– Kanadskog nacionalnog saveta za istraživanje;
– Organizacije za odbrambenu nauku i tehnologiju Australije;
– CF Ustanove za ocenu i ispitivanje aviona;
– RAAF Odeljenja za istraživanje i razvoj aviona; i
– Bombardir Službi za vazdušnu odbranu.

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SKRAĆENICE – ABREVIATIONS

RAAF	Kraljevske australijske vazduhoplovne snage	The Royal Australian Air Force
CF	Kanadske snage	The Canadian Forces
IFOSTP	Međunarodni projekt dodatnih ispitivanja konstrukcija	International Follow-On Structural Test Project
OEM	Izvorni proizvođač opreme	Original Equipment Manufacturer
USN	Američka mornarica	United States Navy
ASI	Integritet konstrukcije aviona	Aircraft Structural Integrity
PLF	Parametarska formulacija opterećenja	Parametric Loads Formulation
QF	Kvantitativna fraktografija	Quantitative Fractography
CBR	Zamena podsklopa centralnog dela trupa	Centre Barrel Replacement
CB	Sklop centralnog dela trupa	Centre Barrel
FINAL	Identifikacija prslina pod dejstvom opterećenja	Flaw IdeNtification through the Application of Loads
PITS	Slučaj pri letu	Points-In-The-Sky
DSTO	Organizacija za odbrambenu nauku i tehnologiju	Defence Science and Technology Organisation
MSDRS	Sistem zapisa podataka signala održavanja	Maintenance Signal Data Recording System
DFCS	Sistem za digitalno upravljanje letom	Digital Flight Control System
SFH	Sati leta u spektru	Spectrum Flight Hours
RST	Ispitivanje preostale čvrstoće	Residual Strength Test
AOA	Napadni ugao	Angle-of-Attack
Q	Dinamički pritisak	Dynamic Pressure
RHS, LHS	sa desne strane, sa leve strane	Right Hand Side, Left Hand Side
LEX	Izduženi deo napadne ivice	Leading Edge Extension
NDI	Ispitivanja bez razaranja	Non-Destructive Inspection
WRBM	Moment savijanja u korenu krila	Wing Root Bending Moment
SRM	Priručnik za opravku konstrukcije	Structural Repair Manual
PWD	Planirani datum povlačenja iz eksploatacije	Planned Withdrawal Date
NRC	Kanadski nacionalni savet za istraživanje	National Research Council of Canada
NLR	Nacionalna vazduhoplovna laboratorija (Holandija)	National Aerospace Laboratory (Netherlands)