SOME OBSERVATIONS TO RECENT FULL SCALE FAIGTUE TESTS

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Abstract: Today, full-scale fatigue testing is required as means of compliance against proof of structure to certify both composite and metallic structures. This paper presents the common practice to set up and to monitor the full-scale fatigue testing of aircraft control surfaces done in GKN Aerospace Services Ltd. These tests include Bombardier projects on testing ailerons, rudder and elevator, etc, and recently a Long Range Business Jet project of testing wing movables consisting of flap, flaperon, aileron and airbrake.
Although full scale fatigue testing has been successfully applied in the past to demonstrate compliance for aircraft certification, some recent full-scale fatigue testing results reveal some issues on structure design philosophy, measurement techniques, and correlations which may affect its implementation for future aircraft structures. This paper outlines some findings based on the results observed using standard practice and measuring techniques to validate the structural analysis. Buckling found during fatigue test cases has been monitored throughout the test duration. Strains and deflection surveys are used for correlation to the predictions, and are used to check test consistency. In cases of crack growth from either natural cracks or saw-cuts, predictions and monitoring to the crack growth are presented.
Finally, from the above mentioned there is a need to review the state-of-art measurement techniques to support full-scale tests. New techniques such as DIC is applied with some level of success but more reliable and mature measuring techniques are still required to be explored in industries.

Keywords: Fatigue, Crack Growth, Residual Strength, DSG, SDS, DIC, Weight Function

INTRODUCTION

Aircraft certification is the process by which a new design, or an amended Aircraft Type, demonstrates its compliance to the airworthiness and environmental protection requirements applicable for the product. For large and medium sized aircraft, these requirements are contained within airworthiness standards, either EASA CS 25 [Ref 1] or FAA FAR-25 [Ref 2]. The current acceptable means of compliance requires full-scale fatigue tests to evaluate fatigue life, damage tolerance and residual strength of the structures.
Generally, metallic fatigue full-scale testing requires demonstration of two Design Service Goal (DSG) durability test and a period of Damage Tolerance testing followed by residual strength test. For most GKN Aerospace testing, one DSG of damage tolerance testing is applied followed by the critical limit load case for residual strength test.

For metallic structures design and certification, a building block approach is the acceptable means of compliance to meet the requirement of analysis supported by tests. The process starts with small coupon testing to derive design values in analysis and then followed by proof of structure full-scale testing, see Figure 1.

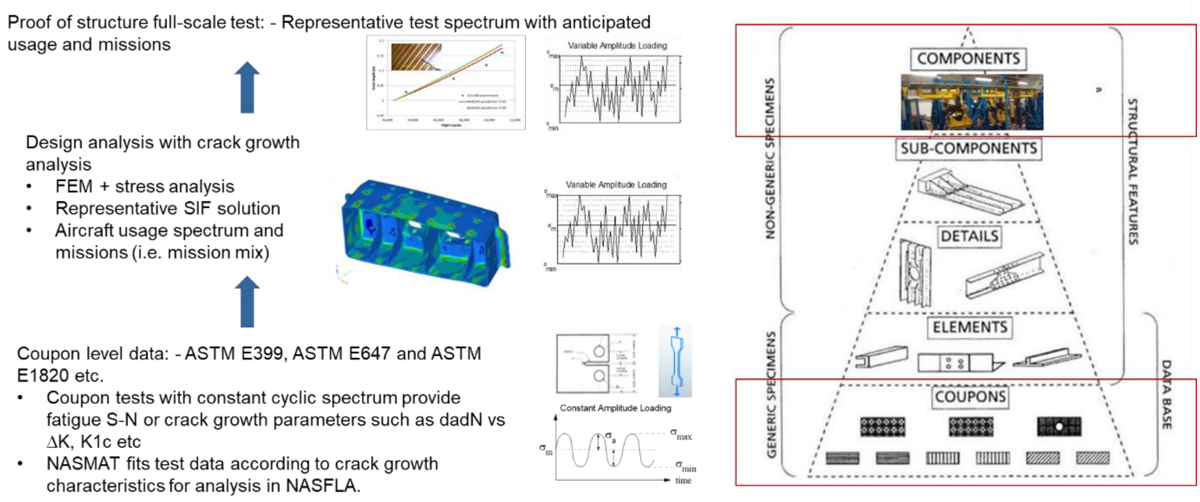

Figure 1 Building block Approach

Figure 2 shows the test sequence for a typical full-scale metallic control surface testing.

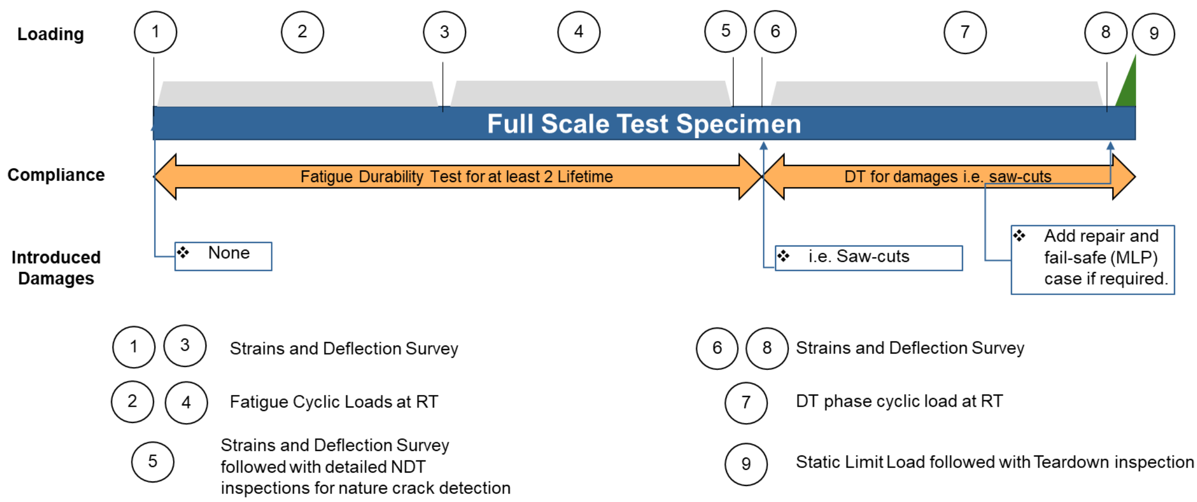

Figure 2 Metallic F&DT Test Sequence

The objectives of proof of structure testing for metallic fatigue and damage tolerance include the followings:

- To verify assumptions made in F&DT analyses and to confirm critical locations from analyses.
- To demonstrate the damage tolerance characteristics of the Principal Structural Elements (PSEs), i.e. demonstrating flaws tolerant or Multi-Load Path (MLP) capability.
- To prove durability of the metallic structure for at least two Design Service Goal (DSG) under representative operational spectrum and loading.
- To validate the crack growth analysis using Damage Tolerance (DT) testing and to verify

the threshold and repeat inspection intervals in order to establish a reliable inspection plan for maintenance.

- To demonstrate Residual Strength capability in the presence of critical flaw from analysis under limit load case defined in CS25.571 at the end of the fatigue and DT testing.
- If required, to provide 1 year ahead of structural fatigue performance to lead aircraft prior to entry into service.
- For any part failed during the test, there is a potential modification to be embodied.
- At the end of the test, there can be a teardown inspection.

In GKN Aerospace, full-scale testing of control surfaces were mostly composite designs or hybrid structure designs in the past. Recently a Long Range Business Jet wing movables are all metallic designs and include flap, flaperon, aileron and airbrakes.

SPECTRUM SIMPLICATION

The fatigue spectrum and loads covering the entire lifetime in design are complex to test. The set-up of the test must consider constraints such as discrete loading in test from limited number of hydraulic jacks to represent continuous aerodynamics pressure load in design, spectrum simplification or truncation for speeding up testing time, dummy structures to represent periphery parts, simulating sympathetic bending to a control surface etc. It is important and crucial to ensure a representative test loading and spectrum to the full-scale test specimen with respect to the analytical and design loading and spectrum in order to obtain required fidelity of test results. To determine the spectrum to apply to the test, the following activities are required:

- Control Point Study: performed on critical fatigue or DT locations and major loading point locations across the test structure in order to determine a simplified test spectrum and testing loads while retaining a representative level of fatigue damage within the structure.
- Test Sequence Derivation (Spectrum Truncation): the full spectrum turning points from design is simplified to test manageable number of turning points without losing accuracy of the spectrum. This study uses the analytical stress and spectrum at each control point location to remove small amplitude cycles that do not have a significant contribution to the damage (see Figure 3). The final test sequence is the combined turning points from all the control points.

TEST LOADING CALCULATION

All load inputs to test to simulate the design loads are applied using hydraulic jacks. Loading pads in whiffletree arrangement connected to limited number of hydraulic jacks are used to represent continuous aerodynamics pressure load. In addition, sympathetic bending to control surface is simulated using hydraulic jacks applied to attachment interface with enforced displacement control.

After combined the simplified test spectrum with discrete test loads, the equivalent once per flight stress approach can be convenient to use for comparison between design and test stress sequences at control point locations. By assuming the S-N curve being a log-linear line defined as $C = N\sigma^b$ (b is the slope parameter of the SN curve), any paired damage cycle in a block spectrum can be converted to stress ratio $R = 0.1$ using the following Walker equation.

$C_i = n_i [s_{max}(1 - R)^m]^b$ Where m is a material parameter and i indicates a cycle

By using equivalent damage theory, one can derive an equivalent once-per-flight stress according to *R = 0.1* as follows:

$$N_{block}\left[\sigma_{eq\_R=0.1}(1-0.1)^m\right]^b = \sum n_i\left[(1-R)^m\sigma_{max,i}\right]^b$$ Where N_{block} is number of flights in a block

Or $$\sigma_{eq\_R=0.1} = \frac{1}{0.9^m}\left\{\frac{1}{N_{block}}\sum n_i\left[(1-R)^m\sigma_{max,i}\right]^b\right\}^{1/b} \qquad (1)$$

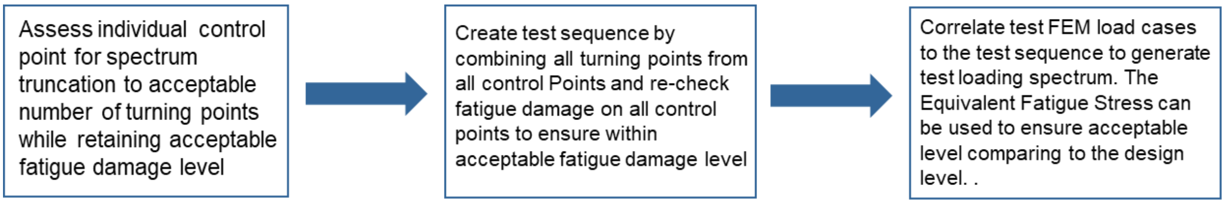

Figure 3 Test Spectrum Simplification and Test Load Derivation

TEST ARTICLE INSTRUMENTATION

Today, the most reliable measurement techniques are still strain gauges, crack growth gauges, load cells and linear displacement transducers etc. To facilitate the full scale test, the test specimen are constructed according to the requirements for instrumentation to the test. Some gauges need to be applied to the pre-assembly part level before the final assembly. Typical usage of gauges are categorised:

- Far Field (verification) Strain Gauges are used to validate the relatively coarse Global FEM (GFEM) which is typically FEM constructed using simple BAR or QUAD elements. These gauges are limited to uni-axial or multi-axial gauges. For control surfaces, uni-axial gauges might be installed along spar or rib flanges where the principal strain direction is generally constant. Multi-axial gauges being used where shears and principal strain directions may vary such as on skins or rib webs.
- Feature Strain Gauges are used at locations in proximity to stress concentrations such as around cut-outs or fillet radii on machined fittings. These locations are normally determined using Detailed 3D FEM (DFEM) stress plots which indicate peak stresses. As such these gauges can be used to validate the DFEM.
- Crack growth gauges are used to all saw-cuts and any found natural crack over areas where crack growth path is expected. These gauges consist of an array of wires that are broken as the crack grows.

Load cells are used to check component level loads on the actuators and linear displacement transducers along areas of peak deflections are used to validate deflected shapes predicted by the GFEM.

COMMISIONING THE TESTS

After derivation of the test spectrum and test loading sequence, two or three load cases in the test sequence are selected for the purpose of Strain and Deflection Survey (SDS). These test load cases allow us to get a set of measured strains and deflections from the test in order to compare with predictions. In the past, a percentage of critical limit load (i.e. approx. 50% LL) case were often used. However, critical limit load case sometimes may not represent the behaviour of load cases in fatigue spectrum. So critical fatigue load cases based on maximum and minimum turning points in spectrum (i.e. Ground-air-ground cycle cases) are better selection for SDS cases. For control surfaces, another case may be selected which consists of maximum effect of sympathetic bending case in spectrum.

Once the SDS cases are applied to take strains and deflections measurements, a comparison against test FEM predictions can be checked if percentages of deviation between both results are acceptable with a tolerance value. Prediction for these strains and deflections must be ready as a part of test readiness review and the predictions should be based on test FEM. The SDS is mandatory to be applied before and after each test stop, especially when the test article is out of rig for service and inspections so that consistency of the test can be checked.

Inspection tasks to be performed during testing include the followings:

- Daily general visual is required to ensure test function normally,
- A general visual examination of test article and attachment fittings supported by detailed visual examination in the critical areas of attachments during every test stop
- Detailed visual inspection as above plus borescope where access permits when the test article is removed from the test rig
- At the end of fatigue phase testing and at the defined interval during DT test with the test article removed from the test rig, there can be requirement to perform eddy current inspections, in additional to Penetrant Flaw Detection (PFD) inspections, covering detailed Fillet radii, saw-cuts or any cracking locations or holes if accessible etc.

All inspections details are recorded in the inspection report and any observations identified such as changes in crack length and any damage or observation identified are recorded. Any saw-cuts and cracks must be measured and recorded at time of inspections.

F6X FLAP TESTING – UPPER SKIN PANEL BUCKLING

During early stage of the F6X flap fatigue test, buckling was discovered in several upper panels during some flight cycles. One of the strain gauges on the top surface upper panel displayed compression spikes in measured data (see Figure 4).

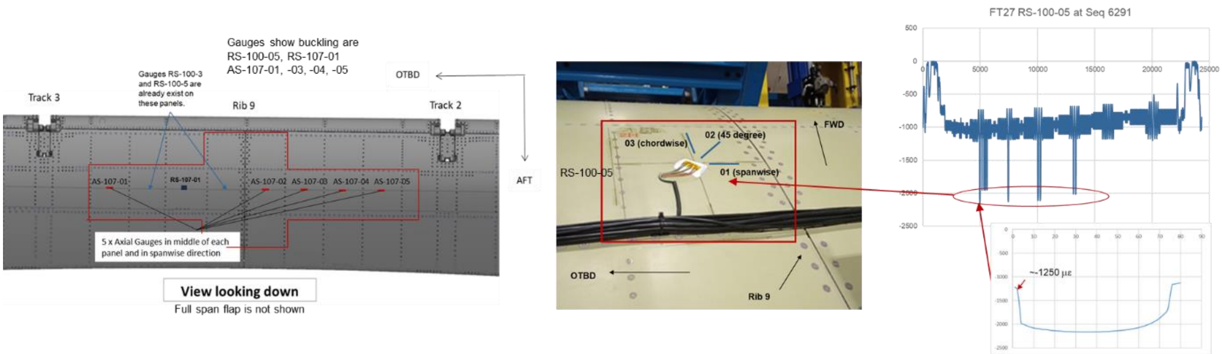

Figure 4 Flap Upper Panel Buckling During

The drive for lightweight structures, especially when using metallic, results in very thin skins. Their behaviour can therefore be more of a thin film than traditional aerospace semi-monocoque structures. These are more susceptible to combined loadings especially for control surfaces that have air loads interacting in proximity with sympathetic bending loads. During the static test regime, no buckling was observed before 70% of any limit load cases. One observation of static limit load case and the fatigue load case with buckling is that buckling happens with large wing bending or large enforced displacements acting on track 2 and track 3. For those cases, the flap aero pressure is not high. Static cases are down-selected out of the enveloping process. Therefore, there is never a maximum wing bending together with maximum aero pressure in a single case. This result gives a doubt to the approach of using 70% limit load for no buckling to cover fatigue, in particularly for control surfaces.

To continue the fatigue test, additional analysis was preformed to account for load redistribution and to ensure that the load level it occurs would not be detrimental to fatigue. During every test stop, additional DVI inspections applied to all fasteners around the panels that show buckling. At the end of the second DSG fatigue test, PFD and Eddy current inspections applied on to all fillet radii and joint locations. There was no natural crack found and the test progressed to damage tolerance phase for saw-cuts.

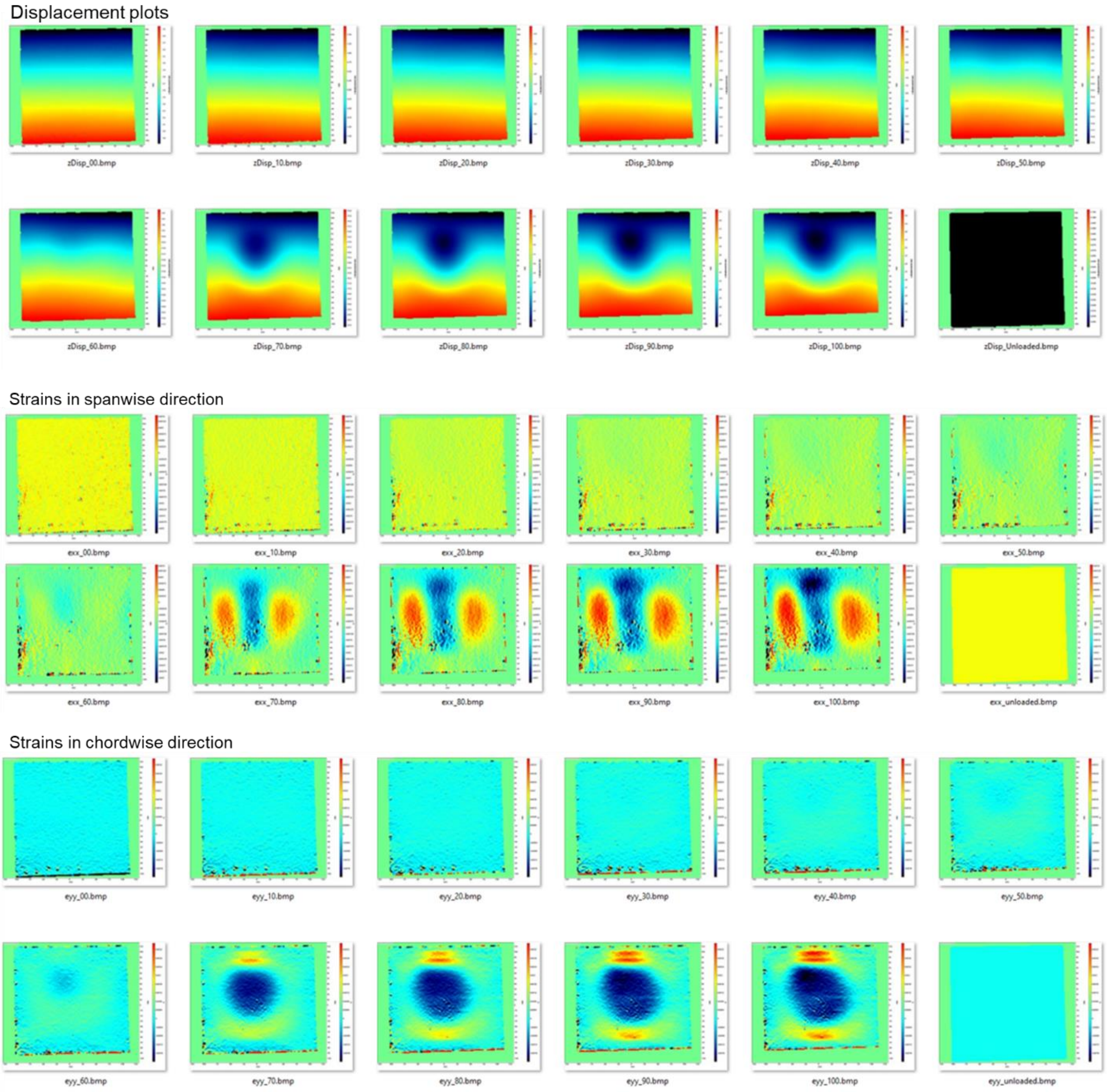

Figure 5 DIC Study of Flap Buckled Panel

Further investigation of the panel buckling with Bath University applied the Digital Image Correlation (DIC) technique on one of the buckled panel (RS-107-01). The SDS load case showing buckling from strain gauge readings was applied in 10% increment with DIC shots and the results are shown in Figure 5. It should be noted that the SDS case is a fatigue based case rather than a percentage of limit load base case for the reasons discussed earlier.

DIC plots showing buckling may even started at 60% of the applied load case as shown in Figure 5. After the panel buckled, there were tensile strain fields in addition to compression strains in both spanwise and chordwise directions. Although there was an effort to estimate strains around fasteners pre and post panel buckling, the result was not conclusive and only confirmed that the strains were no longer linear to the applied load increments.

CRACK GROWTH CORRELATIONS

After two DSG fatigue test, saw-cuts are applied to the crack growth critical locations from analysis. In most cases, saw-cuts may not grow and if they grow or any natural crack found during DT test, the crack growth rates from testing are monitored against predictions to demonstrate correlation between test and analytical prediction.

<u>F6X Flap Testing – Track 2 Saw-Cut Growth Monitoring</u>

The fatigue and crack growth critical location is the fillet radius on Track 2 fitting of the flap. Although some top skin panels showed buckling in fatigue cycles, strain gauges comparison showed that buckling has insignificant effect to the fatigue and crack growth critical locations. The saw-cut (a through cut of 2 mm in length and 0.2 in width) on Track 2 fitting fillet grew during the third DSG for damage tolerance testing.

In order to monitor the saw-cut on Track 2 fitting fillet radius, analytical prediction of crack growth is performed using test FEM to generate the spectrum sequence on Track 2 and using 3DFEM with the critical load case to confirm strains near the stress hot spot on the fillet. These FEM results are correlated with measured strain gauge data as shown in Figure 6. Since the crack grows from a stress hot spot, stress gradient is studied from the 3D FEM so that a Weight Function (WF) solution such as NASGRO stress intensity factor (SIF) TC12 can be used.

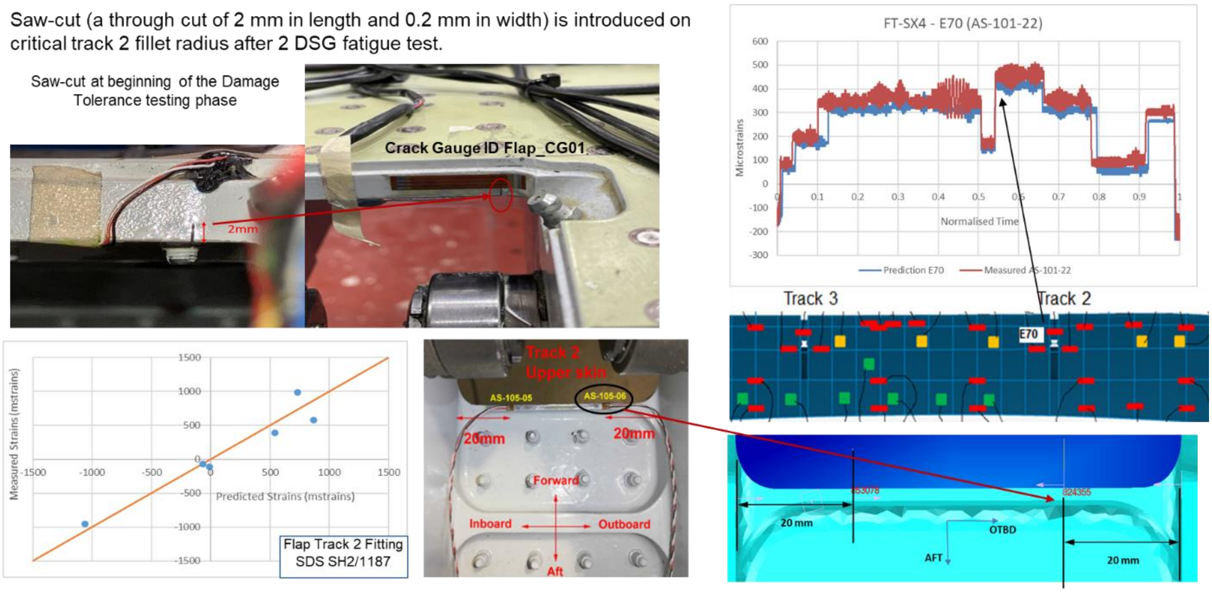

Figure 6 Track 2 Fillet Radius strain and turning points checks

The WF method or the Green's function method is a generic class of structural analysis method utilising the theory of superposition. If the closed–form or semi closed-form solution due to a point force is known, the stress intensity can be evaluated by integrating the stress gradient function multiplied with the point force solution [Ref 5].

$$K_I = \frac{1}{\sqrt{\pi c}} \int_0^c \sigma(x) g(x)\, dx \tag{2}$$

Where the function *g(x)* is a closed-form or semi closed-form [Ref 6] function from a point force and $\sigma(x)$ is the stress gradient obtained from FEM. The weight function solution gives a representative Stress Intensity Factor (SIF) solution for a crack emanating from a stress hot spot.

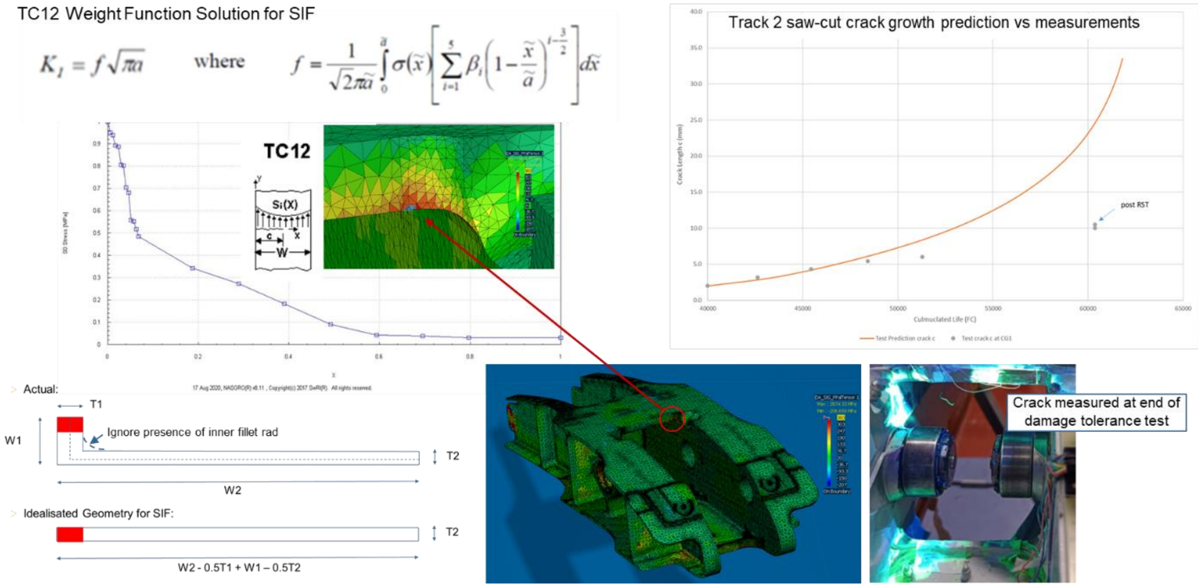

Figure 7 Flap Track 2 Fillet Radius through crack growth correlation between test and prediction analysis

Figure 7 shows the idealised section and the stress gradient used to derive the SIF in NASGRO with TC12 solution. It also shows the correlation between predicted crack growth curve using test GFEM spectrum sequence with the DFEM peak stress from the maximum fatigue load case to TC 12 against the measured data points from crack growth gauges. Note that the prediction analysis bases on Linear Elastic Fracture Mechanics (LEFM) and has no consideration of retardation effect or crack plasticity.

<u>F6X Flaperon Testing – Crack Found during DT Test</u>

After half DSG in the DT test phase for the flaperon, inspection found a natural crack on the fillet radius of the Inboard (IB) bell crank arm. This crack was reported from Penetrant Flaw Detection (PFD) inspection as a corner flaw of 5mm and 3 mm in sizes (see Figure 8).

Predictions of the crack growth rates for the remaining half of the DSG were performed using test GFEM and test spectrum sequence. The stress gradient input to NASGRO CC09, which is a corner flaw weight function solution, is derived using the DFEM stresses. Further, the peak stress from the maximum fatigue load case is used with the CC09 NASGRO solution. The weight function solution can give representative SIF for a crack emanating from a stress hot spot as indicated from the DFEM shown in Figure 8. Again, the prediction was only LEFM without consideration of retardation.

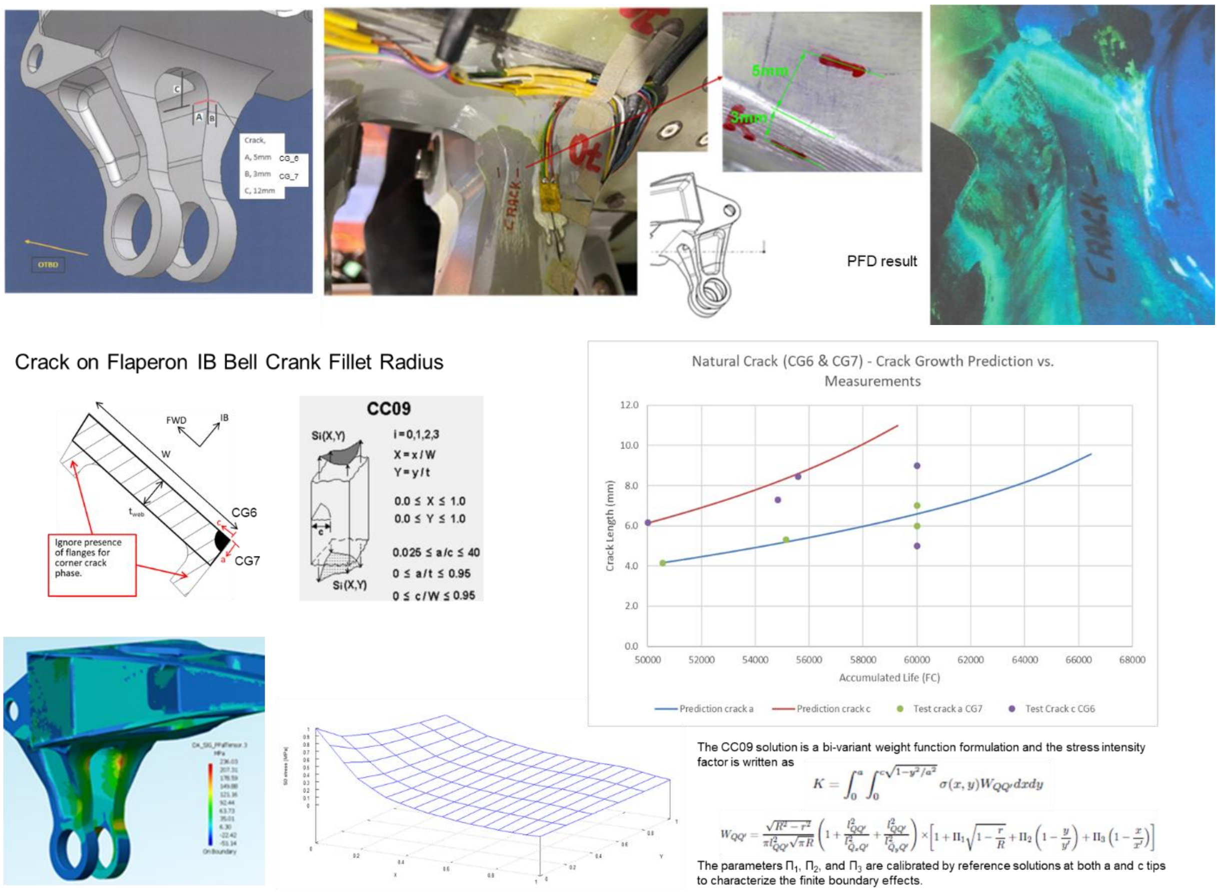

Figure 8 Flaperon Bell Crank corner crack growth correlation between test and prediction analysis

Subsequently, crack growth gauges CG06 and CG07 were added to the tips of the crack. The correlation between the predictions and measured crack growth rates from crack growth gauges are shown in Figure 8. It should be noted when the test re-started, the crack growth gauge CG06 tripped off straight away. This indicted that the 5 mm crack length measured using PDF might not be accurate. By switching to the next line on the crack growth gauge CG6 the test continued as expected. Then shortly after the restart, similar problem happened to CG7 and hence the initial crack sizes in the prediction analysis were 6.1mm and 4 mm rather than the PFD measured 5 mm and 3 mm. In the final measurements at the end of DT test (at end of the 3rd DSG), eddy current measurements were used that gave better correlated crack lengths to the measured sizes from Crack Growth Gauges (CG6 and CG7) and the predictions.

OBSERVATIONS AND CONCLUDING REMARKS

The control point study into spectrum and loading is based on fatigue critical and major load introduction points. If buckling is the critical static sizing criteria for the structure and in particular, the on-set of buckling is under limit load, the fatigue test assessment must check for any possible buckling during fatigue test. This is because buckling can cause local nonlinearity, which is normally not accounted in fatigue or DT analyses.

For monitoring the test, the selection of strain and deflection survey (SDS) cases is more appropriate using a maximum load case and a minimum load case in the fatigue spectrum. These cases diagnose the test specimen better under fatigue cycling range than factored limit load cases. The SDS cases shall be performed before and after each time when the test specimen is taken off from the test rig so that consistency of the test case can checked.

In case of crack or saw-cut growth monitoring, the following correlations are necessary in order to give comparable predicted crack growth rates versus measured crack growth rates.

- Stress level and sequence correlation: it is necessary to check at crack or near crack locations the predicted strains against the measured strains and if possible to compare sequence turning points between predicted and test spectra.
- Representative stress intensity factor solution: the crack growth prediction analysis should apply a SIF solution representing to the hardware structure dimensions and boundaries. The weight function method of stress intensity factor is a powerful method if the crack is emanating from a stress hot spot.

If the above two points giving good matching, the crack growth correlation is likely to be good. All predictions base on LEFM. All fitting materials are Aluminium Alloy 7040 and the cracks are relatively small size comparing to the size of the fitting structures. These may be the reasons that LEFM works for those structures.

Strain gauges measurements at selected locations can confirm high strains from FEM predictions. There may be a need in future analysis to resolve non-linear behaviours to ensure critical areas and load redistributions understood for fatigue cases. This is especially important if buckling is allowed below limit loads.

The limitations in resolution of strains measurements also make it difficult to investigate root causes and devise solution paths for issues found during test. For future testing improvements, there are increasing needs to investigate more advanced measurements and monitoring techniques (i.e. DIC or other state-of-the-arts techniques). With improvements such as DIC, not only validation of FEA will be easier, but it can also provide realistic strain data with which to substantiate problems subsequently found during the testing phases. Since most cracks are emanating from stress hot spots, it is necessary to have a measured plot of critical strain/stress hot spots in order to compare with the DFEM predicted hot spots. In addition, the crack length measurements at test stops require accurate and consistent measurements to avoid any misleading results against crack growth gauges.

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ABBREVIATIONS

DIC: Digital Image Correlation

DSG: Design Service Goal

DT: Damage Tolerance

DFEM: 3D FEM or Detailed FEM

F&DT: Fatigue and Damage Tolerance

FEM: Finite Element Method

GFEM: Global FEM

LEFM: Linear Elastic Fracture Mechanics

MLP: Multi-Load Path

PFD: Penetrant Flaw Detection

PSE: Principal Structural Element

SDS: Strains and Deflections Survey

WF: Weight Function

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