GKN Structural Analysis Function – Structural Testing

Some Observations to Recent Full Scale Fatigue Tests

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GKN Aerospace East Cowes and Structural Testing Facilities

Flying Boats (Saunders-Roe started 1929)

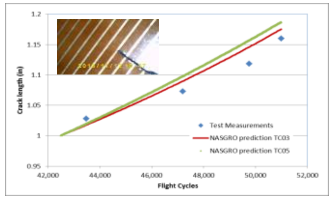
Rocket Design, Build and Testing (Saunders-Roe 1955 - 1971)

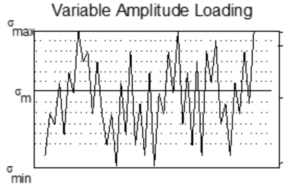
British Hovercraft Corporation (BHC 1966 - 1984)

Westland Aerospace and GKN Aerospace plc

Building Block Approach (Analysis supported by tests - Metals)

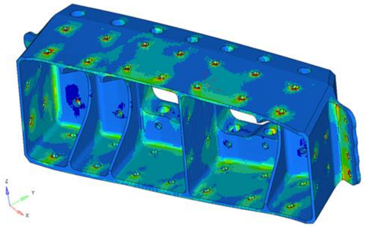
Proof of structure full-scale test: - Representative test spectrum with anticipated usage and missions

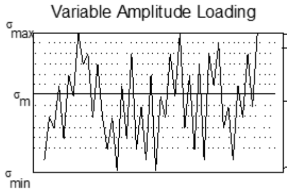




Design analysis with crack growth analysis

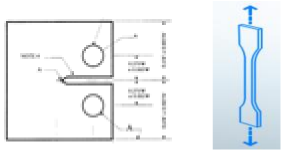
- FEM + stress analysis
- Representative SIF solution
- Aircraft usage spectrum and missions (i.e. mission mix)

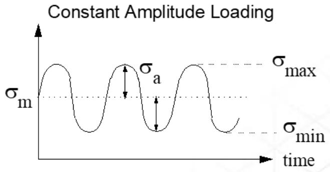


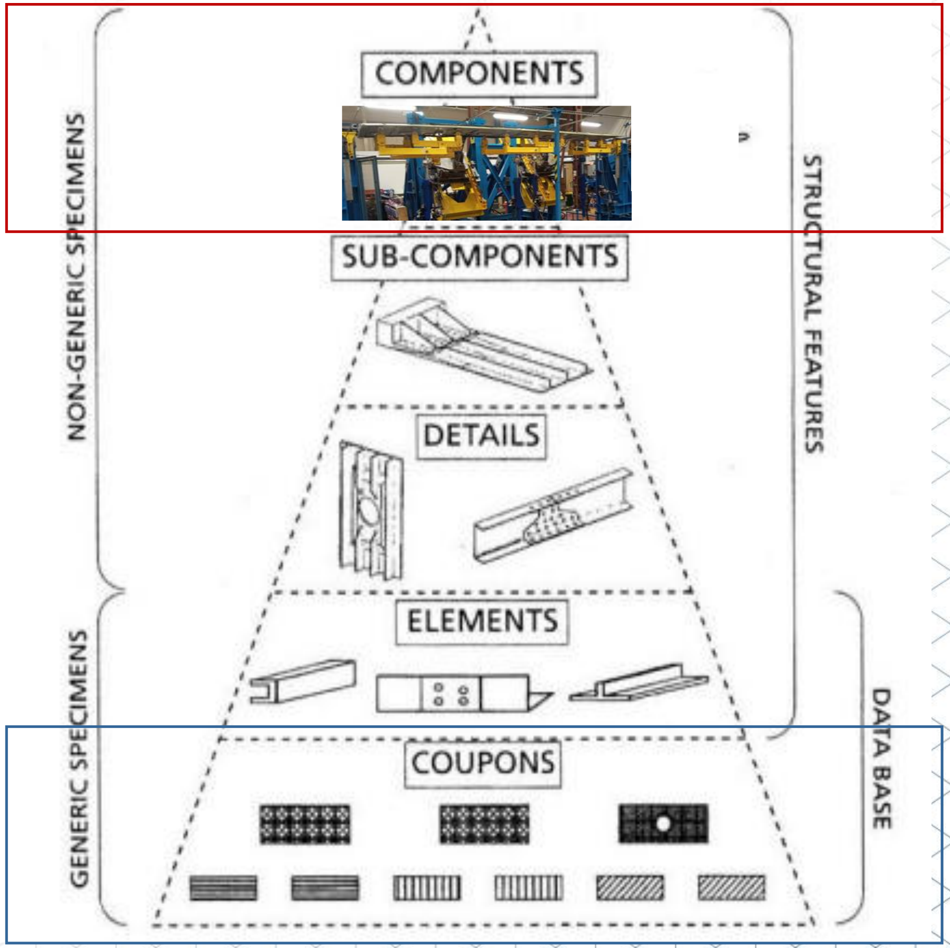


Coupon level data: - ASTM E399, ASTM E647 and ASTM E1820 etc.

- Coupon tests with constant cyclic spectrum provide fatigue S-N or crack growth parameters such as dadN vs ΔK, K1c etc
- NASMAT fits test data according to crack growth characteristics for analysis in NASFLA.







Control Points and Test Sequence Derivation

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.

Assess individual control point for spectrum truncation to acceptable number of turning points while retaining acceptable fatigue damage level

→ Create test sequence by combining all turning points from all control Points and re-check fatigue damage on all control points to ensure within acceptable fatigue damage level

→ Correlate test FEM load cases to the test sequence to generate test loading spectrum. The Equivalent Fatigue Stress can be used to ensure acceptable level comparing to the design level.

A control points study on critical fatigue or DT locations and major loading point locations across the test structure is performed in order to determine a simplified spectrum and applied loads while retaining a representative level of fatigue damage within the structure. Control Points Selection criteria include:

- Critical fatigue / DT locations
- Major Loads introduction points

Perform Truncation and simplification Study with Design FEM

- Test Sequence Truncation (i.e. Removal of intermediate points, eliminating small turning point cycles that contribute insignificant damage, and discarding small amplitude but high frequency cycles that are less than a certain range contributing to no damage in LCF)

Generating Representative Spectrum and Loading for Test using Test FEM

- Test Loading Calculation and Comparison

Equivalent Fatigue Damage Stress

Spectrum truncation study bases on fatigue damage comparison between full design spectrum and truncated spectrum by an acceptable tolerance, which delivers a test spectrum with average turning points for required test duration.

$$Fatigue\ damage = \sum \frac{n_i}{N_i}$$

Where *i* represent a turning point cycle either in full spectrum or truncated spectrum

The truncation study shall be based on only one FEM results, normally the design FEM, and after truncation study the test FEM results can be combined with the truncated spectrum.

Then the equivalent once per flight stress approach can be convenient to use for comparison between design and test stress sequences.

- If we consider 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 cycles in a block spectrum can be converted to stress ratio $R = 0.1$ using the Walker equation.

  $C_i = n_i\,[\sigma_{max}(1 - R)^m\,]^b$ 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 $R = 0.1$.

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

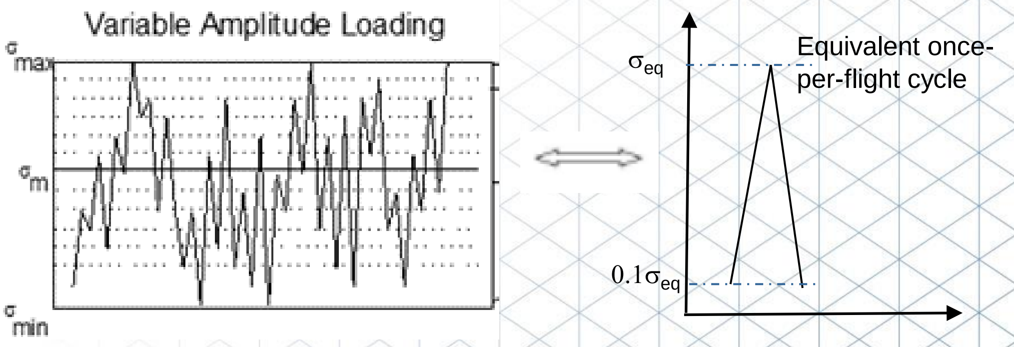
- Or

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

Where N_{block} is number of flights in a block

Flights or a block of N_{block} Flights

Equivalent Once per Flight

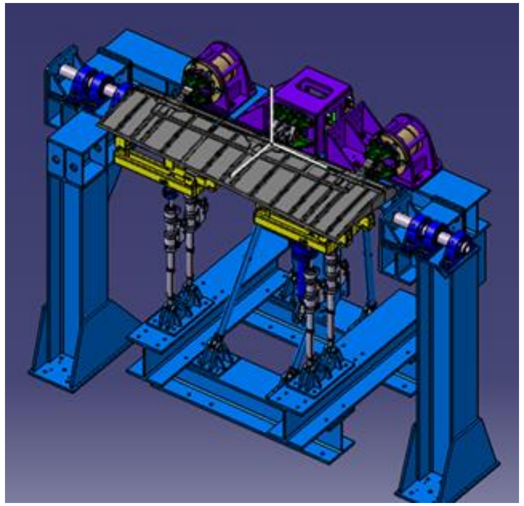


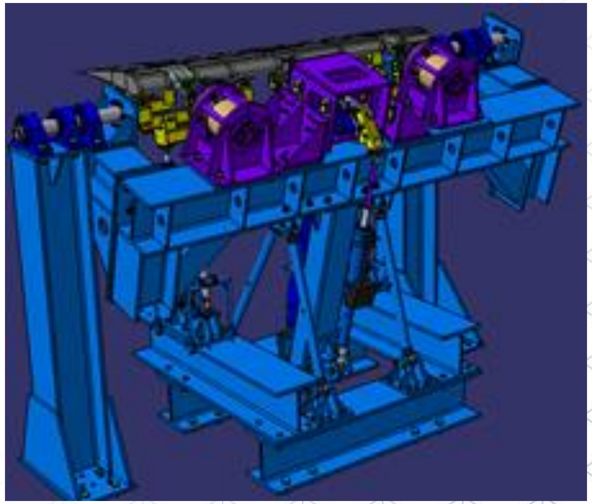
Selection of Strain and Deflection Survey (SDS) Cases

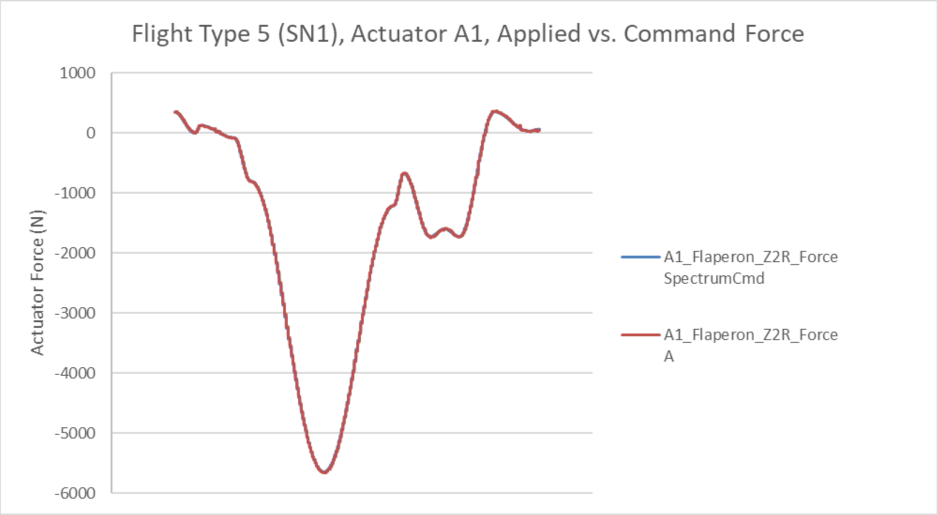
- Before starting cycling the test, two or three load cases are selected to allow us to get a set of strain and deflection measurements from the test article. These test cases are termed as Strain and Deflection Survey (SDS) cases. Some Criteria to select SDS test cases are as follows
  - A percentage of critical limit load (i.e. approx. 50% LL) case could be used.
  - Critical fatigue load cases are found on maximum and minimum turning points in spectrum (i.e. Ground-air-ground cycle cases)
  - For control surfaces, a case may be selected that consists of maximum effect of sympathetic bending case in spectrum
- Prediction for these strains and deflections must be ready as a part of test readiness review items and the predictions should be based on test FEM. Once the SDS was applied and strains and deflections measurements are taken, a comparison against test FEM predictions must be done to check if percentage of deviation between both results does not exceed a certain tolerance value.
- Today, the most reliable measurement techniques are still strain gauges, crack growth gauges, load cells and linear displacement transducers.
- The SDS is <u>mandatory</u> to be applied before and after each test stop, especially when the test article is out of rig for service and inspections.
  - Far-field Strain Gauges
  - Feature Strain Gauges

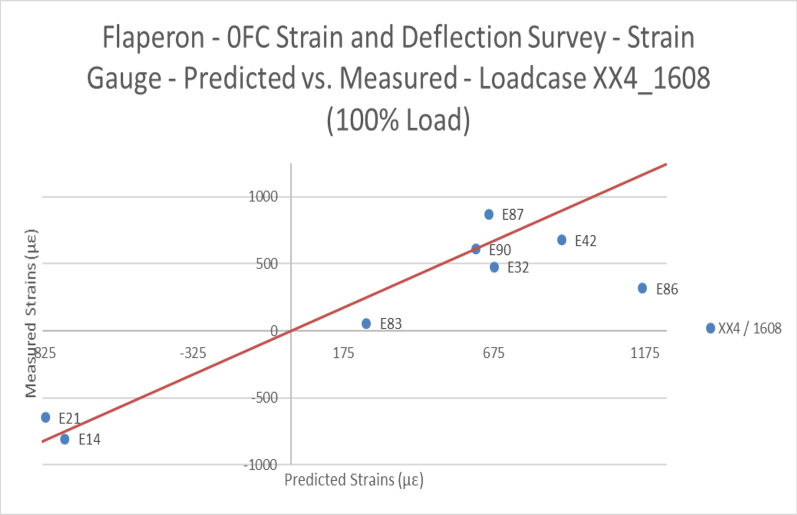
Commissioning the Test

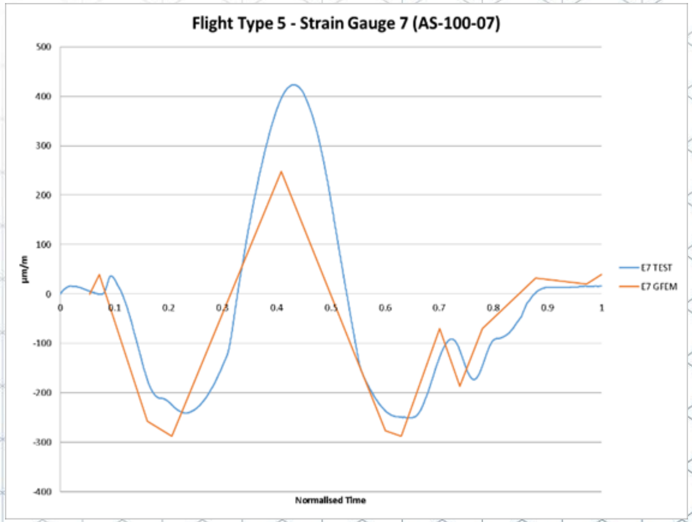
- For example the F6X flaperon test is set to 15 degree on the rig.
- Pre-start the fatigue cycling, SDS cases are applied to check
  - All applied jack loads are with +2% accuracy tolerance
  - All monitoring strain gauges are in acceptable range
- Then starting cycling and acquire a complete flight strain gauge measurements to check against prediction flight.





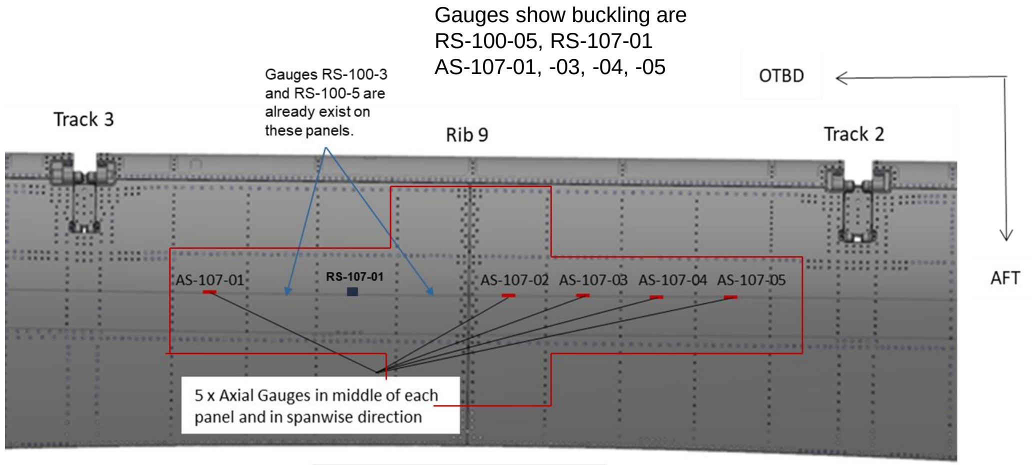






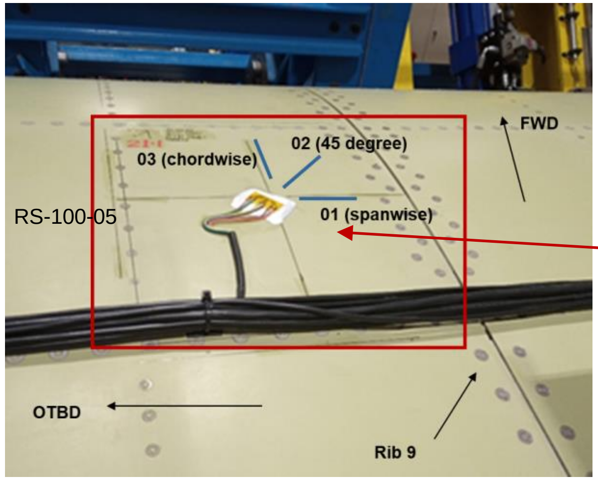
Flap Testing – Upper Skin Panel Buckling

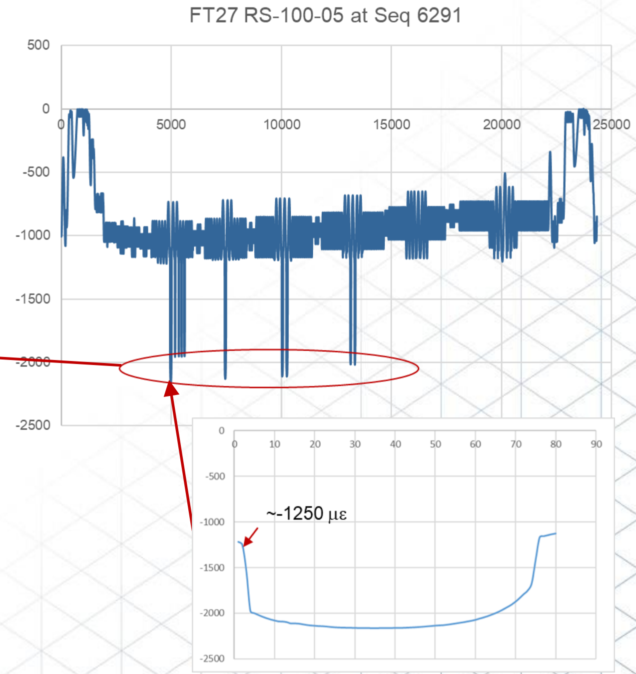
- During early stage of the F6X flap fatigue test some upper panels buckling were found in <u>some</u> cycles during <u>some</u> of flights in test.



View looking down

Full span flap is not shown



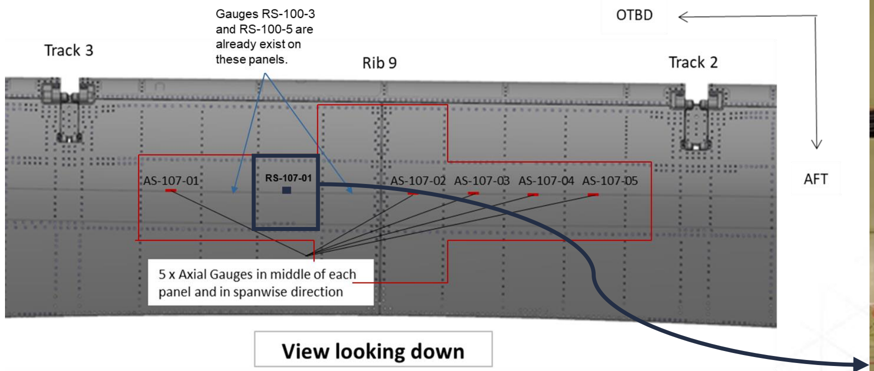


- The fastener joints fatigue life of the upper skin were re-checked with buckled panels and estimated load increase due to buckling. Also the F&DT critical locations (track 2 and track 3 fitting fillets) have been checked by strain gauges comparison that buckling has no effect to these critical locations. Furthermore, during every test stop, DVI inspections were applied to all fasteners in the red box area as shown above.

- At the end of the second DSG fatigue cycling test, PFD + Eddy current inspections were called on all fillet rad locations. No natural crack found on GKN designed structures.

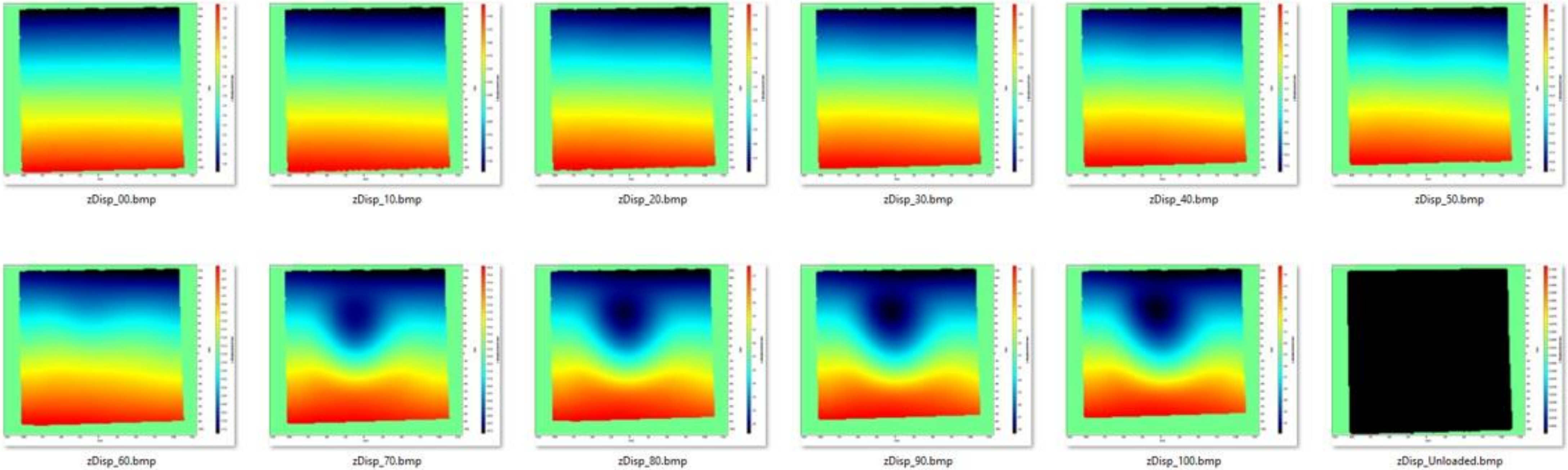
DIC Study on Flap Panel - Displacement Plots

- Towards the end of flap DT testing phase, GKN Aerospace collaborated with Uni of Bath on a trial project that used Digital Image Correlation (DIC) technique to investigate one of the buckled panel (RS-107-01).
- One of SDS load case showing buckling from strain gauge readings on this panel was applied, and the strain gauge was removed and replaced with DIC pattern.
- The load case was applied in 10% increment with DIC shots.



Full span flap is not shown

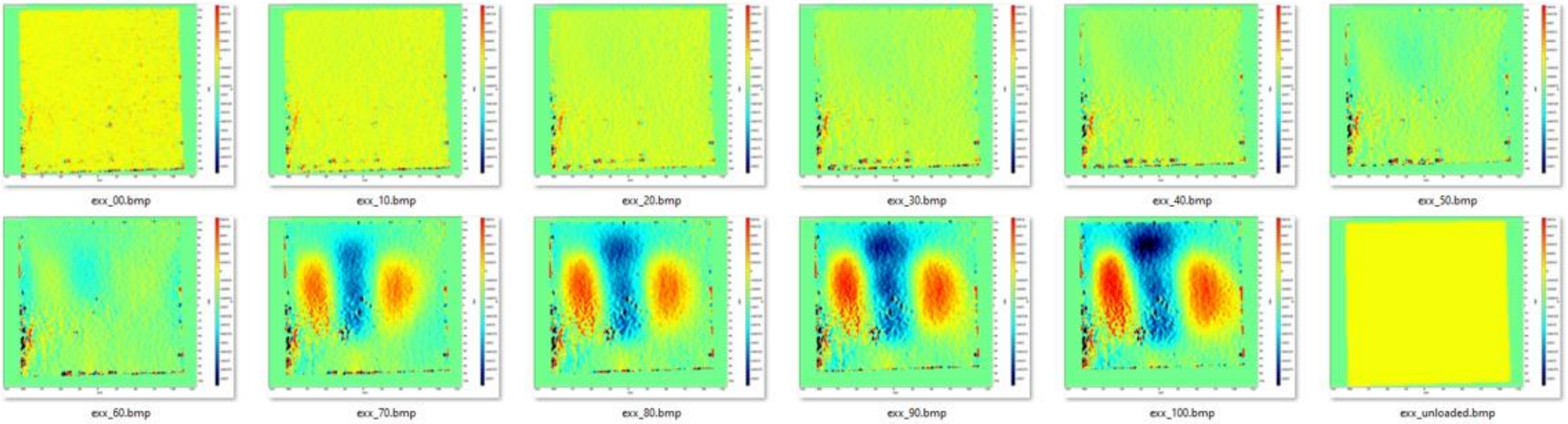
Displacement plots



DIC Study on Flap Panel - Strains in X direction (spanwise)

- Strains along flap spanwise were showed from DIC plots in 10% increment of the applied load case. Buckling may even started at 60% of the applied load case.
- After the panel buckled, there were tensile strain fields in addition to compression strains.
- In the trial test, although there was an effort to estimate strains around fasteners pre and post panel buckling, the result was not conclusive and only could confirm that the strains were no longer linear to the applied load increments. This implied that the strains around fasteners would be higher than as predicted after the panel buckled.

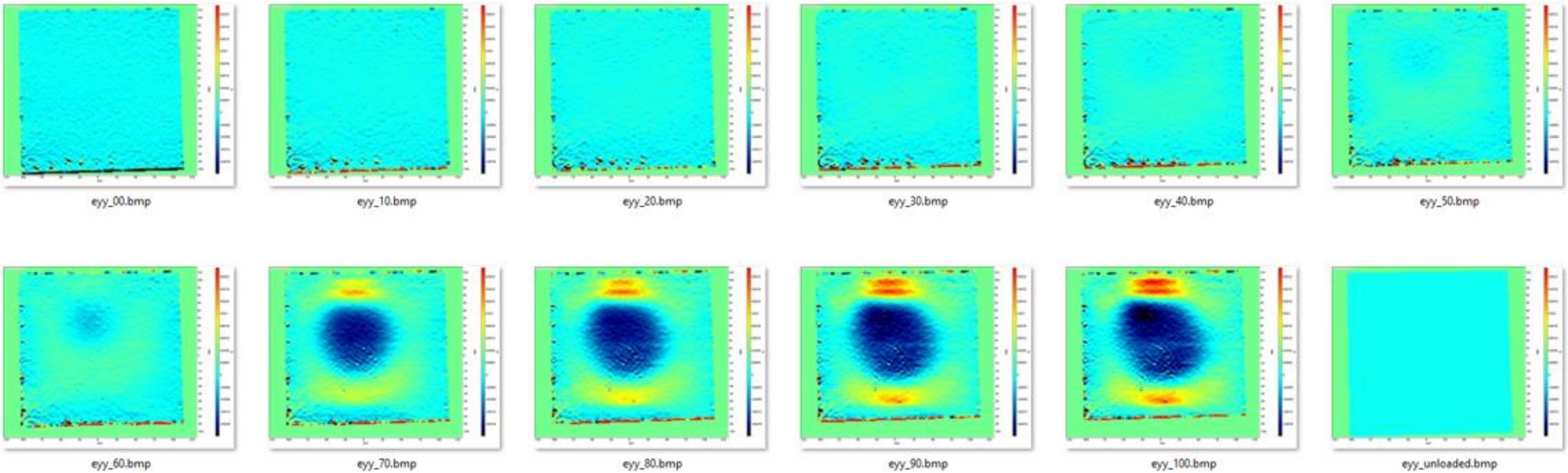
Strains in spanwise direction



Strains in Y direction (Chordwise)

- Again, tensile strains were shown in Chordwise in addition to compression strains from DIC plots after the panel buckled.
- One observation to the tensile strains was the fact that they were close to the fastener joints giving concern to effect of joints fatigue performance after panel buckled.

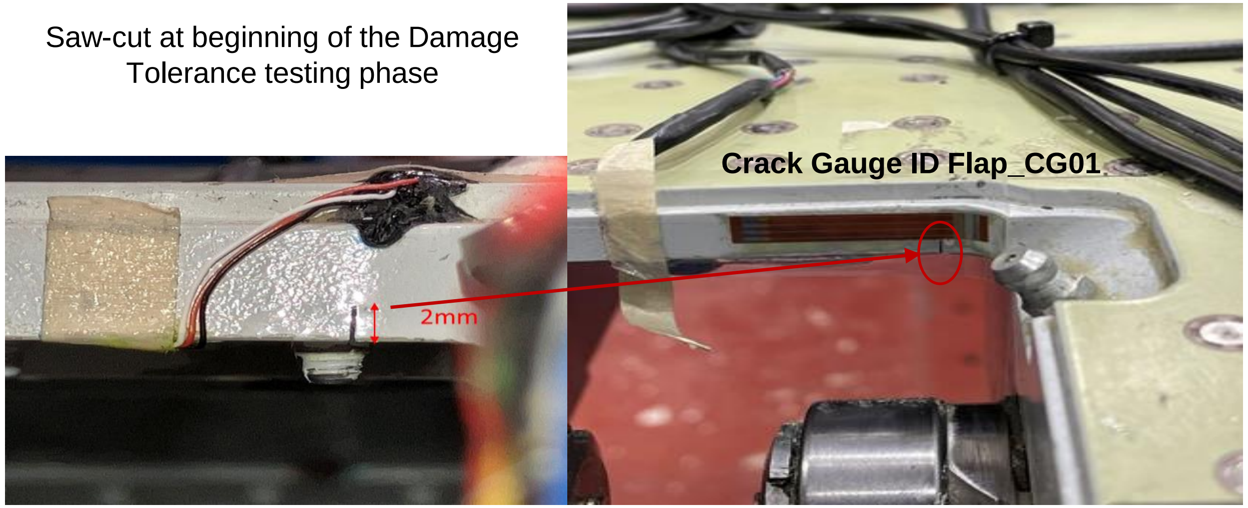
Strains in chordwise direction

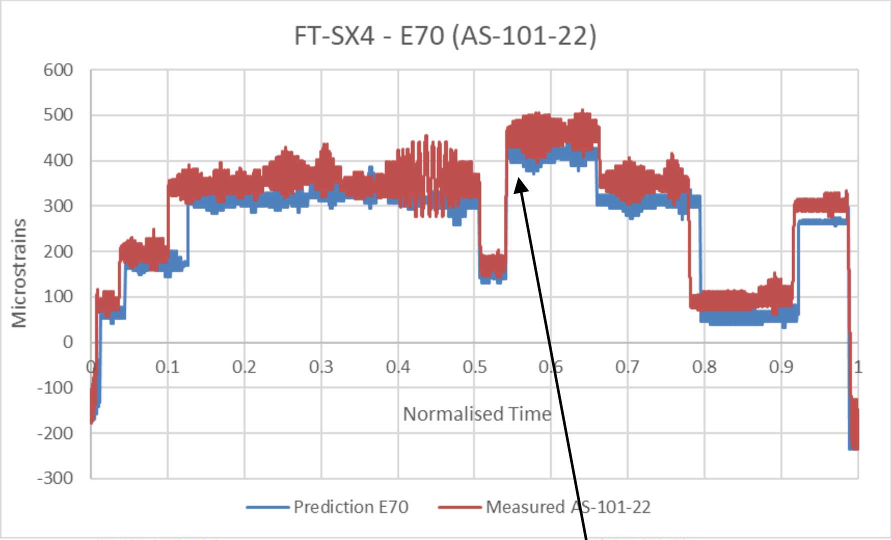


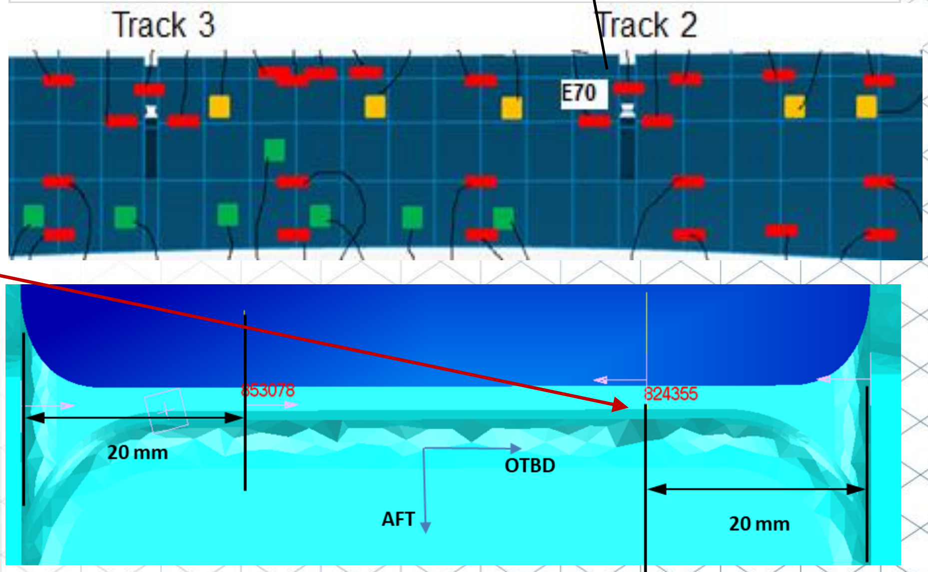
Flap Testing – Track 2 Saw-Cut Growth Monitoring

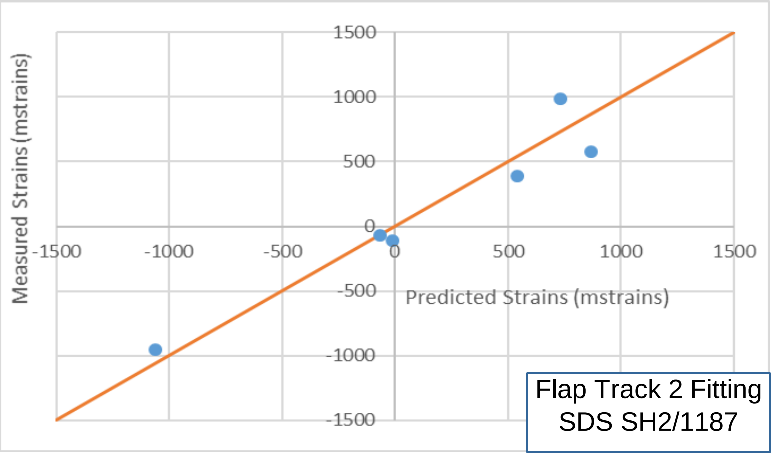
Saw-cut (a through cut of 2 mm in length and 0.2 mm in width) is introduced on critical track 2 fillet radius after 2 DSG fatigue test.

Saw-cut at beginning of the Damage Tolerance testing phase

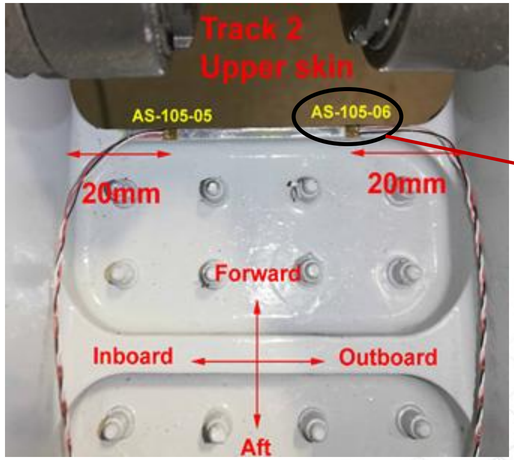








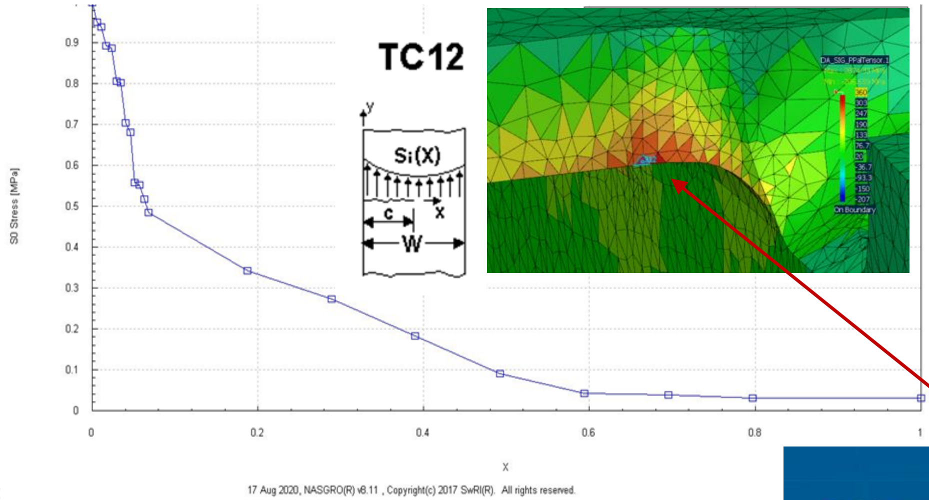
Flap Track 2 Fitting
SDS SH2/1187

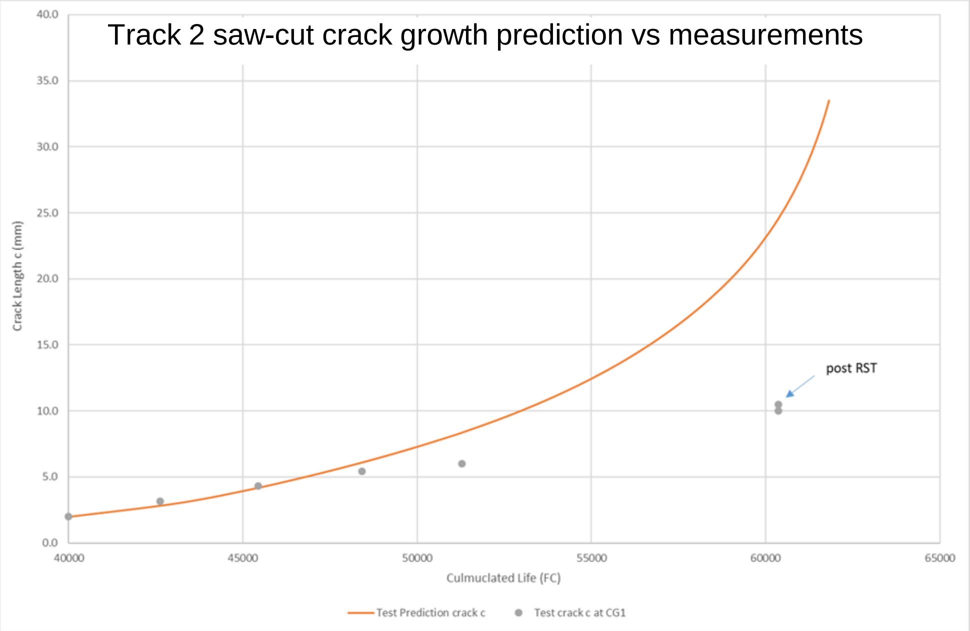


Validation of Crack Growth Analysis – Track 2 Saw-Cut Correlation

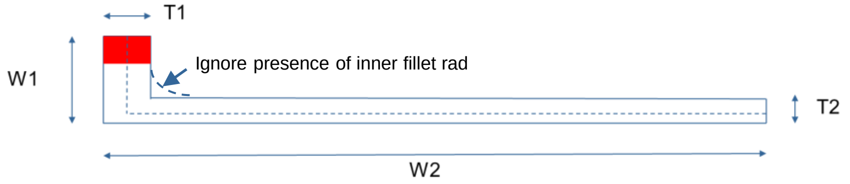
TC12 Weight Function Solution for SIF

$$K_I = f\sqrt{\pi a} \quad \text{where} \quad f = \frac{1}{\sqrt{2\pi\tilde{a}}}\int_0^{\tilde{a}} \sigma(\tilde{x})\left[\sum_{i=1}^{5}\beta_i\left(1-\frac{\tilde{x}}{\tilde{a}}\right)^{i-\frac{3}{2}}\right]d\tilde{x}$$

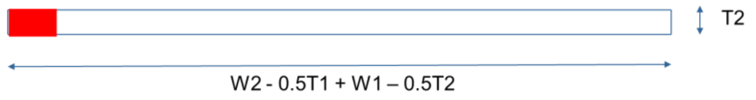


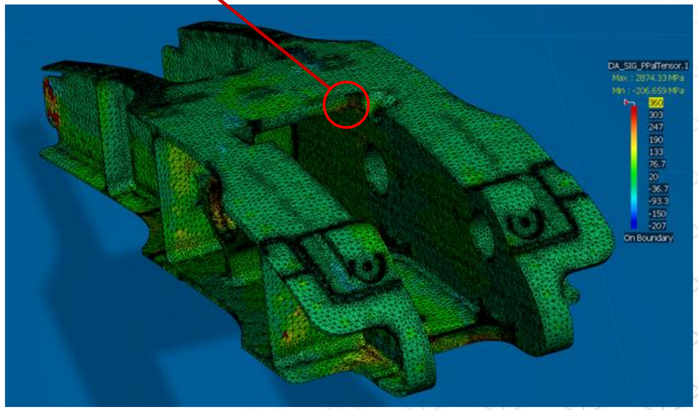


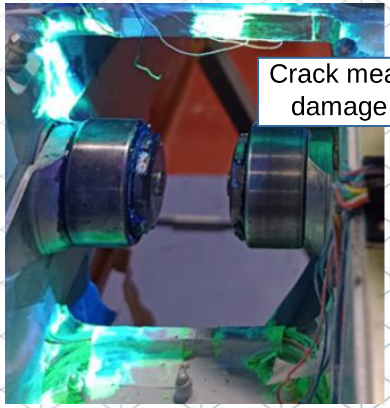
- Actual:



- Idealisated Geometry for SIF:



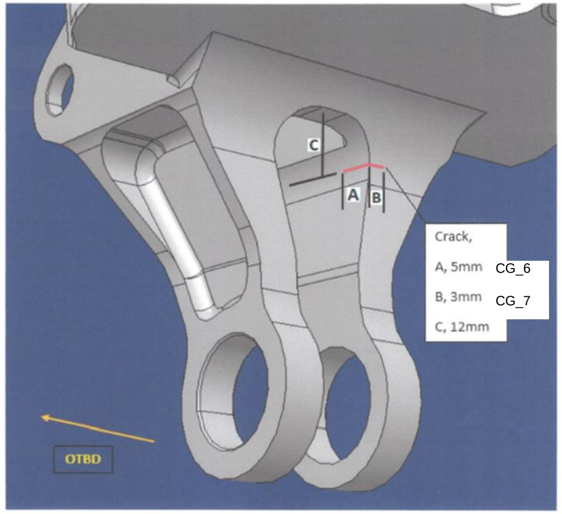


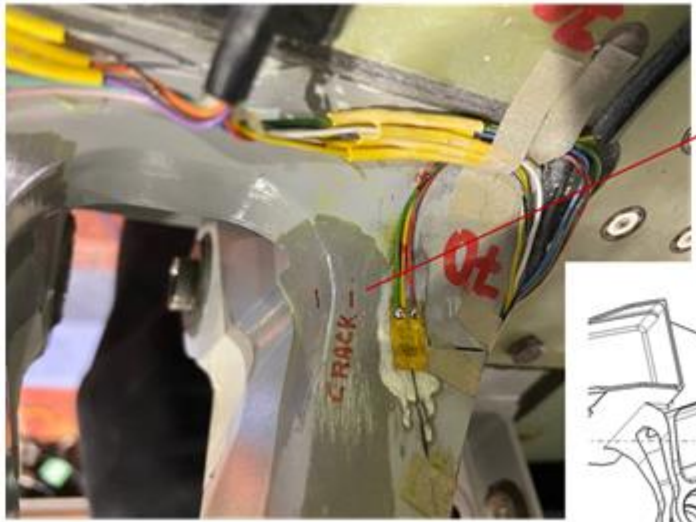


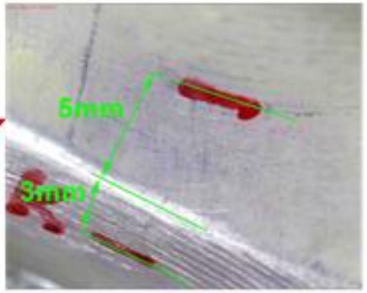
Crack measured at end of damage tolerance test

Flaperon Testing – Crack Found during DT Test

- At 50,000 FC inspection (or 10,000 FC after DT cycling), a natural crack has been found on the IB Bell Crack Arm Fillet.





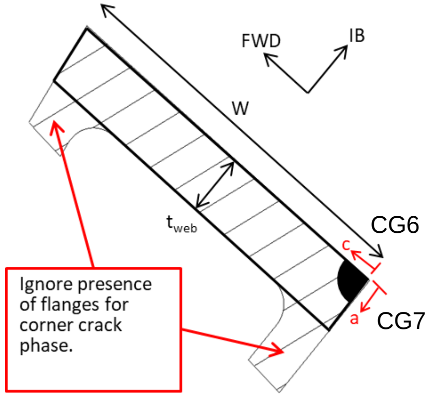


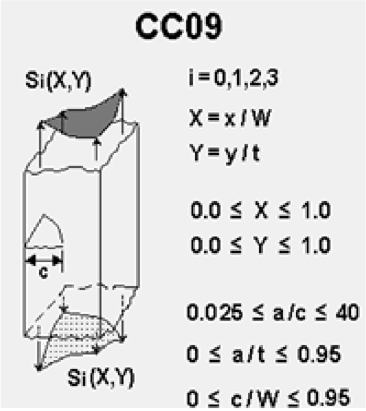
PFD result

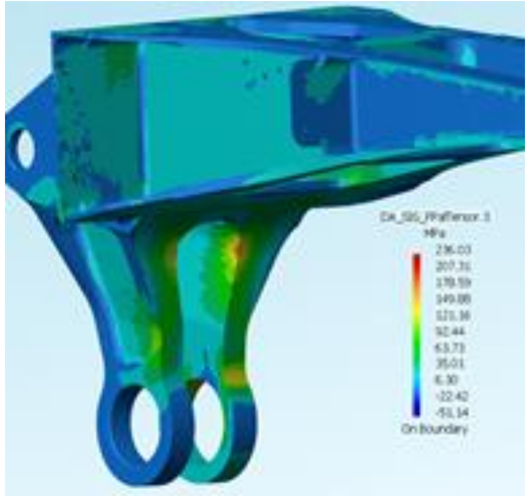
- This flaw size (5mm by 3mm from PFD) was monitored against prediction for the remaining 10,000 FC
- Finally residual strength limit load (WB14) was applied.
- The final crack length after RST is around 9mm (eddy current measurement).
- The proposed detectable size is 2mm in MRB for maintenance requiring NDT.

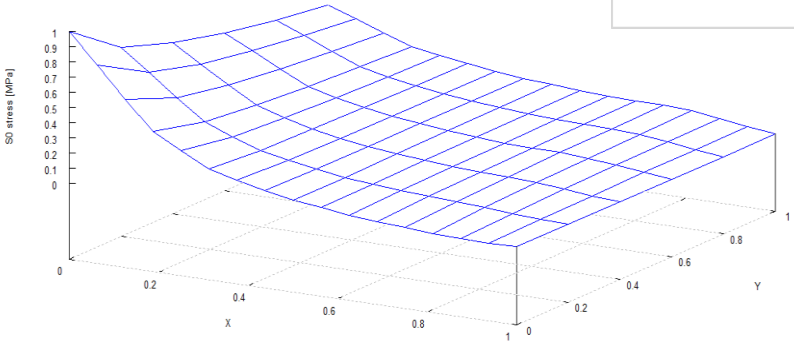
Validation of Crack Growth Analysis - Flaperon Bell Crank Fillet Rad

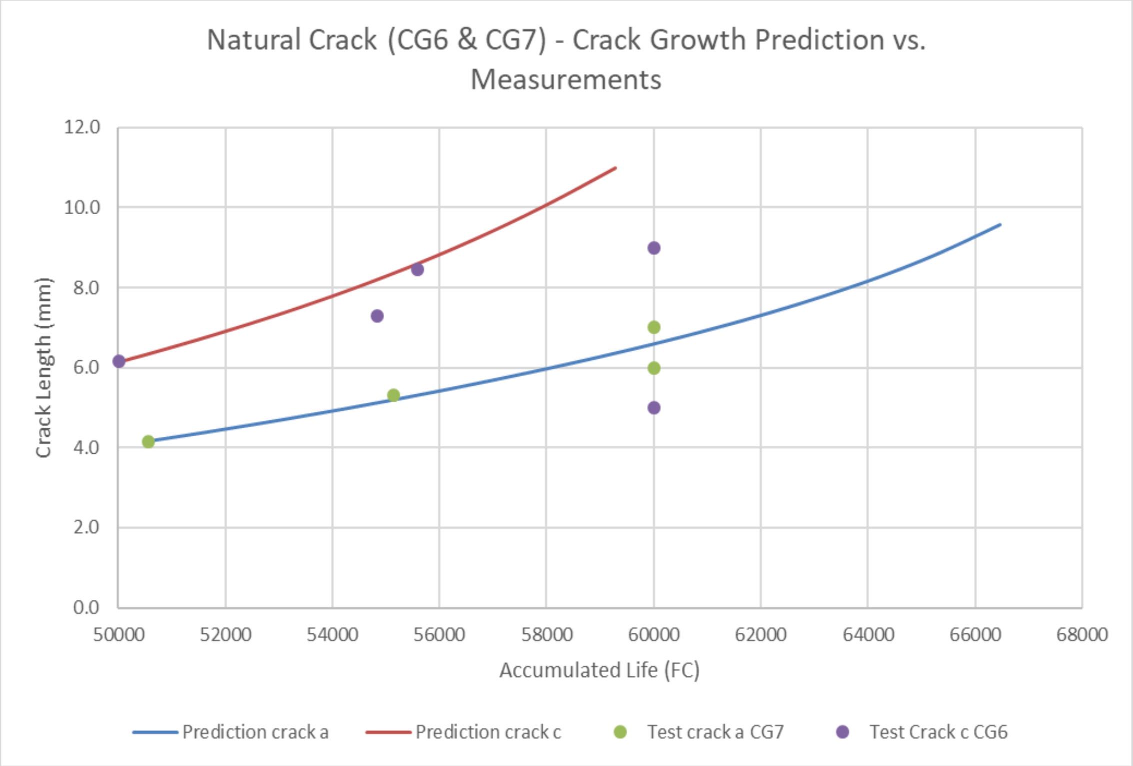
Crack on Flaperon IB Bell Crank Fillet Radius











The CC09 solution is a bi-variant weight function formulation and the stress intensity factor is written as

$$K = \int_0^a \int_0^{c\sqrt{1-y^2/a^2}} \sigma(x,y) W_{QQ'} \, dx dy$$

$$W_{QQ'} = \frac{\sqrt{R^2-r^2}}{\pi l_{QQ'}^2 \sqrt{\pi R}} \left(1+\frac{l_{QQ'}^2}{l_{Q_xQ'}^2}+\frac{l_{QQ'}^2}{l_{Q_yQ'}^2}\right)\times\left[1+\Pi_1\sqrt{1-\frac{r}{R}}+\Pi_2\left(1-\frac{y}{y'}\right)+\Pi_3\left(1-\frac{x}{x'}\right)\right]$$

The parameters Π_1, Π_2, and Π_3 are calibrated by reference solutions at both a and c tips to characterize the finite boundary effects.

Observations and Concluding Remarks

- The control point study into spectrum and loading was based on fatigue critical and major load introduction points. If buckling is the critical static sizing for the structure and in particularly the on-set of buckling is under limit load, the fatigue test assessment must be checked for any possible buckling during fatigue test. This is because buckling can cause local nonlinearity, which is normally not include 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 can be useful 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 compare to the size of the fitting structures. These may be the reason that LEFM works for those structures.
- Strain gauges give good results if selected locations match with high strains from FEM. 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). 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 FEM 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.

Thank you for your attentions

Question Time

Overview

- Overview the process for setting up a metallic full-scale fatigue test
  - Control points selections
  - Spectrum sequence simplification (truncation)
  - Test loads idealisation and comparison
- Metallic fatigue test Commissioning
  - Strains and Deflections Survey Checks
  - Test Sequence comparison
  - Flap Upper Skin Buckling Observations and Investigations
- Crack Growth Measuring and Monitoring in Damage Tolerance (DT) and Residual Strength Test (RST) phase
  - Feature strain gauge comparison with DFEM to confirm critical site
  - Crack growth measurements against predictions for crack monitoring

References and Acknowledgements

References

1) EASA CS 25

2) FAA FCR 25

3) ASTM

4) NASGRO Manual v9.0

5) Bueckner, H.F., “A novel principle for the computation of stress intensity factors”, Z. Angew. Meth, 1970.

6) Glinka G., “Development of Weight Functions and Computer Integration Procedures for Calculating Stress Intensity Factors Around Cracks Subjected to Complex Stress Fields”, Progress Report, 1996.

Acknowledgements:

We would like to thank every GKN F&DT Engineer who involved in the recent Wing Movable project, and the test facilities in particularly test engineers Alex Souter and Jon Kingman, who started and followed the tests during the COVID lockdown period to ensure all testing successfully performed and delivered in quality.