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SWISS TITANIUM RESEARCH EXPERIMENTS ON THE CLASSIC HORNET (STRETCH)

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Abstract: The Swiss Titanium Research Experiments on the Classic Hornet (STRETCH) was a collaboration between Swiss and Australian Governments, with support of RMIT University and RUAG Switzerland, to experimentally evaluate small fatigue crack growth (FCG) in titanium combat aircraft structures, to improve related analytical tools and finally to support, through its results, the Swiss F/A-18 life extension program. The centrepiece of the collaboration was the full-scale fatigue test (FSFT) of a Swiss F/A-18 C/D centre barrel. Research undertaken included coupon level small FCG studies, damage induction studies, and full-scale durability and damage tolerance (DaDT) testing.

Coupon level testing focussed on spectrum truncation, marker band (MB) design and FCG rate measurement for recrystallisation annealed Ti-6Al-4V, the primary material in the centre barrel bulkheads. Using quantitative fractography (QF), these studies provided the groundwork for the FSFT spectrum design, validating a truncated fighter aircraft wing root bending moment (WRBM) spectrum with marker bands. During the course of the FSFT, two novel instrumentation techniques beyond conventional foil strain gauges were demonstrated and an innovative method of plasma arc spot melting for damage induction during the damage tolerance phase was also demonstrated for Ti-6Al-4V bulkheads. This method was shown to impart controllable crack-like damage to depths less than 0.01 inches (0.254 mm). Finally, full-scale testing of the F/A-18 C/D centre barrel demonstrated the DaDT of the Ti-6Al-4V centre barrel design through multiple lifetimes of applied equivalent service loading.

This paper presents an overview of each of these research streams encompassed within the STRETCH project with a focus on the preparation for and conduct of the DaDT phases of the titanium centre barrel FSFT.

Keywords: Full-scale fatigue test, titanium alloys, fatigue crack growth.

INTRODUCTION

Titanium alloys, specifically the titanium, aluminium and vanadium alloy Ti-6Al-4V, have become increasingly prevalent in combat aircraft primary structure applications [1],[2]. Ti-6Al-4V has a favourable combination of properties including high strength, low weight, durability and damage tolerance. Considering its higher cost relative to aluminium alloys, as measured in both raw material terms as well as the increased expense of machining finished parts, it remains an attractive material selection for large, highly loaded aircraft parts of unitized design such as wing carry-through bulkheads. To explore both specific and general structural integrity challenges arising from the use of this material in combat aircraft applications, the Swiss Titanium Research Experiments on the Classic Hornet

(STRETCH) was formed as a collaborative project between the Swiss and Australian Governments [3]. With the support of RMIT University in Australia and RUAG in Switzerland, STRETCH aimed to experimentally evaluate small fatigue crack growth in titanium combat aircraft structures. This was done to improve related analytical tools and to support, through its results, the Swiss F/A-18 life extension program. The centrepiece of the collaboration was the full-scale fatigue test (FSFT) of a Swiss Ti-6Al-4V F/A-18 C/D centre barrel (Figure 1) known as 'FTS3'. Research undertaken included coupon level small fatigue crack growth (FCG) studies, damage induction studies, and full-scale durability and damage tolerance (DaDT) testing.

Figure 1: The STRETCH Project logo (left) and Centre Barrel FSFT rig (right).

The following sections of this paper focus on spectrum truncation, marker band (MB) development, test article instrumentation and the DaDT phases of the titanium centre barrel FSFT. Future stages of the test at the time of writing this article are discussed briefly at the end.

COUPON TEST TRUNCATION AND MARKER BAND STUDIES

To explore the effects of combat aircraft spectrum truncation, marker banding and fatigue crack growth rates (FCGR) in this material, a series of coupon test studies were completed using Ti-6Al-4V recrystallised annealed (RA) specimens (Figure 2). Ti-6Al-4V RA forging material was used for manufacture of wing carry-through bulkheads in the Swiss F/A-18 C/D fleet as well as later F/A-18 E/F and EA-18 G aircraft. A Swiss F/A-18 C/D wing root bending moment (WRBM) loads spectrum was used as the basis of these studies with a 9% rise-fall truncation level being found acceptable for FSFT purposes.

The truncation level was chosen by conducting a study of the analytical crack initiation and growth life in comparison to the total reduction in load lines. Both a rise-fall filter and a dead band filter were investigated. It was found that the dead band filter, which removed load cycles that fell within a defined range around zero, had a more adverse effect on total life. As such, only a rise-fall filter was used for the FSFT spectrum. The 9% truncation level was chosen as it reduced the total number of load lines by 97% whilst analytically having less than a 1% effect on total life.

Both a MB [4],[5] and a constant amplitude (CA) block were applied at key points within each representative service lifetime in order to mark the fracture surface and aid quantitative fractography

(QF). The CA block was applied at the commencement of each life of the FSFT, and it was designed to produce comparable FCG to the 9% truncated variable amplitude (VA) block. This CA block produced different fracture surface topography compared to the VA blocks, thus allowing the crack depth at the start of each lifetime to be identified. The MB was applied at the end of each CA and VA block in order for regular crack front measurements to be taken using QF. This allowed FCGRs to be ascertained for each investigated fatigue crack. An example of the CA block, MB, then VA block sequence applied at the start of each testing lifetime is shown in Figure 3. Each lifetime of testing consisted of one CA block and 19 VA blocks, each followed by MB's.

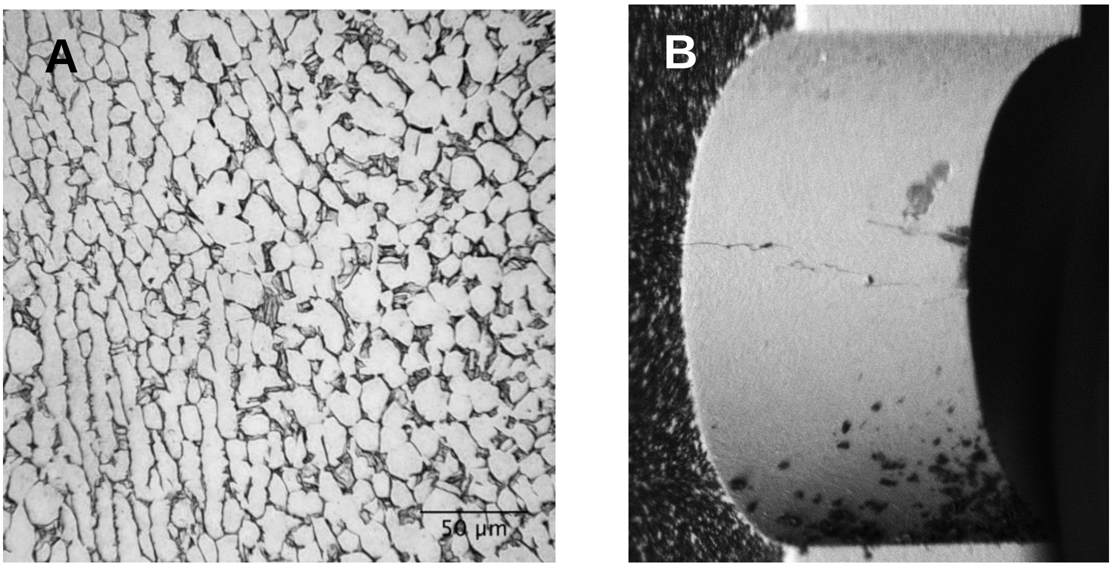

Figure 2: Microstructure of the Ti-6Al-4V RA specimens (Figure 2A) which was found to consist of fine-grained (10-20 µm) equiaxed alpha (flat grey areas in Figure 2A). Crack nucleation sites in the side edge-notched specimens used for these studies (Figure 2B).

The readability and hence viability of this FSFT block sequence was demonstrated via this coupon test program. Multiple different MB sequences were tested to iteratively develop the final version used for the FSFT. The goal was to apply a sequence that would produce easily identifiable marks on the fracture surface over as many different crack lengths as possible without having crack growth dominated by the MB's. The final MB sequence chosen is shown in Table 1. Coupon tests found that this MB was identifiable in some cases down to very small crack depths near the edge of the nucleating feature, such as is shown in Figure 4. These tests also found that the MB's were responsible for roughly 10% of the total FCG which was deemed as an acceptable portion of growth and added a level of conservatism to the fatigue life estimates.

Table 1: The load sequence used in the final FSFT MB.

Name	**Min. (normalised)**	**Max. (normalised)**	**Cycles**
High R	0.7	0.9	1499
Low R	0.05	0.9	20
Load Line	0.02	-	0.5
Load Line	-	0.99	0.5
Load Line	-0.26	-	0.5
Load Line	-	1	0.5
High R	0.7	0.9	1499

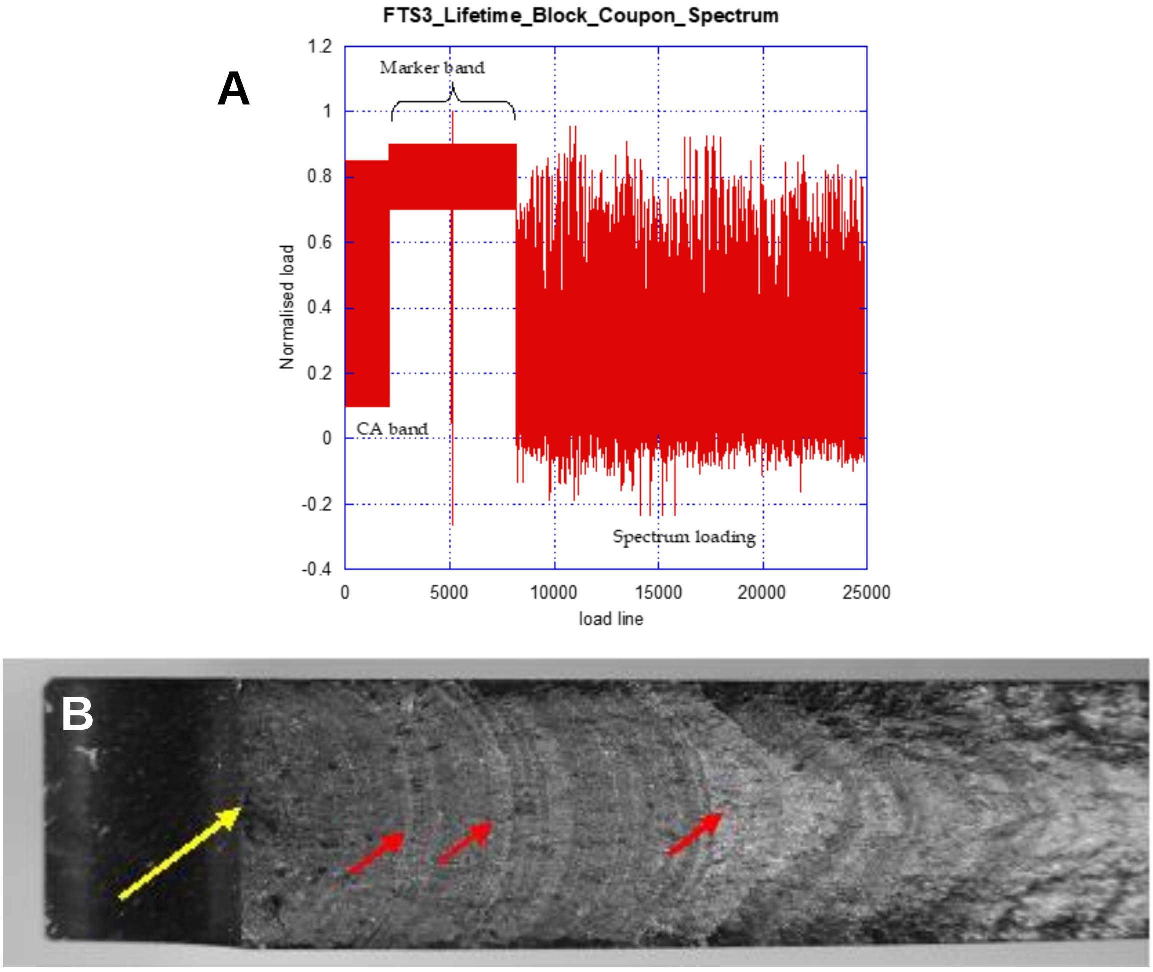

Figure 3: The FSFT sequence of CA, marker band and VA spectrum loading (Figure 3A) as applied to the article and the fracture surface of the trial specimen (Figure 3B) with the origin identified by a yellow arrow and spectrum repeats with red arrows.

The coupon test program and MB development work also served as a basis for FCG research into Ti-6Al-4V under combat aircraft spectra. Observations of nucleation and small crack growth mechanisms were made and FCGR measured using QF for this combat aircraft spectra at representative stress levels (Figure 4). The black arrows in Figure 4 point to the MB's on the fracture surface while the blue arrow points to what is believed the be the nucleation point of the fatigue crack. These MB's could be measured to within a micron of the nucleating feature, allowing extensive small FCGR data to be gathered that can help improve crack growth predictions in comparable aircraft structures. The data from the small crack region was combined with other regions of the coupon where the MB's could be identified, ultimately allowing a crack growth curve to be obtained, as is shown in Figure 5.

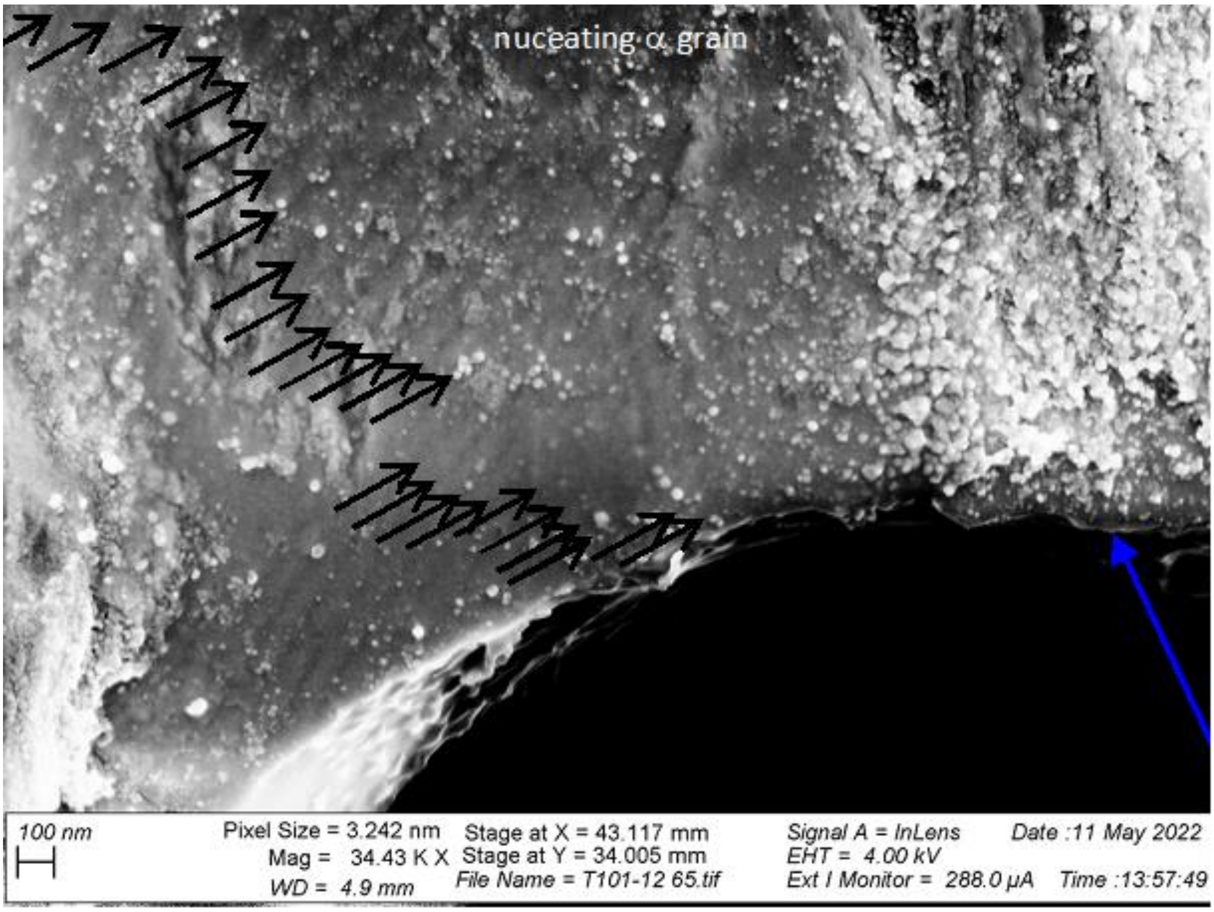

Figure 4: A close-up view of the origin of the specimen in Figure 3B. The black arrows indicate the repeat in the block loading where each is a block of the VA spectrum. The region thought to be the fatigue nucleating feature is indicated with a blue arrow.

The MB’s are not always visible at all crack lengths, which ultimately means that the crack growth curves can be disjointed, as is the case in Figure 5. This lack of visibility is often due to the fracture surfaces rubbing out these features as the crack continues to grow. As a result, the various locations at which the MB’s can be seen must be visually aligned. This can be done using the knowledge that the fastest growing crack in a structure typically grows exponentially until near final failure, where its growth rate accelerates rapidly [6]. This allows the data to be aligned as shown in Figure 5, ultimately allowing FCGRs to be interpolated between the data points from near nucleation up to final failure. This provides extensive representative FCGR data that can be used to guide and enhance fleet decision making in regards to inspections, modifications, and repairs.

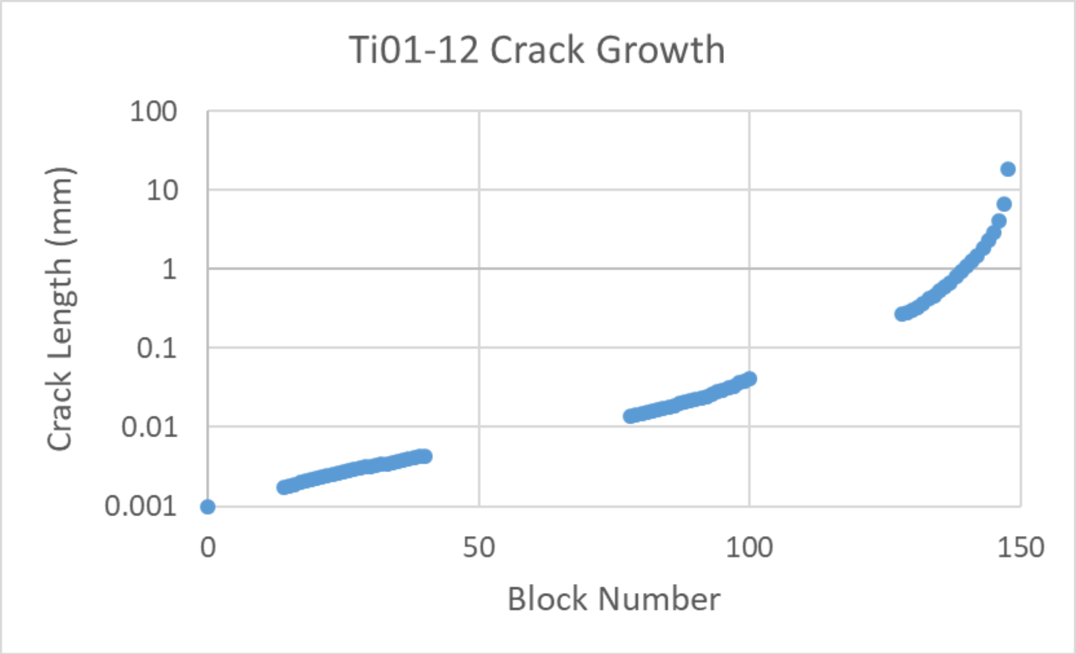

Figure 5: Fatigue crack growth data obtained from the test coupon shown in Figure 3 and Figure 4.

TEST ARTICLE INSTRUMENTATION

The FSFT article, designated ‘FTS3’ had three type of instrumentation systems monitoring surface strains throughout the structure during all phases of testing [7]. These were, a set of 89 conventional foil strain gauges, distributed fibre optic sensors (FOS) [8] and thermo-elastic stress analysis (TSA) cameras.

Conventional Strain Gauges

The foil strain gauges consisted primarily of uniaxial gauges, though a small number of rosettes were also installed in key locations to allow principal strains to be determined. These gauges were installed in a multiple key locations near known or suspected fatigue hotspots, and were utilised for a range of purposes. One purpose was to provide a comparison to strains measured from the Swiss full-airframe FSFT, designated ‘FTS1’. This was possible as many of the gauges were installed in identical locations for both FTS1 and FTS3, and thus formed a basis for FTS3 load scaling prior to spectrum test commencement. A select number of load lines within each spectrum repeat were also monitored on a regular basis for evidence of potential FCG in the structure associated with a change in structural response. This could provide an early warning for FCG and was used to trigger additional visual and non-destructive testing (NDT) inspections in that region. Strain limits were also set in the test control system for each gauge to automatically shut the test down should any exceed their pre-defined limits. Finally, the strain data gathered was used to correlate the physical test with finite element methods, thus improving the overall accuracy of numerical stress analysis methods.

Fibre Optic Sensors (FOS)

The distributed FOS system was a series of stand-alone fibre optic cables adhered to the test structure and remotely interrogated to monitor surface strains along the length of the cables. These cables were installed at various structural points of interest over the test article, including the bottom flange surface of the lower carry-through structure for the two aft bulkheads (Figure 6). Additional lines were also installed around the inside boss or flange of various penetrations in the bulkheads that were used for routeing of aircraft systems. The FOS lines provided a strain reading every 1.6 mm, thus allowing large amounts of strain data to be gathered in a manner that would be impractical using conventional gauges.

To demonstrate the capability of the FOS, its lines were often routed beside strain gauges to allow direct comparison with them. Additionally, different adhesives were trialled on adjacent FOS lines to ascertain whether this would have an effect on the strain data. In general, it was found that the readings from the FOS lines and conventional strain gauges closely aligned [8], and that each of the different bonding methods performed comparatively well under the FTS3 testing conditions [9].

Thermo-elastic Stress Analysis (TSA)

TSA cameras were located to monitor analytical fatigue hotspots in the FTS3 structure throughout the various stages of the STRETCH test program (Figure 6). TSA uses microbolometers, an in-field of view strain gauge and a signal from the control system to produce wide area stress imaging of the structure using the 'thermoelastic effect' (Figure 7) [10]. To produce the highest fidelity data, it is best to cycle the structure at a fast rate using CA cycles. However, it is still possible to obtain reasonable data using the comparatively slow cycling rate and variable loads that are present in the majority of the applied lifetime blocks.

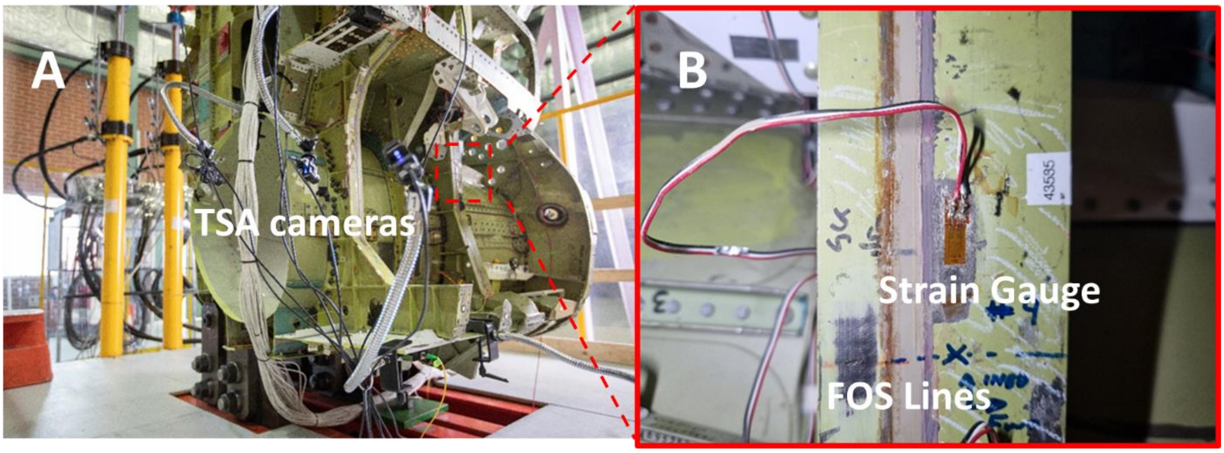

Figure 6: An image of the test article showing TSA cameras surveilling the structure in the test rig (Figure 6A) and a close-up of one of the lower wing carry-through bulkhead's lower flange with two FOS lines fitted in parallel to a conventional foil strain gauge (Figure 6B).

As a result, a dedicated period of CA cycling was applied to FTS3 prior to lifetime testing, as well as continuous monitoring during the lifetimes. The CA cycling prior to lifetime testing was done over a period of multiple days, where the TSA cameras were regularly moved to capture different regions of the test article. Doing this allowed a detailed 3-dimensional stress map of the structure to be generated. The primary hotspots of interest were then chosen to be continuously monitored during DaDT testing of the structure. This allowed a visual method by which cracks or other load changes could be identified during the course of testing.

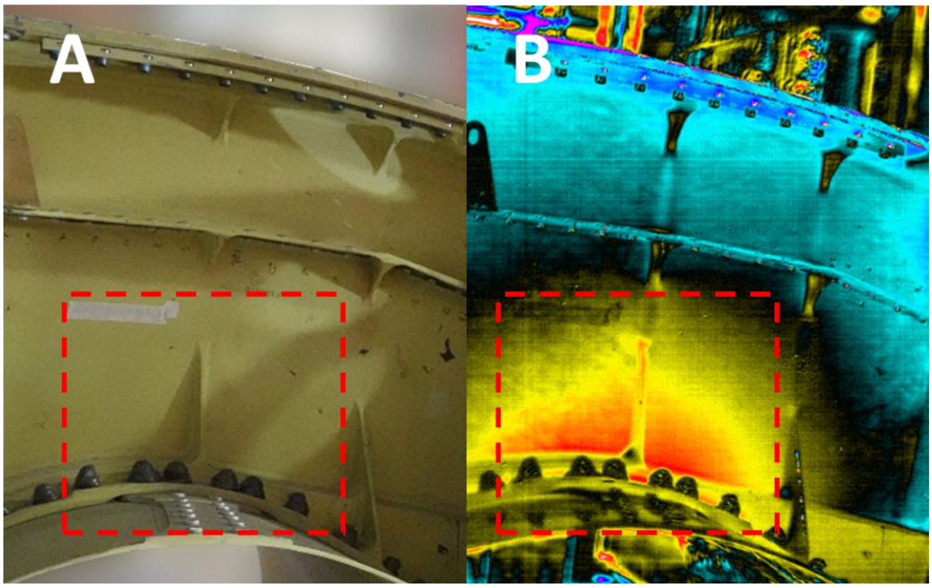

Figure 7: An example TSA image for a bulkhead upper duct flange stiffener location. The raw image is at Figure 7A and the TSA image showing local surface stresses is at Figure 7B. Warmer hues (i.e. red) indicate increased surface stress over cooler colours (i.e. blue).

CENTRE BARREL FULL-SCALE FATIGUE TEST

The centrepiece of the STRETCH project was the FSFT of a Swiss F/A-18 C/D Hornet Ti-6Al-4V centre barrel from the former Swiss F/A-18 C/D FSFT article, FTS1, which underwent 10,400 simulated flight hours (SFH) of durability testing to the Swiss design spectrum before completing a thorough NDT examination. The centre barrel test article, designated FTS3, was extracted from the test aircraft fuselage via cuts forward of the fuselage station (FS) Y453 and aft of the FS Y488 wing carry-through bulkheads.

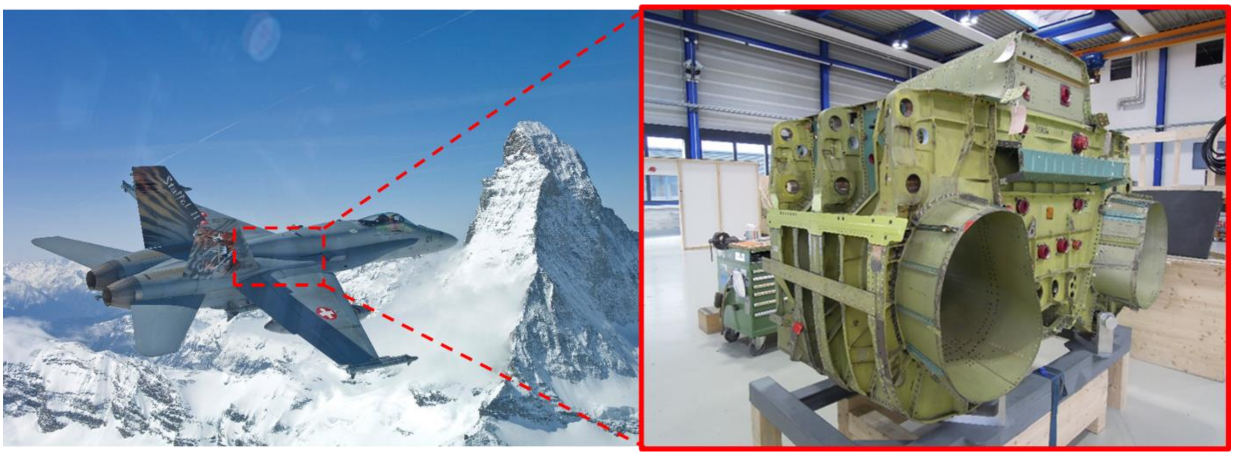

Figure 8: The FTS3 centre barrel test article comprising three Ti-6Al-4V wing carry-through bulkheads.

The test article was transported to DSTG laboratories in Fishermans Bend, instrumented per the previous section and installed into a refurbished test rig from the legacy DSTG FINAL test program for RAAF F/A-18 A/B aluminium centre barrels [11] (Figure 9). This rig loads the test article with both positive and negative WRBM loads via the F/A-18's wing attachment lugs at each bulkhead using three sets of opposing actuators working to load each bulkhead in unison and to a flight representative loading distribution across the structure.

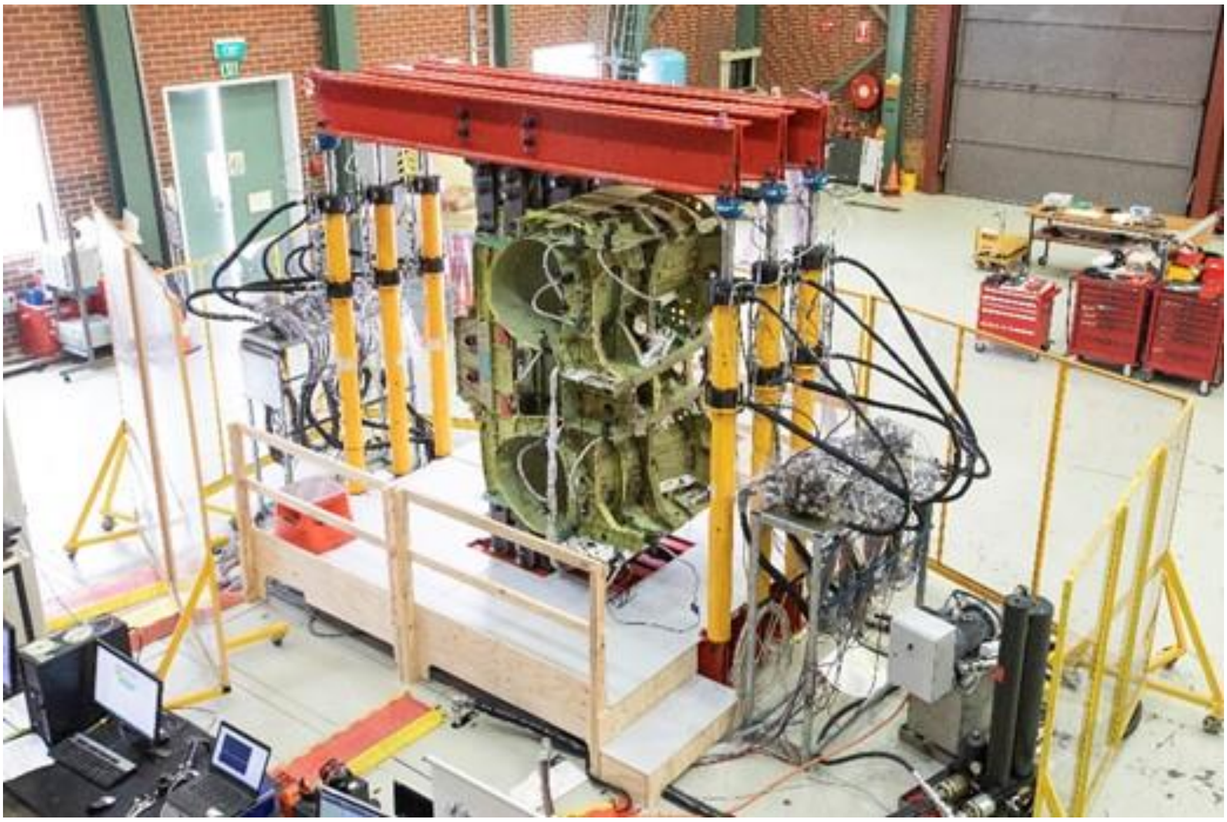

Figure 9: FTS3 ‘STRETCH’ Centre Barrel installed in the test rig at Fishermans Bend.

The STRETCH project aimed to apply 3 service lifetimes of a Swiss usage spectrum, 3 x 6,000 = 18,000 SFH for durability test loading and a further 3 lifetimes, 18,000 SFH, for damage tolerance loading to the FTS3 article. This testing was in addition to the 10,400 SFH completed during FTS1 (deemed to be equivalent to 2 FTS3 lifetimes). Each repeated block of loading was equivalent to approximately 300 SFH. A lifetime of testing therefore included a single CA equivalent block and MB, plus a further 19 repeats of the VA + MB spectra. Daily visual inspections of the article were completed and a full NDT inspection period (typically 3 days) was completed at the end of each lifetime (6,000 SFH) using predominately visual and eddy current inspection. At the time of publication, the FTS3 test article was still cycling during its final lifetime of damage tolerance testing. The achieved FTS3 FSFT schedule is shown in Figure 10.

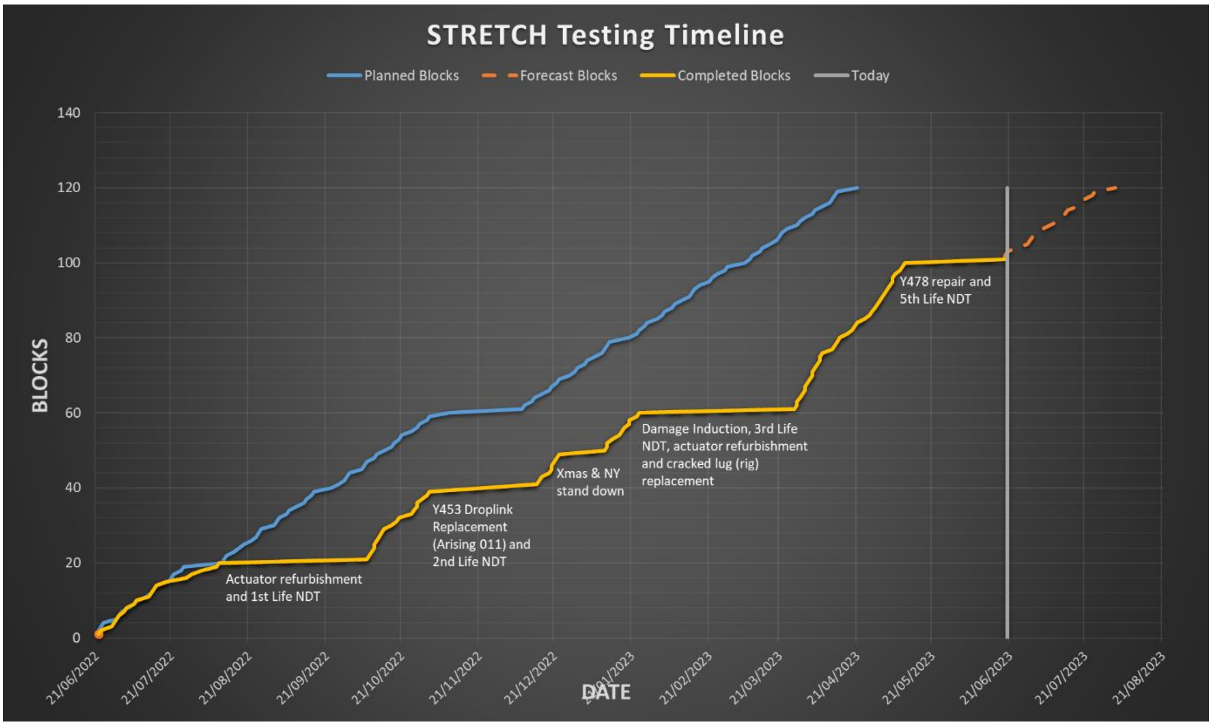

Figure 10: FTS3 'STRETCH' Centre Barrel FSFT Test Schedule.

Durability Phase

The durability testing phase of FTS3 encountered a small number of technical issues relating to actuator reliability/performance and only two notable instances of fatigue cracking, both in non-primary structure locations that were manufactured from aluminium alloys. The actuator issues required them to be sent externally for refurbishment at the end of the first lifetime, and one of the secondary structure cracks necessitated a replacement of the cracked component at the end of the second lifetime. Both these activities resulted in significant test down time, thus causing the end of the durability phase (60 blocks) to be completed roughly two and half months behind schedule. Despite this, the testing rate during the remaining lifetimes was usually at a rate equal to or greater than predicted, particularly as the testing continued. This outcome was due to refinements in rig tuning as the test continued as well as the refurbished actuators allowing the loading rate to be increased without negatively effecting test accuracy.

Damage Tolerance Phase

Prior to the start of the damage tolerance phase, 17 fatigue hotspots of the test article had damage induced of sizes ranging from approximately 0.254 mm (0.01 inch) to 1 mm (0.04 inch) in depth. Damage was imparted using either an e-Drill [12] or the DSTG developed selective plasma arc spot melting (SPASM) method. Prior coupon testing was undertaken to validate equipment settings for Ti-6Al-4V, heat affected zone size and effects and the onset of stable FCG. Preliminary results from damage tolerance phase testing indicate these methods are likely to be very successful with fatigue crack nucleation and growth observed from this induced damage during the test phase (Figure 11).

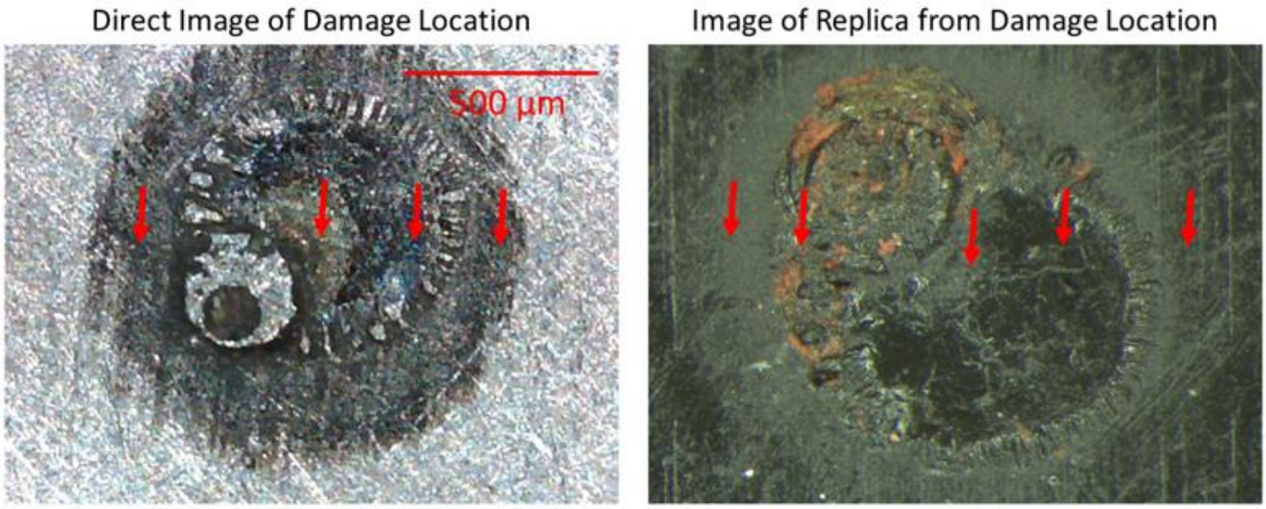

Figure 11: An example of fatigue crack growth from a bulkhead DT location. The direct image of the SPASM arc burn is at left and a replica of the damage and cracking is on the right.

The e-Drill method utilised the e-Drill gun with a modified electrode to allow the tool to spark erode a crack-like feature. An image of the e-Drill gun setup in a temporary rig prior to cutting is shown in Figure 12A, while an example electrode used for cutting crack-like features is shown in Figure 12B. This method was primarily used for imparting the 1 mm damage in the structure.

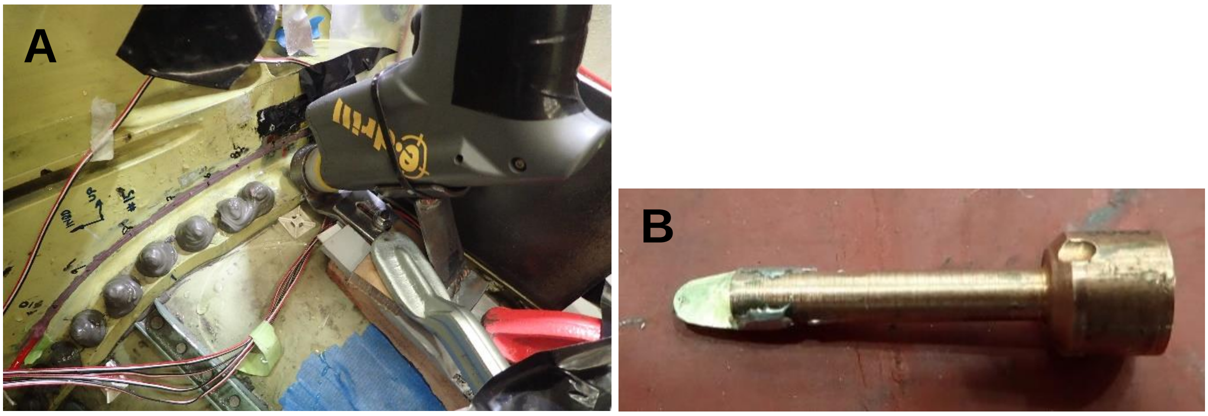

Figure 12: An image of the e-Drill gun setup in a temporary rig to allow it to cut a crack-like feature in a fastener hole (Figure 12A), and an image of a modified electrode with a rounded cutting tip (Figure 12B).

The DSTG developed SPASM method made use of a capacitor that would be charged to a specific energy level, and then rapidly discharged on the target area to locally melt the region. That region would then rapidly cool due to the surrounding material and environment, causing it to crack from the thermally induced internal stresses. This produced a small crater and burn on the target surface, as can be seen in Figure 11. This method was found to be particularly ideal for imparting damage of the order of 0.254 mm.

TEARDOWN AND FRACTOGRAPHY

A full teardown and thorough NDT inspection of the test article, as of the time of publication, is currently being planned. This shall include QF of significant fatigue cracks and damage induction locations in each of the wing carry-through bulkheads. Any FCG data gathered from this process will assist with the life extension of the aircraft by allowing improved predictions of the allowable service life of the various components.

CONCLUSIONS AND RECOMMENDATIONS

This paper has presented progress to date under a joint Switzerland and Australia research collaboration into FCG in titanium combat aircraft structures known as STRETCH. Considerable experimentation into Ti-6Al-4V FCG at both a small-scale material and full-scale structural level have been completed. This has been undertaken with a heavy reliance on direct observation of FCG behaviour using QF techniques which provides increased confidence when making decisions using this data compared to previous analytical predictions. Two unique strain analysis methods, FOS and TSA, have been successfully utilised in a manner that is complimentary to the conventional strain gauges. A DSTG developed damage induction method, SPASM, has also been used to impart roughly 0.254 mm damage in the structure. One of these locations has a detectable fatigue crack growing from it providing evidence that this method can be successfully utilised to impart small-scale crack-like damage in FSFT articles.

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