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Crack growth prediction challenge in wide 7075-T7351 panels

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DST Science and Technology for Safeguarding Australia

Acknowledgements

- The authors appreciate and acknowledge the efforts from the participants in this challenge
- The authors acknowledge and appreciate QinetiQ Australia for their support of this work in collaboration with DST Group.
- The help and support from Mr Ben Dixon from DST Group, and Mr Seb Stobart from QinetiQ Australia is greatly appreciated

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QINETIQ

Outline

- Background
- Aim
- Challenge description
- Details of blind submissions including comparison with test results
- Review and investigation
- Conclusion including lessons learned and recommendations

Background

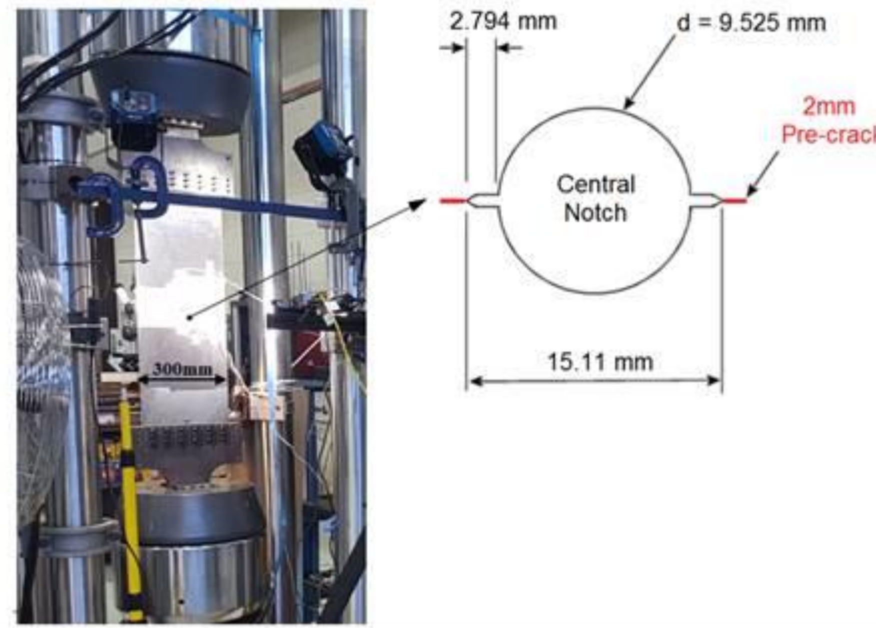
- DST Group have been running a program called "Advancing Structural Simulation to drive Innovative Sustainment Technologies" ASSIST
- Several blind fatigue crack growth prediction challenges have been offered including:
  - Thick section fighter aircraft wing attachment structure with complex geometry
  - Helicopter load spectrum involving very large number of small amplitude load cycles
- The challenge being presented here was around symmetric through-thickness cracks growing from a central hole in very wide (300 mm) and 6.8 mm thick flat panel specimens made from 7075-T7351 bare plate. The specimens were pre-cracked to a specified length, and then subjected to a load spectrum representative of a large military transport aircraft lower wing.
- Participants in the challenge were provided with the details of the material, specimen geometry, load arrangement, pre-cracking, and load spectrum. The challenge was to predict the crack propagation and failure, and to do so in a "blind" way, i.e. with no knowledge of the test results.
- The results from three validated test results, which were very consistent, are now known and can be compared with the blind predictions.

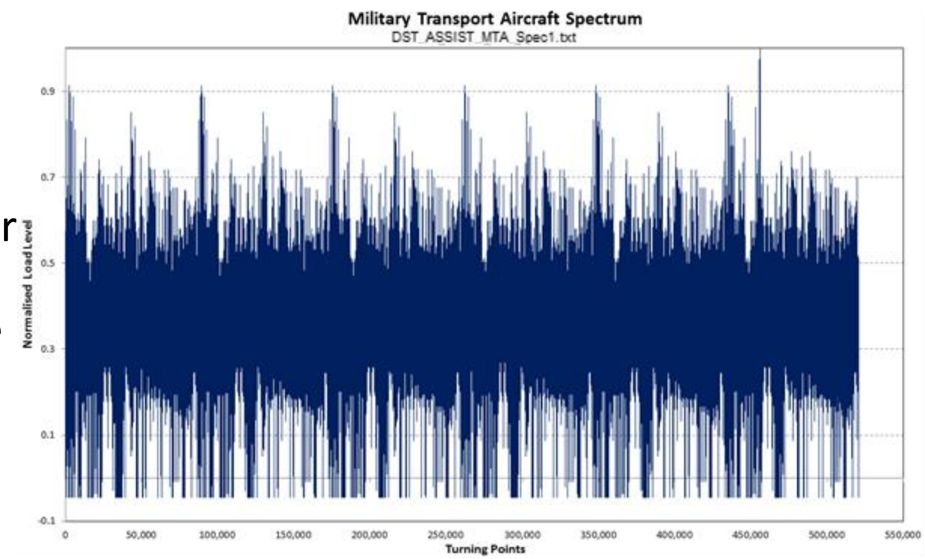
Aim

- Review the submissions received and compare against the test results.
- Identify which aspects of the predictions had the most impact in terms of comparison with the test result, and difference from other predictions.
- Determine any lessons learned and recommendations for future work to improve the accuracy and reliability of such predictions.

Challenge description

- 300 mm wide, 6.8 mm thick flat panel specimens
- 7075-T7351 bare plate material
- Central hole with 2.8 mm EDM notch on each side
- Pre-cracked under CA loading for 2 mm each side
- Spectrum loading, representative of a large military transport aircraft wing lower surface (tension dominated) loading
- Max stress 150.6 MPa, min stress -6.9 MPa
- One full block consisted 520,550 turning points (peak-valley sequence). Six identical sub-blocks, but one with the peak load 5% higher. Full Blocks applied one after another until failure.
- Challenge – predict crack growth and failure





Summary of submissions

- 9 submissions received from around the world.
- Three participants used LEFM fracture mechanics based AFGROW code
- One participant used LEFM fracture mechanics approach with AFGROW/BAMF/StressCheck®
- Two participants used the FASTRAN strip-yield analytical crack closure approach
- One participant used the NASGRO code with the strip-yield closure model, and the same participant also used the LEFM option in NASGRO
- One participant applied a novel equivalent energy based approach

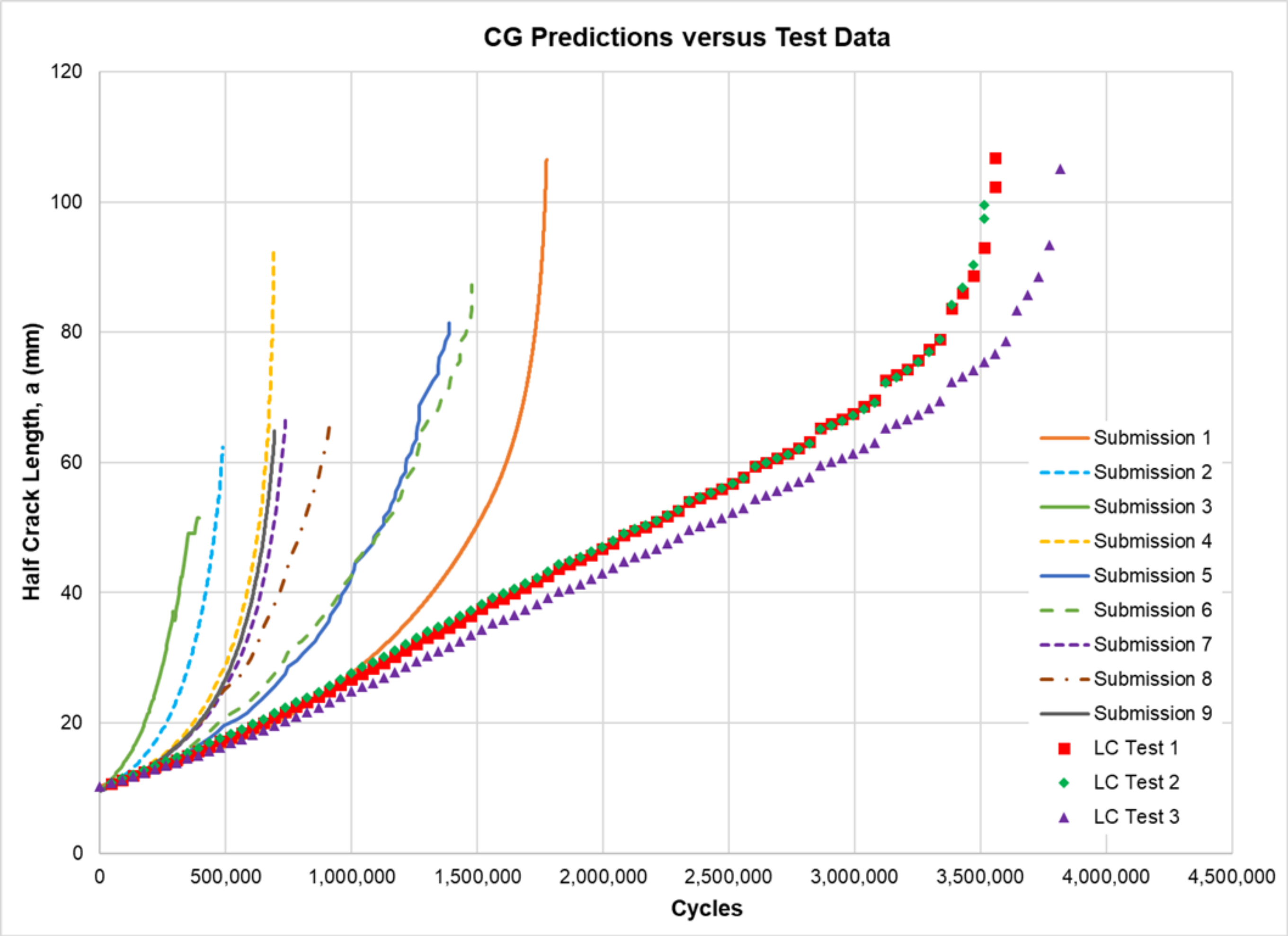
Summary of test results

Test Case	Final Crack Length[1] (mm)	Life (Cycles)
1	106.7	3,557,773
2	99.5	3,514,526
3	105.1	3,817,298
Average	103.7	3,629,866

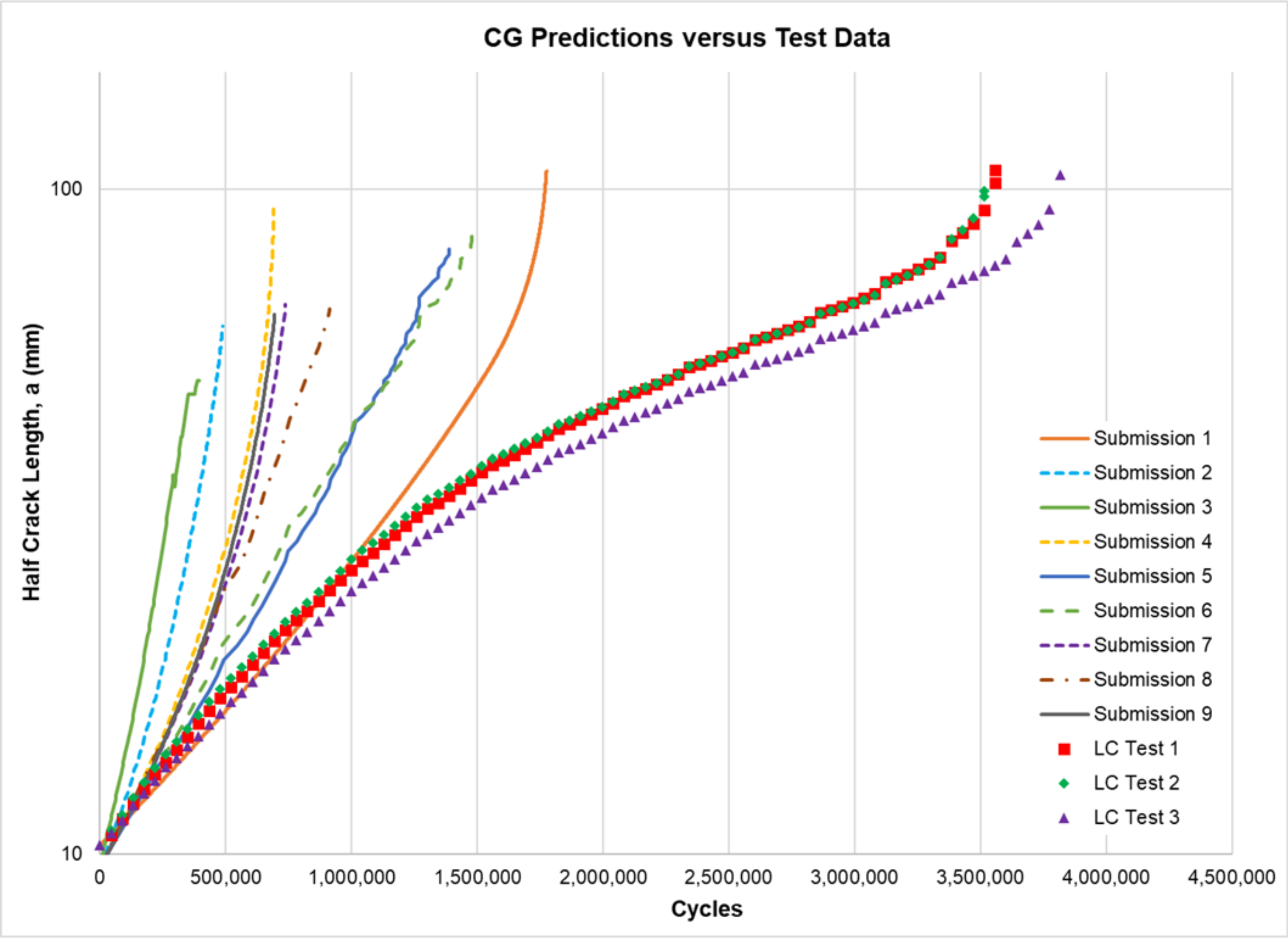
Summary of submitted results

Submission No.	Final Crack Length (mm)[1]	% Test Average	Rank	Life (Cycles)	% Test Average	Rank
1	106.5	103%	1	1,774,651	49%	1
2	62.3	60%	8	488,066	13%	8
3	51.5	50%	9	395,079	11%	9
4	93.2	90%	2	689,571	19%	7
5	81.4	78%	4	1,389,045	38%	3
6	87.3	84%	3	1,476,765	41%	2
7	67.1	65%	5	737,255	20%	5
8	66.1	64%	6	911,688	25%	4
9	64.8	62%	7	694,694	19%	6

Comparison of submissions vs test results



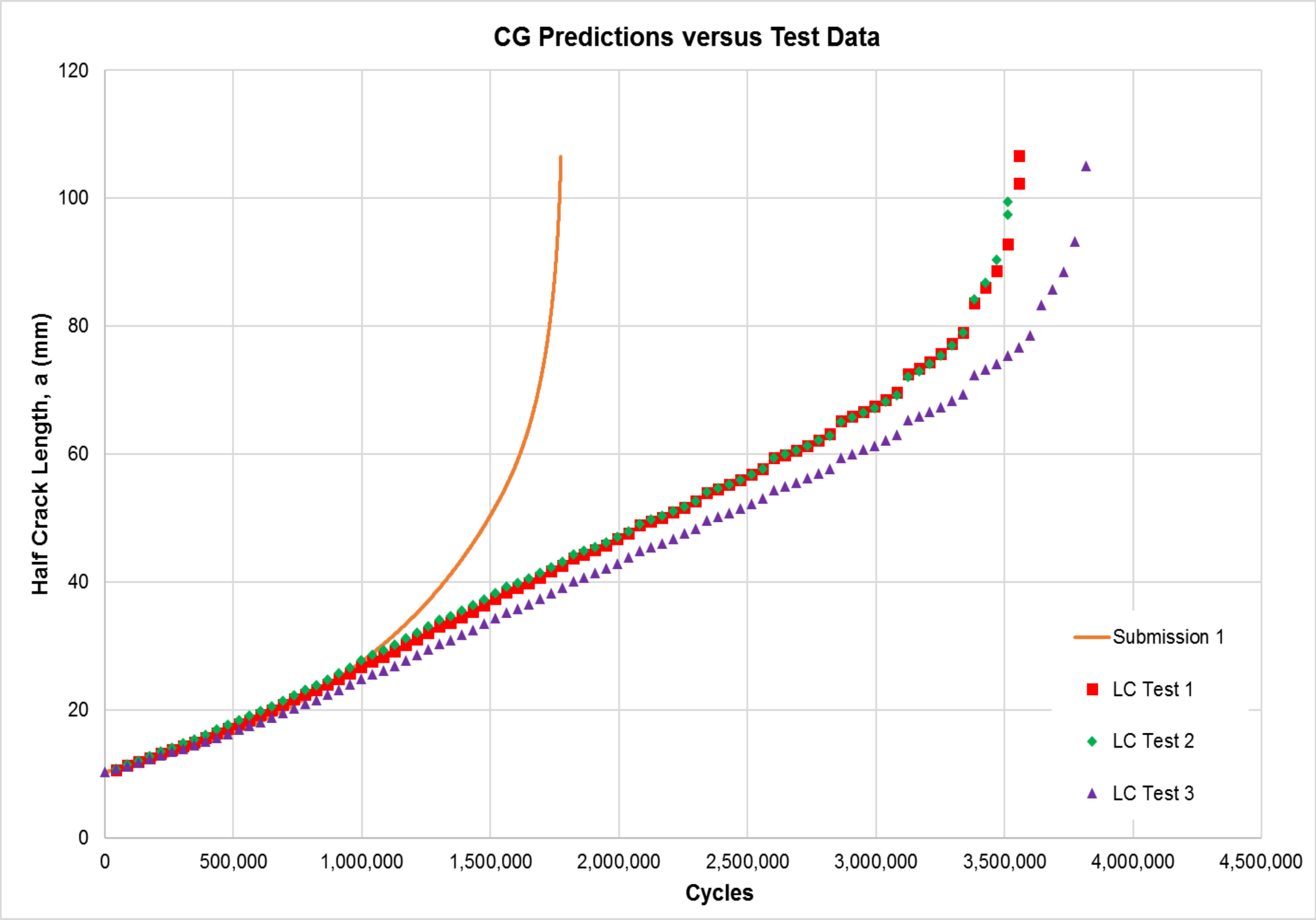
Comparison of submissions vs test results – log scale



Submission 1 : Equivalent Energy Approach

- This submission was the highest rank (1st) in terms of closest to the test result for both life and failure size. Predicted Life of 1,744,651 cycles (49% of test average) and failure length of 106.5 mm (103% of test average)
- Similar to the "Effective Block Approach" where crack growth under a given spectrum identified as growth per block, rather than per cycle.
- A novel method used to calculate the average energy per variable amplitude cycle in the spectrum
- Spectrum was truncated at the second highest stress in the spectrum, 137.6 MPa. Original highest stress is 150.6 MPa. This was done to ensure that a very high stress applied relatively infrequently did not bias the result.
- K-solution was for a central crack in a finite width plate, i.e. no hole and notches. As will be shown later, however, this was a reasonable assumption.
- Two predictions of failure were provided.
  - Net section failure – 106.5 mm (within 3% of average test failure length 103.7 mm)
  - Failure by fracture calculation – 64.0 mm (62% of average test failure length)
- Full technical details of this submission not available yet. Technical paper pending.

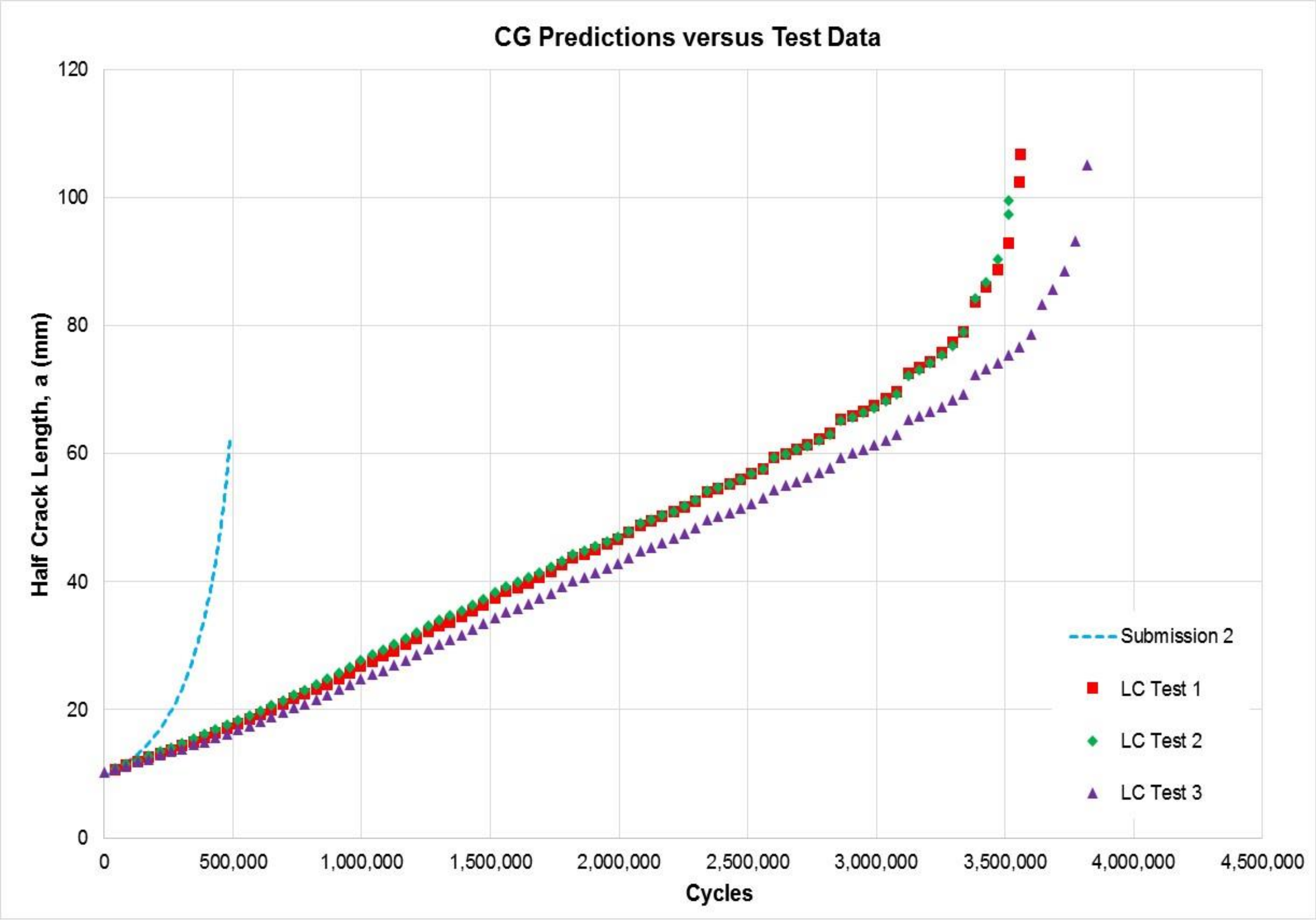
Submission 1 Crack Growth Plot Comparison



Submission 2 : LEFM Approach

- This submission ranked 8th in terms of closest to the test result for both life and failure size. Predicted Life of 488,066 cycles (13% of test average) and failure length of 62.3 mm (60% of test average)
- LEFM AFGROW approach
- Used the AFGROW advanced solution for the stress intensity calculation
- Crack growth rate data was based on tabular data provided for two values of stress ratio "R" only, i.e. 0.02 and 0.5.
- No retardation
- Spectrum applied exactly as supplied, which means that peaks and subsequent valleys are paired to form closed cycles for the calculation

Submission 2 Crack Growth Plot Comparison



Submission 3 : LEFM Approach

- This submission was 9th in terms of closest to the test result for both life and failure size. Predicted Life of 395,079 cycles (11% of test average) and failure length of 51.5 mm (50% of test average)
- Used the BAMF/StressCheck® approach for the stress intensity calculation
- Crack growth rate data was based on tabular data provided for two values of stress ratio "R" only, i.e. 0.02 and 0.5. Same as Submission 2.
- No retardation. Same as Submission 2.
- Spectrum applied exactly as supplied, which means that peaks and subsequent valleys are paired to form closed cycles for the calculation. Same as Submission 2.

BAMF/AFGROW/StressCheck® Overview

- BAMF – Broad Application for Modelling Failure
- Recently re-branded as Broad Application for Multi-point Fatigue (BAMpF) with new logo
- USAF sponsored code, managed and being further developed/validated by Hill Engineering
- BAMF is a "plug-in" for the AFGROW fatigue crack growth analysis code
- StressCheck p-element FE code used here for stress intensity factor (SIF) solution development
- StressCheck model runs to calculate SIF, this is fed to AFGROW for the crack growth. Crack is grown by an incremental amount, and new shape returned to StressCheck to update SIF solution
- Iterative process continues to advance the crack through to final failure

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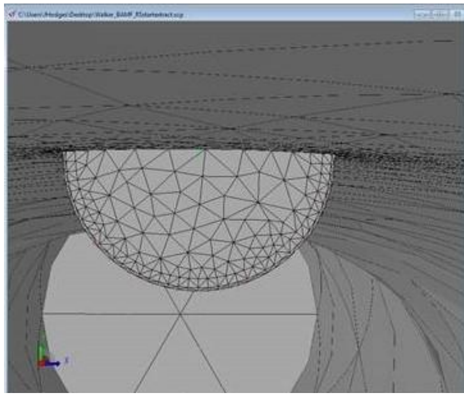
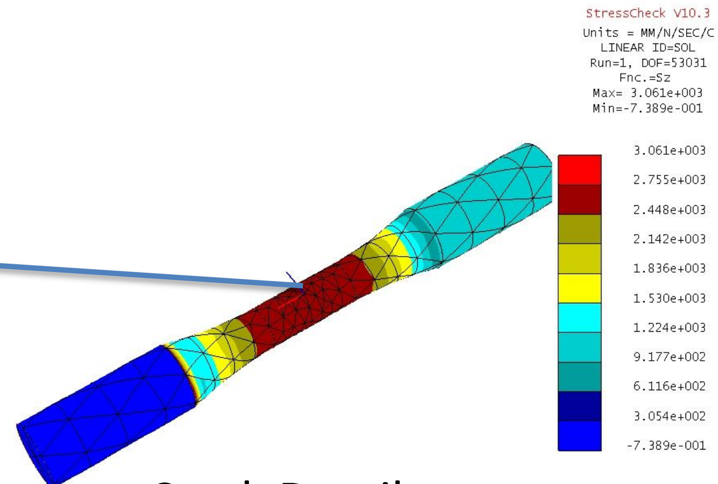
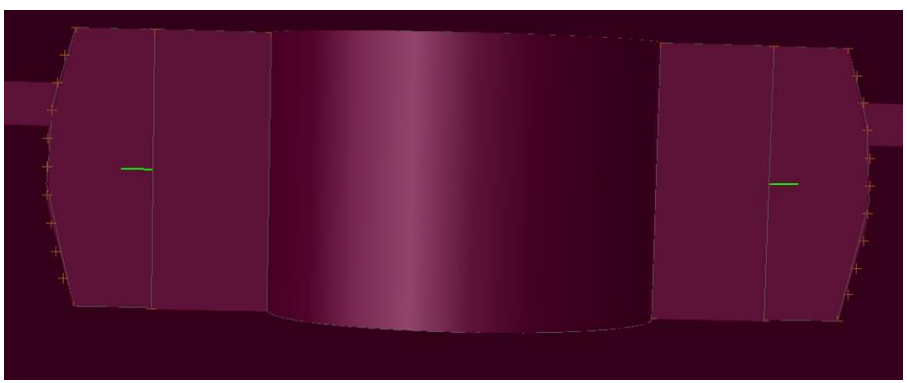
BAMF/AFGROW/StressCheck Model Overview

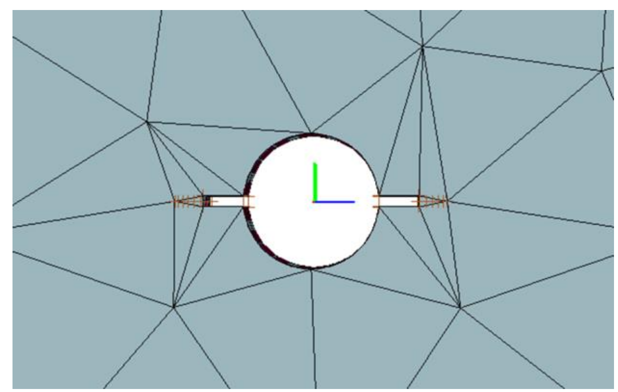




Crack Detail

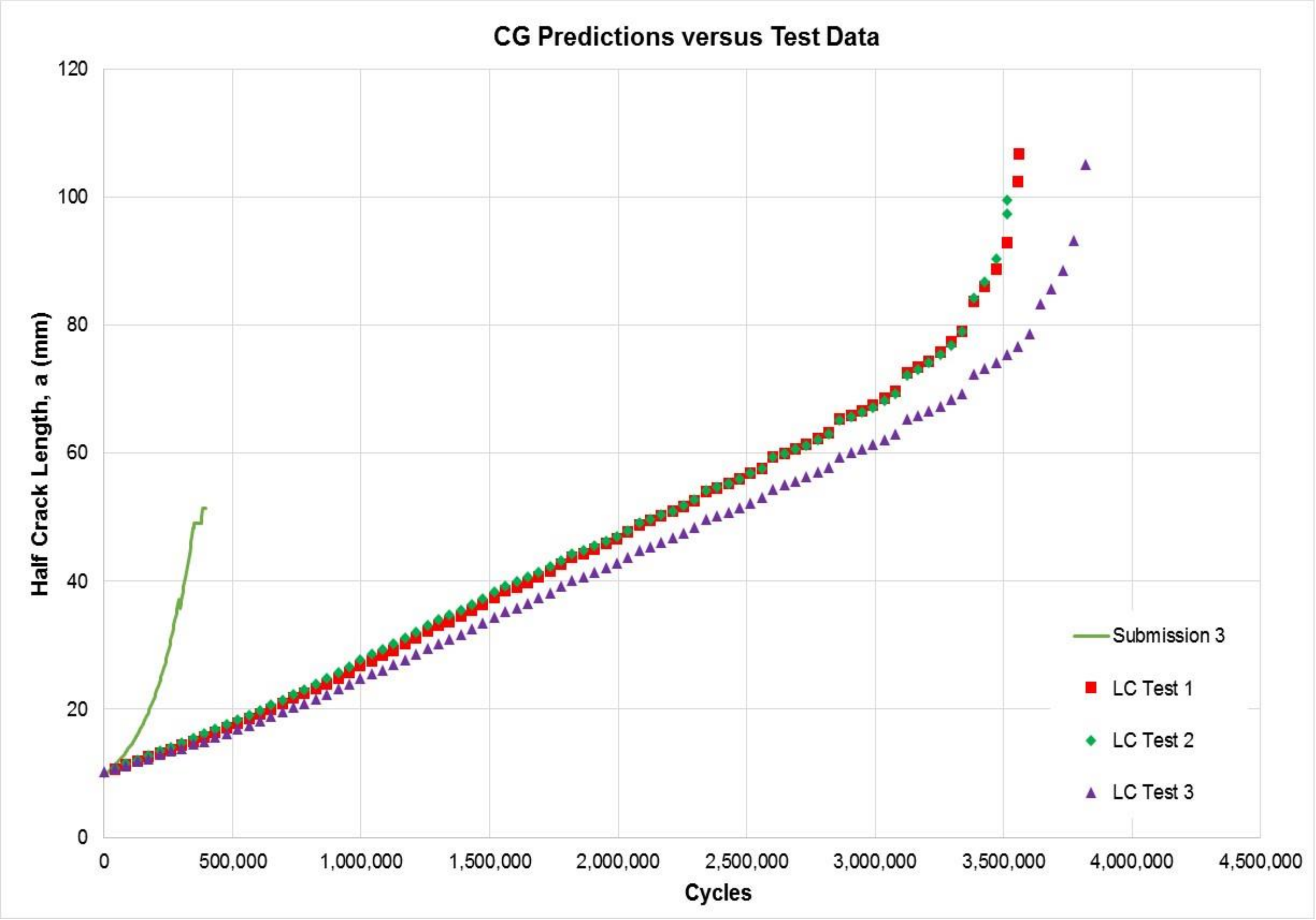
Example StressCheck® p-version FE Model





StressCheck® FE Model – Submission 3

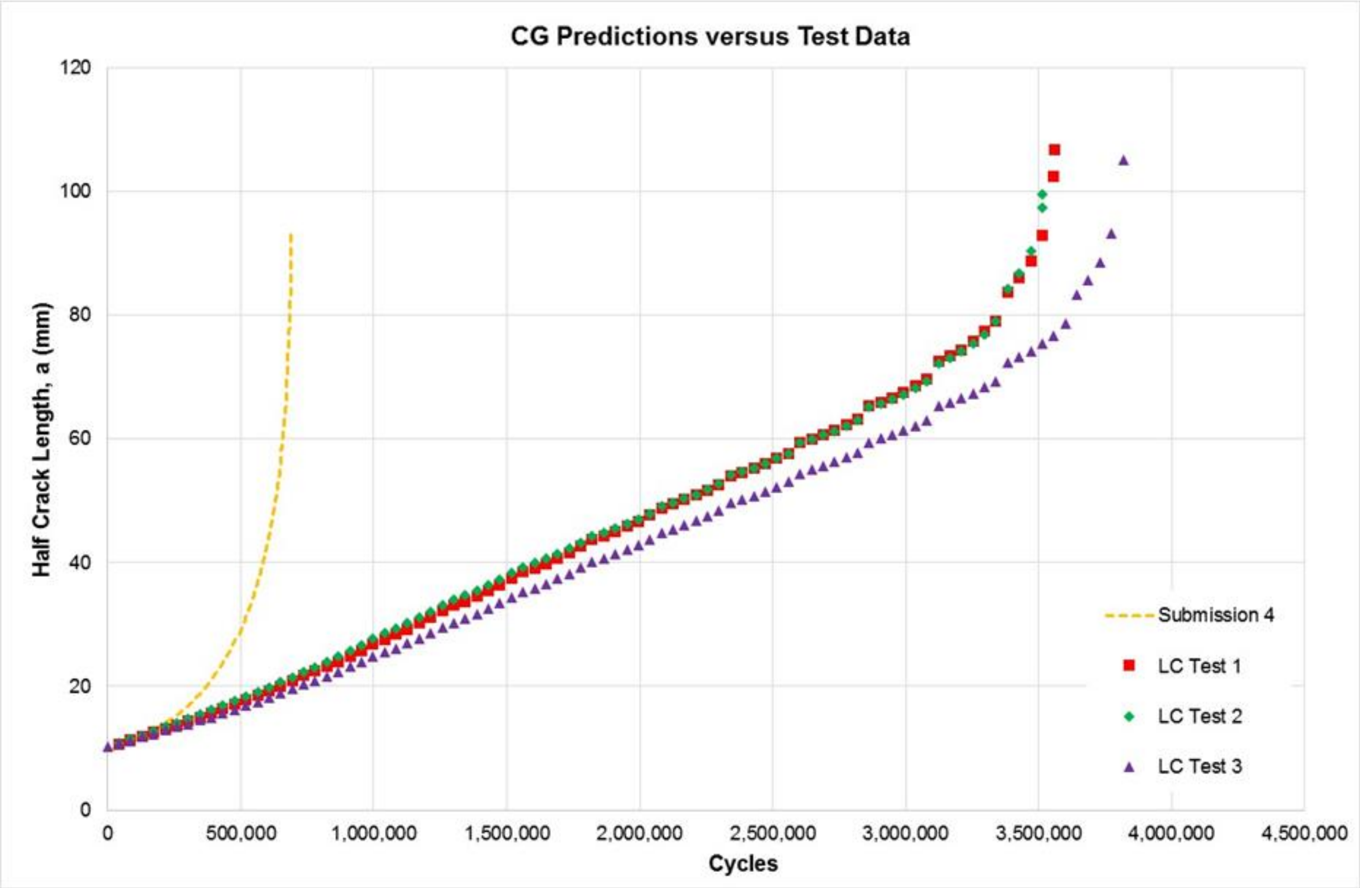
Submission 3 Crack Growth Plot Comparison



Submission 4 : LEFM Approach

- This submission ranked 7th in terms of closest to the test result for life, and 2nd in terms of failure size. Predicted Life of 689,571 cycles (19% of test average) and failure length of 93.2 mm (90% of test average)
- LEFM AFGROW approach
- Crack growth rate data was obtained from the AFGROW AFMAT database which consisted of tabular data for four values of stress ratio "R", i.e. 0.02, 0.1, 0.3 and 0.5.
- Retardation was applied using the Generalised Willenborg retardation model with an Overload Shutoff Ratio (SOLR) of 2.5.
- The spectrum was rain-flow counted using the built-in AFGROW cycle counter.

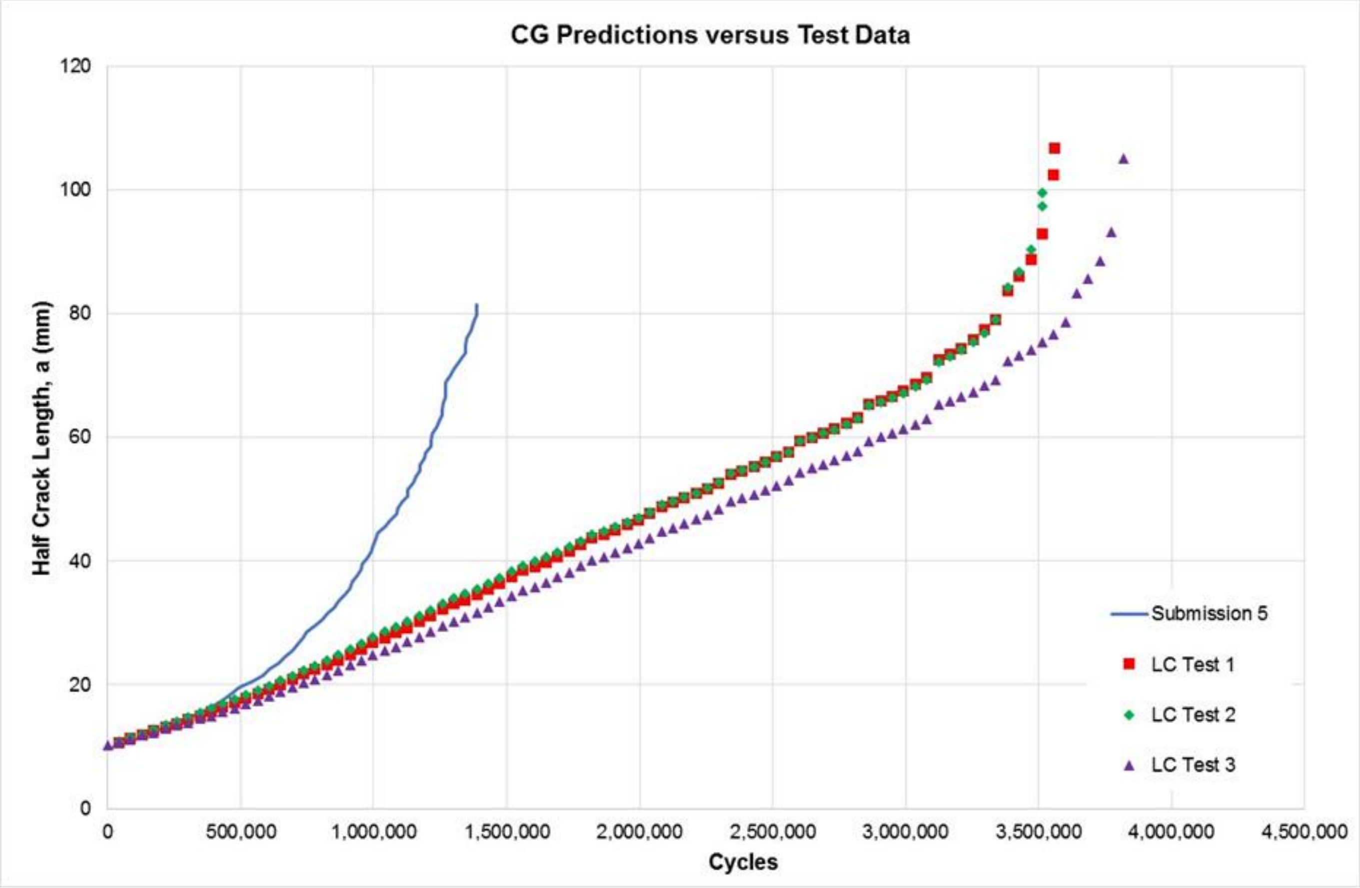
Submission 4 Crack Growth Plot Comparison



Submission 5 : Strip Yield Approach

- This submission ranked 3rd in terms of closest to the test result for life, and 4th in terms of failure size. Predicted Life of 1,389,045 cycles (38% of test average) and failure length of 81.4 mm (78% of test average)
- FASTRAN Strip-Yield analytical crack closure model
- Newman-Raju stress intensity solution for two symmetric through-thickness cracks at a hole in a finite width and thickness plate under remote tension
- Crack growth rate data from multiple sources used to develop ΔK_{eff} – dc/dN relationship.
- Stress ratio and load interaction (retardation) effects accounted for in the strip yield model
- Pre-cracking stage was explicitly modelled
- FASTRAN employs a "rainflow on the fly" algorithm internally if the conditions of the load spectrum require it at certain stages, but otherwise the spectrum was applied as supplied with no separate changes.

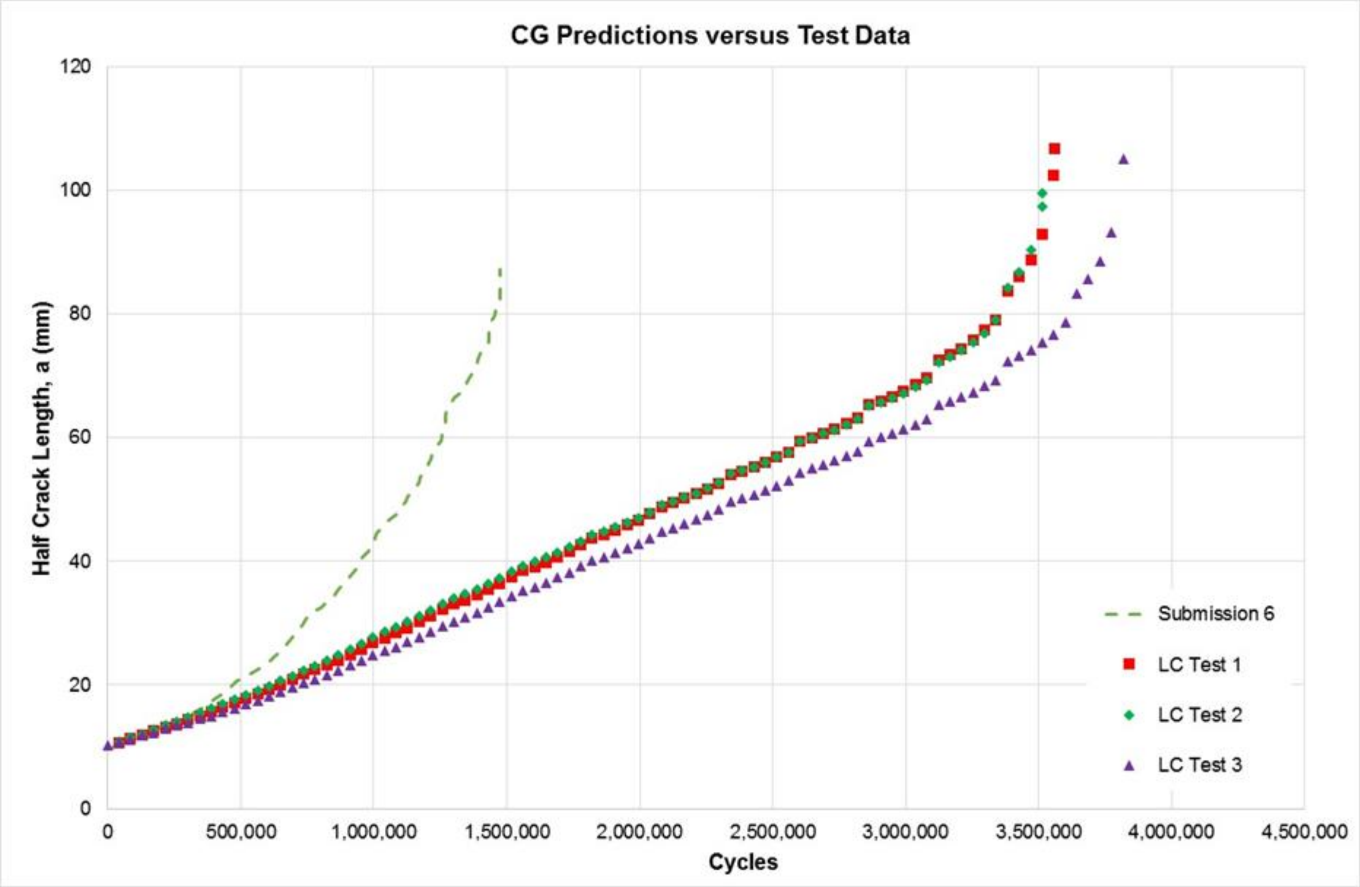
Submission 5 Crack Growth Plot Comparison



Submission 6 : Strip Yield Approach

- This submission ranked 2nd in terms of closest to the test result for life, and 3rd in terms of failure size. Predicted Life of 1,476,765 cycles (41% of test average) and failure length of 87.3 mm (84% of test average)
- FASTRAN Strip-Yield analytical crack closure model
- Newman-Raju stress intensity solution for two symmetric through-thickness cracks at a hole in a finite width and thickness plate under remote tension
- Crack growth rate data from multiple sources used to develop ΔK_{eff} – dc/dN relationship.
- Stress ratio and load interaction (retardation) effects accounted for in the strip yield model
- FASTRAN employs a “rainflow on the fly” algorithm internally if the conditions of the load spectrum require it at certain stages, but otherwise the spectrum was applied as supplied with no separate changes.

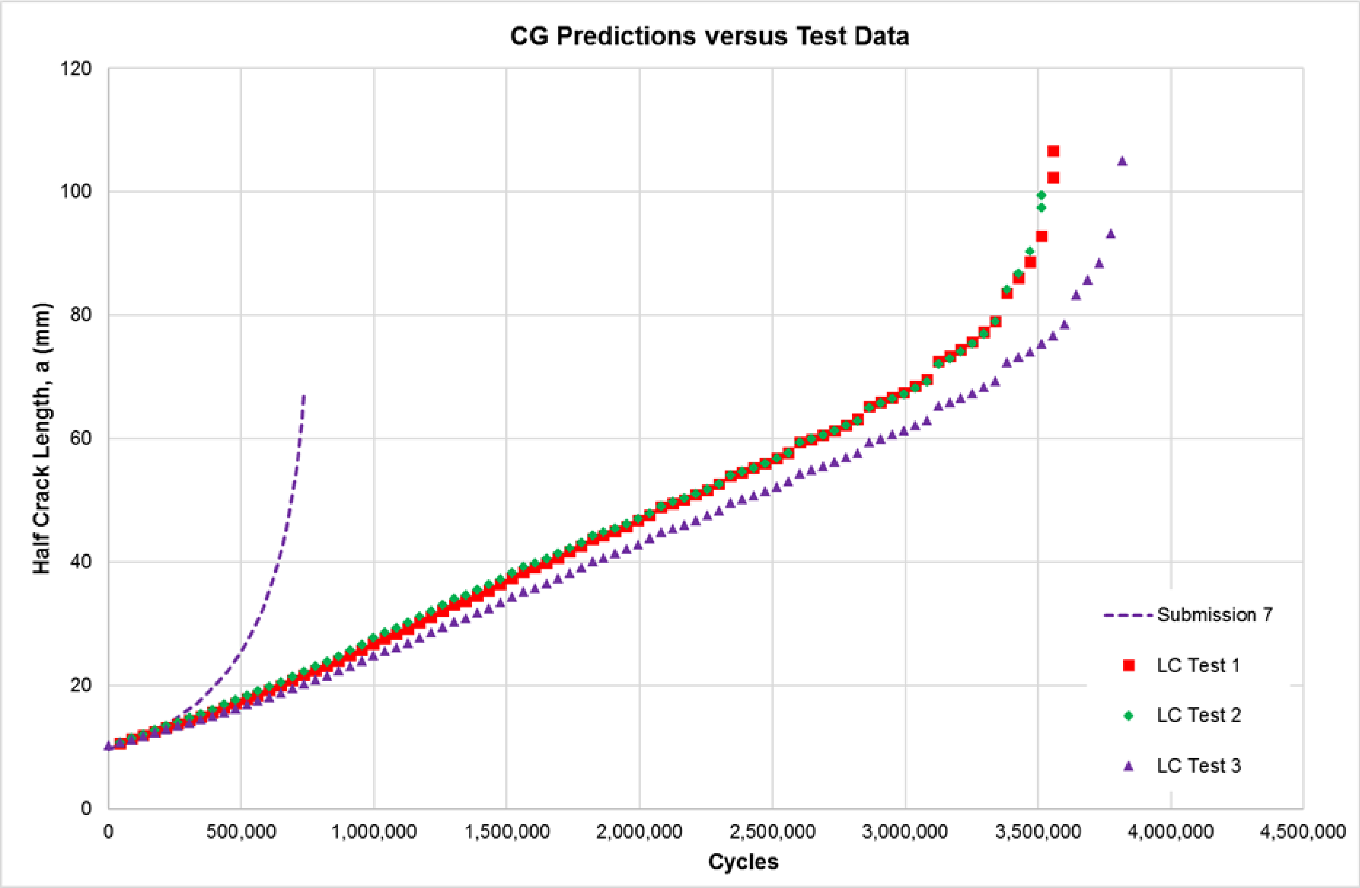
Submission 6 Crack Growth Plot Comparison



Submission 7 : LEFM Approach

- This submission ranked 5th in terms of closest to both the test result for life, and in terms of failure size. Predicted Life of 737,255 cycles (20% of test average) and failure length of 67.1 mm (65% of test average)
- LEFM approach using the NASGRO code
- Stress intensity based on NASGRO solution TC11.
- Crack growth rate data from NASGRO database for 7075-T7351 plate, supplied for the following values of Stress Ratio R: -0.3, 0.0, 0.1, 0.3, 0.5, 0.7, 0.8 and 0.9
- Load interaction (retardation) effects accounted for using the Generalised Willenborg model and an SOLR value of 3.0
- The spectrum was applied as provided, no cycle counting

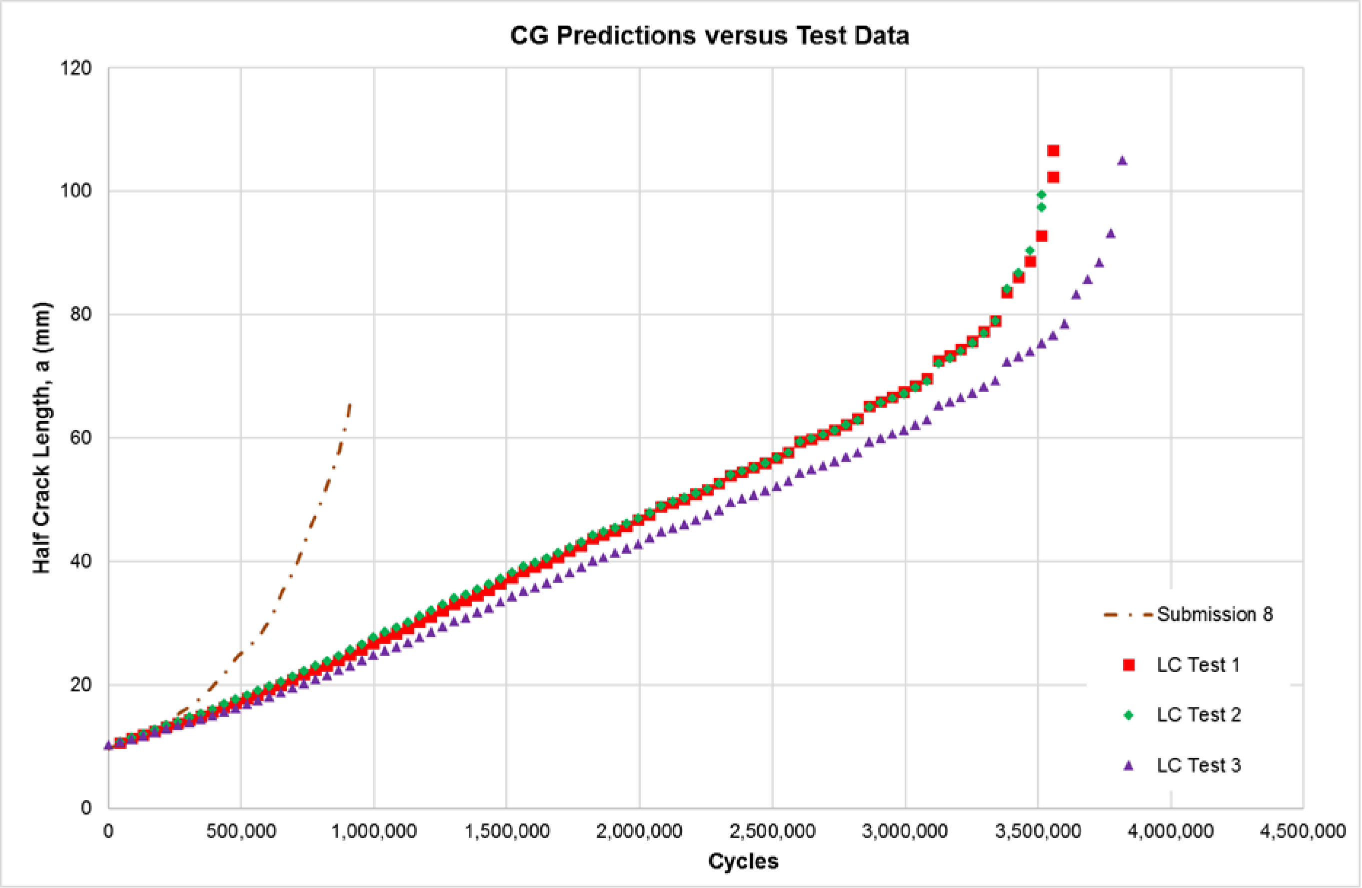
Submission 7 Crack Growth Plot Comparison



Submission 8 : Strip Yield Approach

- This submission ranked 4th in terms of closest to test result for life, and 6th in terms of failure size. Predicted Life of 911,688 cycles (25% of test average) and failure length of 66.1 mm (64% of test average)
- Strip yield model approach using the NASGRO code
- Stress intensity based on NASGRO solution TC11.
- Crack growth rate data from NASGRO database for 7075-T7351 plate, supplied for the following values of Stress Ratio R: -0.3, 0.0, 0.1, 0.3, 0.5, 0.7, 0.8 and 0.9
- The spectrum was applied as provided, no cycle counting

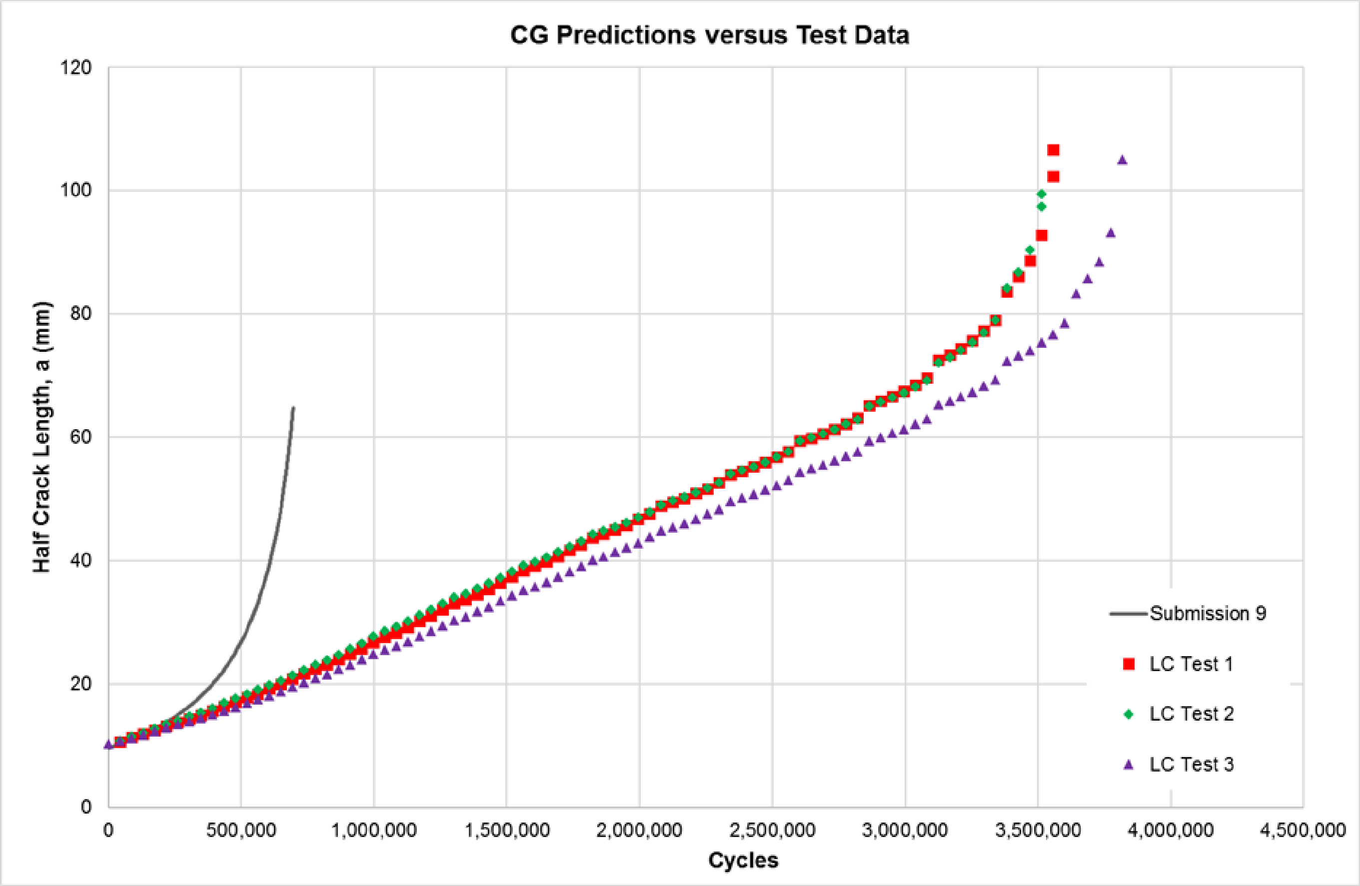
Submission 8 Crack Growth Plot Comparison



Submission 9 : LEFM Approach

- This submission ranked 7th in terms of closest to the test result for life, and 2nd in terms of failure size. Predicted Life of 694,694 cycles (19% of test average) and failure length of 64.8 mm (62% of test average)
- LEFM AFGROW approach
- Used the AFGROW advanced solution for the stress intensity calculation
- Crack growth rate data was based on tabular data provided for four values of stress ratio "R" only, i.e. -0.3, 0, 0.1 and 0.8.
- No retardation
- Spectrum was rain-flow counted using the AFGROW supplied tool, and the maximum cycle formed by the highest peak and the lowest valley was placed at the start of the spectrum block

Submission 9 Crack Growth Plot Comparison

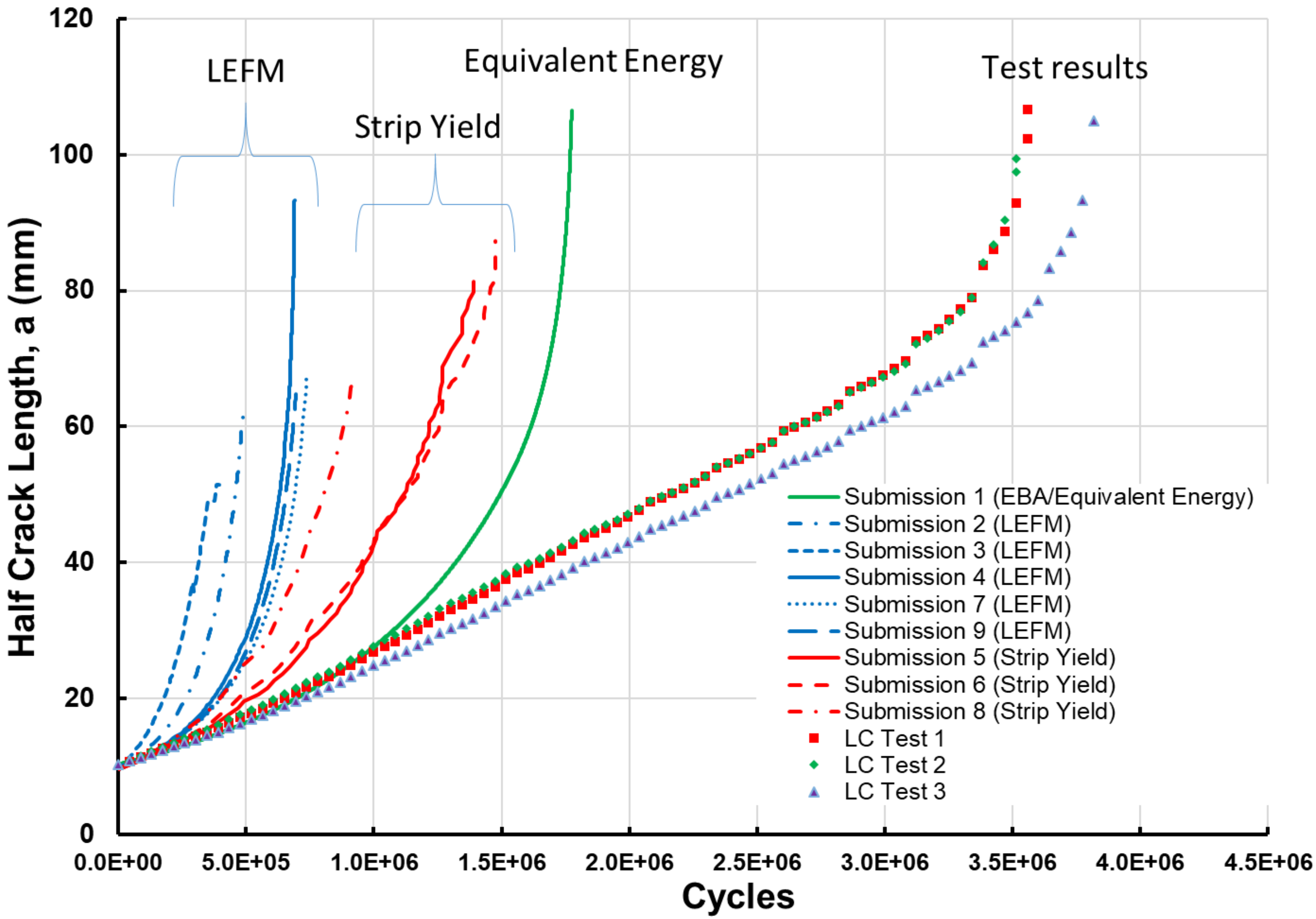


Review of the Submissions

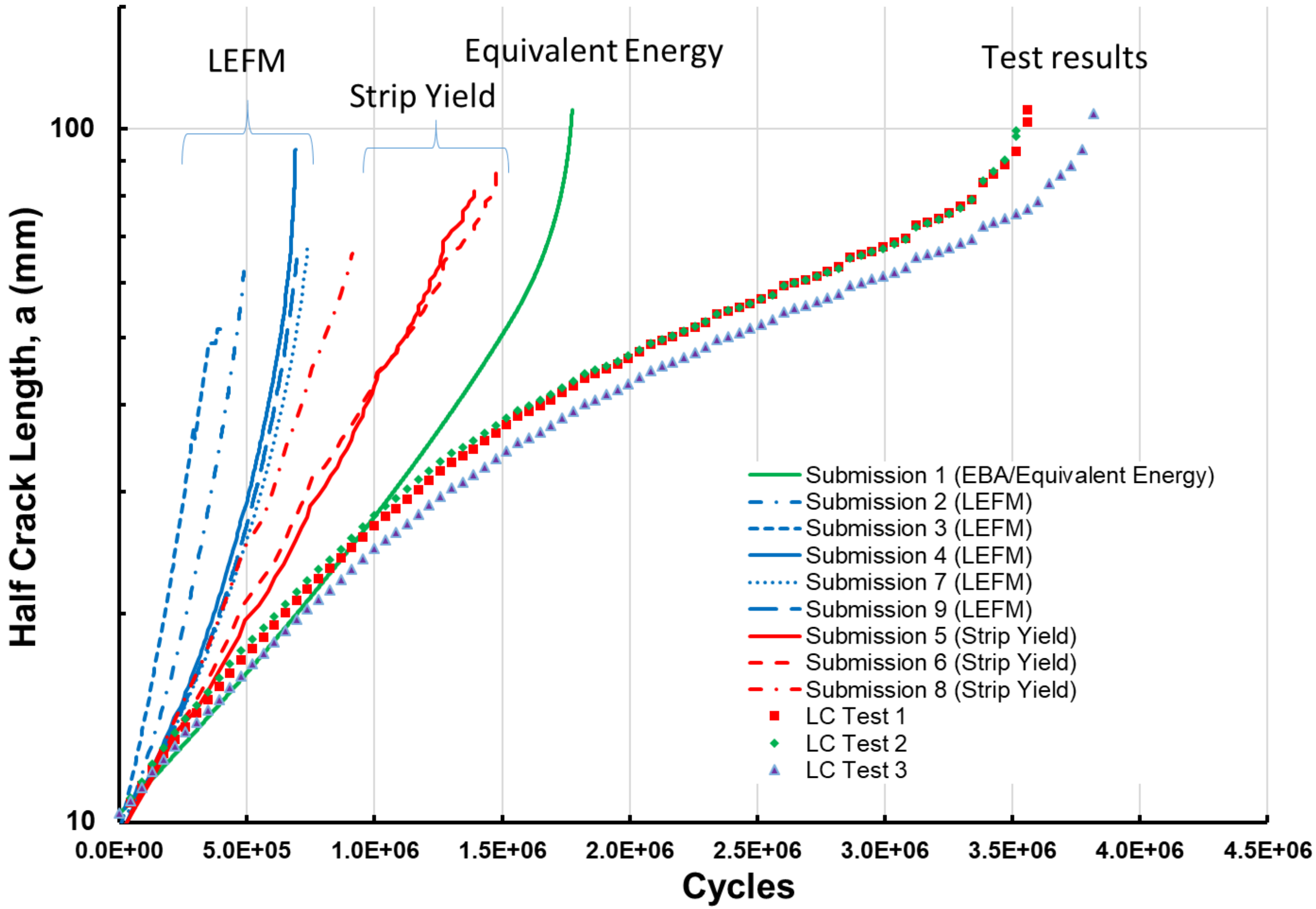
- Major areas considered:
  - Comparison of submissions grouped by type of approach
  - Stress intensity factor solution
  - Crack growth rate data
  - Retardation model
  - Spectrum processing

- Further investigations with "calibrated analyses"

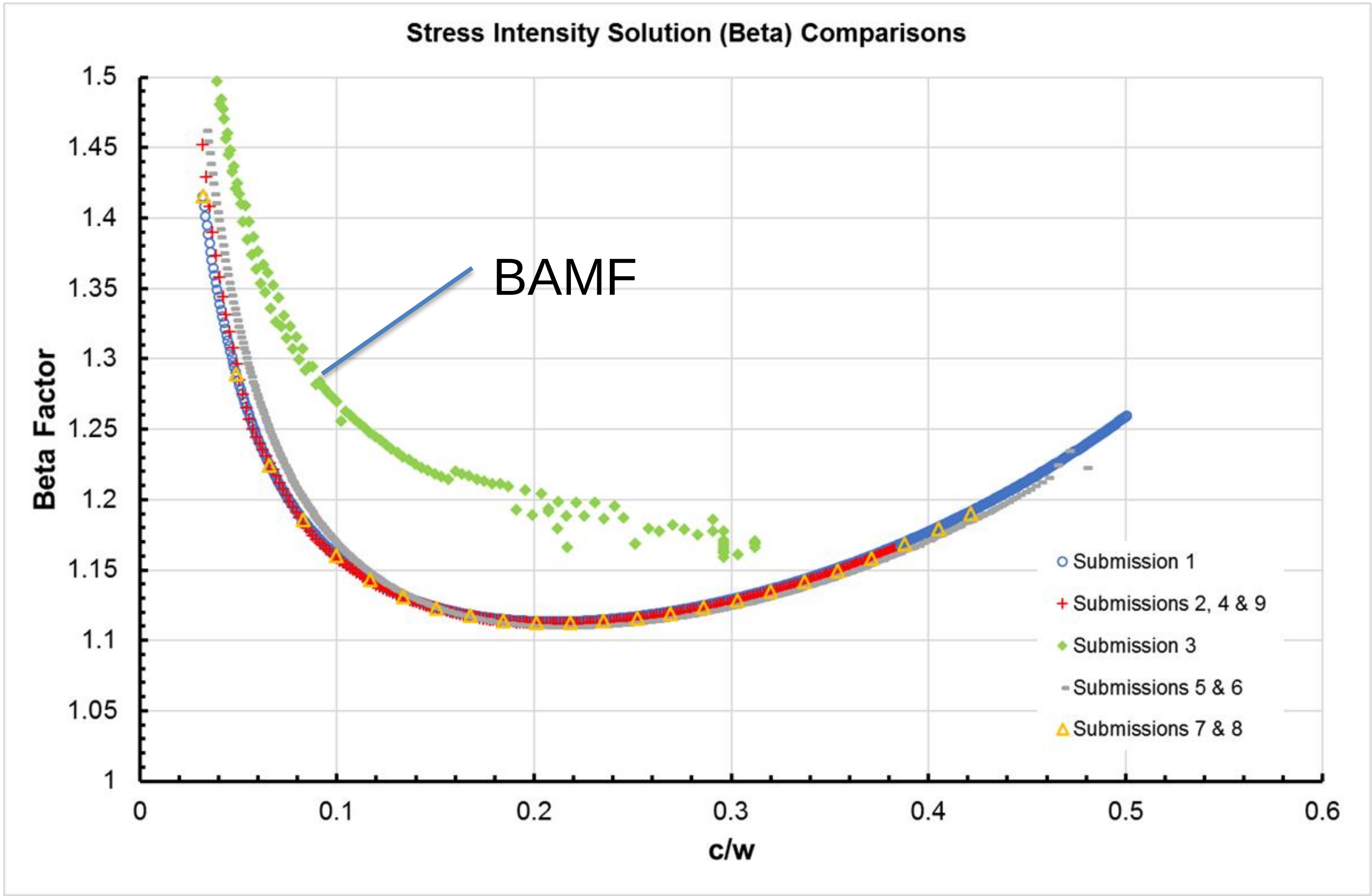
Comparison of submissions grouped by type of approach



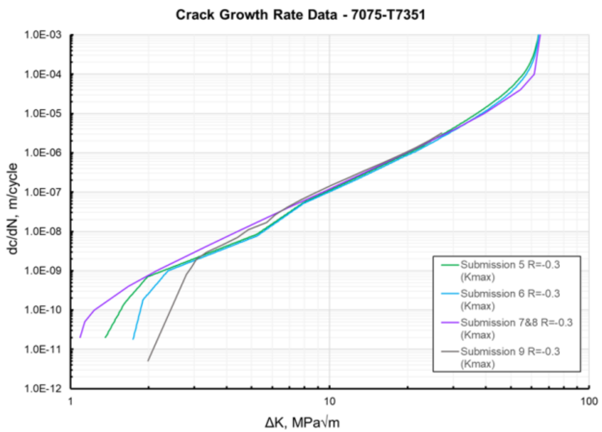
Comparison of submissions grouped by type of approach – log scale

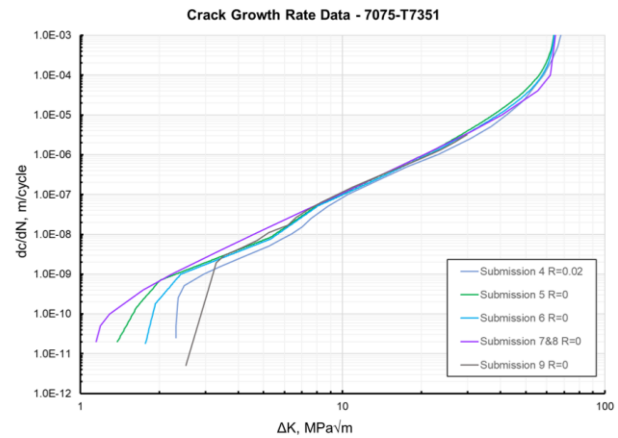


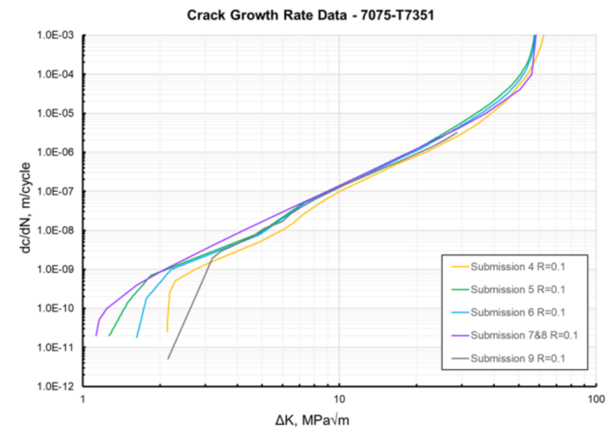
Comparison of stress intensity factor solutions

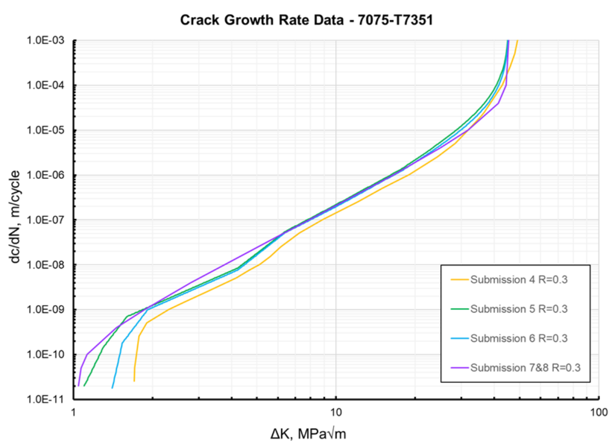


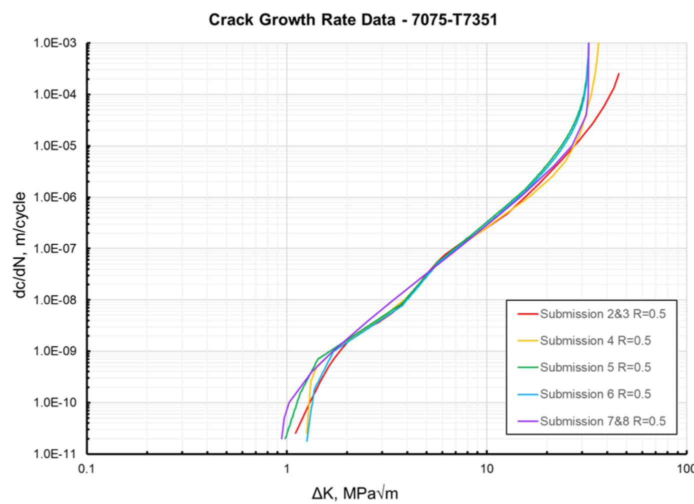
Crack growth rate data comparisons







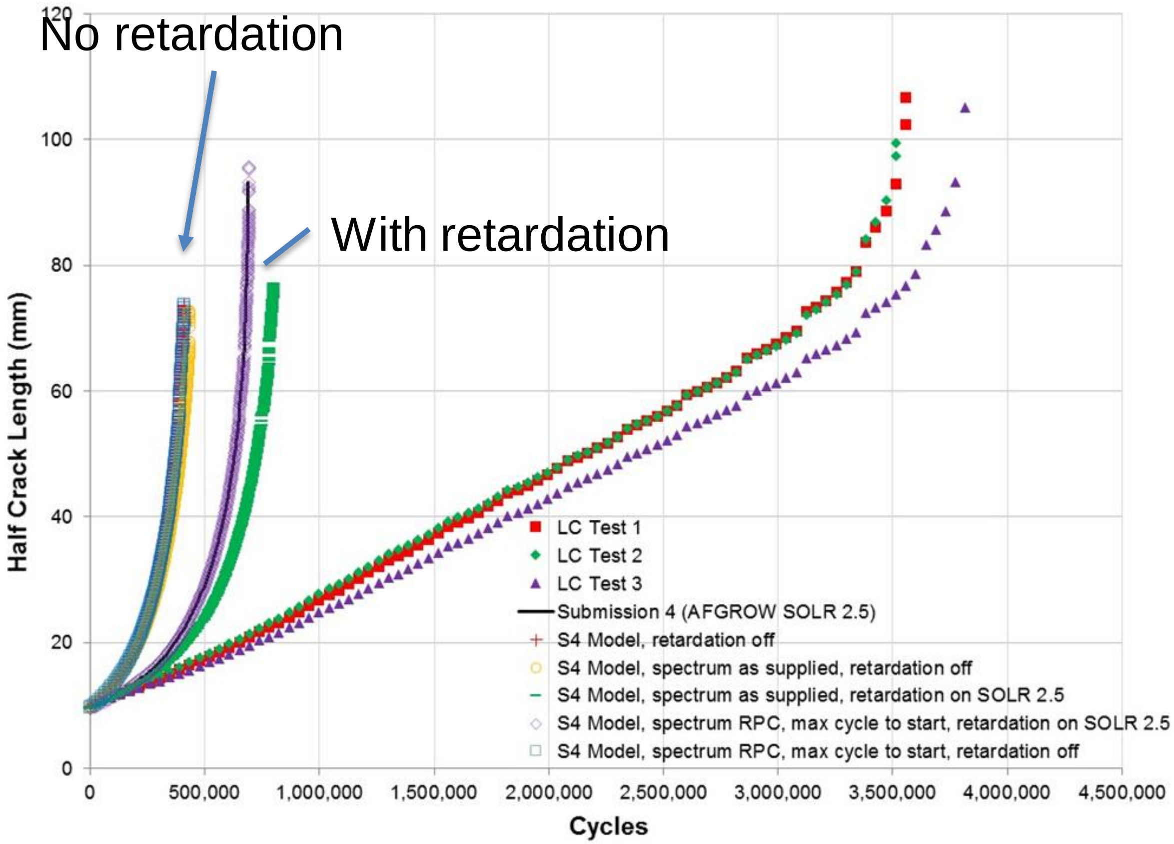




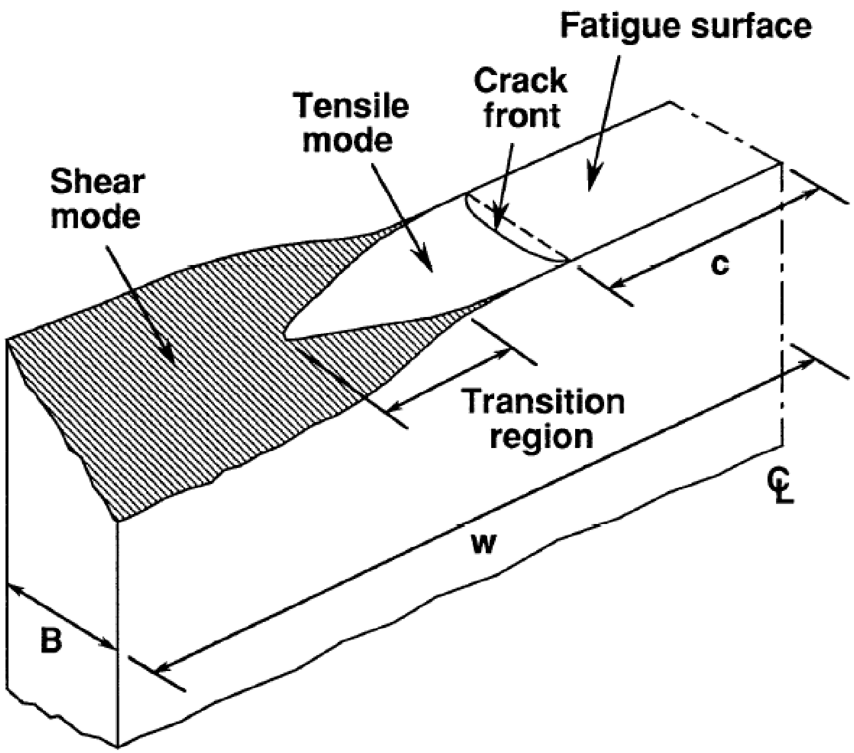
- Data diverge at low ΔK, but that didn't impact here

Spectrum processing and retardation model

- Submission 4 performed RPC of the spectrum, and applied Willenborg retardation SOLR=2.5
- Ran 6 variations on this:
  - 3 spectrum options - as supplied, RPC and RPC with max cycle to start
  - 2 retardation options – no retardation, and Willenborg SOLR=2.5

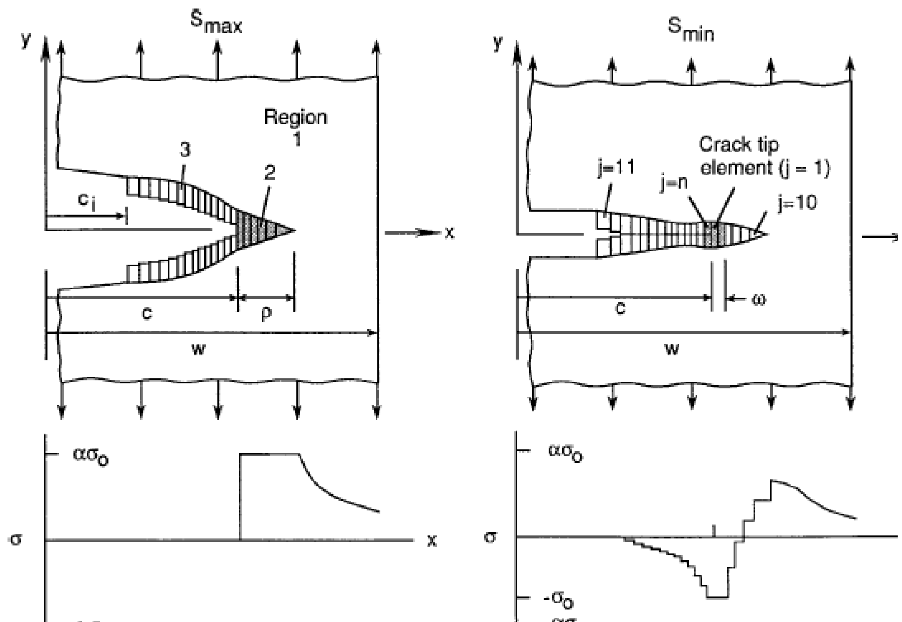


FASTRAN Investigation – Constraint Loss Regime

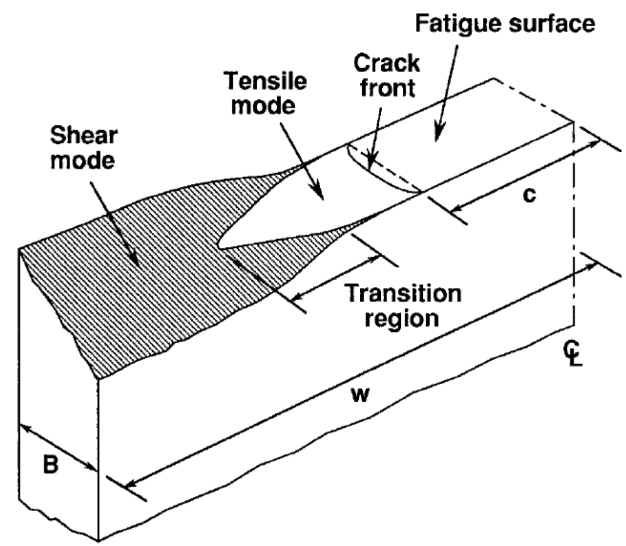


FASTRAN/CGAP Analytical Model

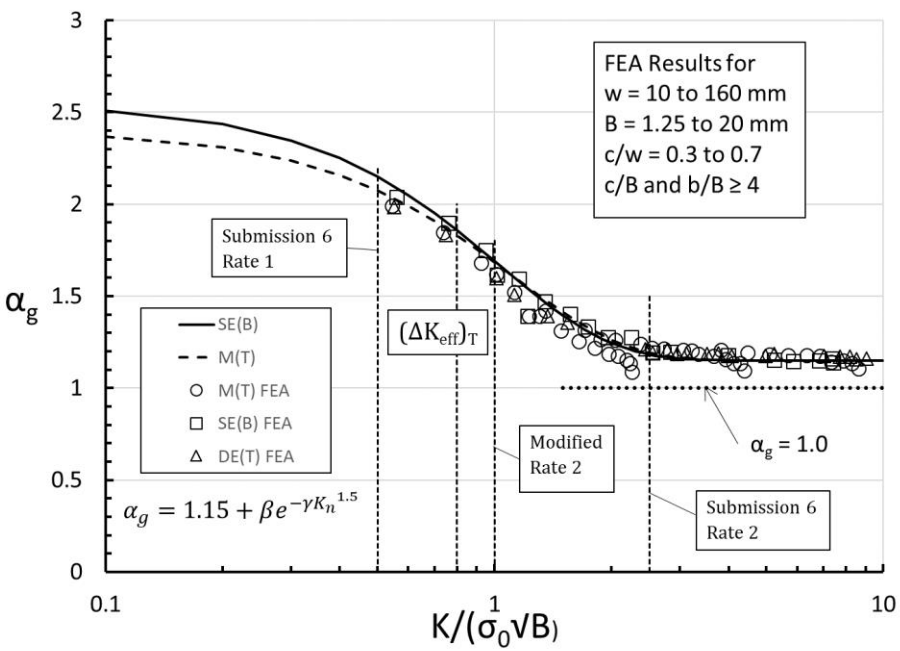
- Plasticity induced crack closure model
- Based on Dugdale strip yield model, but modified to leave plastically deformed material in the wake of the crack
- Important feature is the ability to model 3D stress state effects with the constraint factor

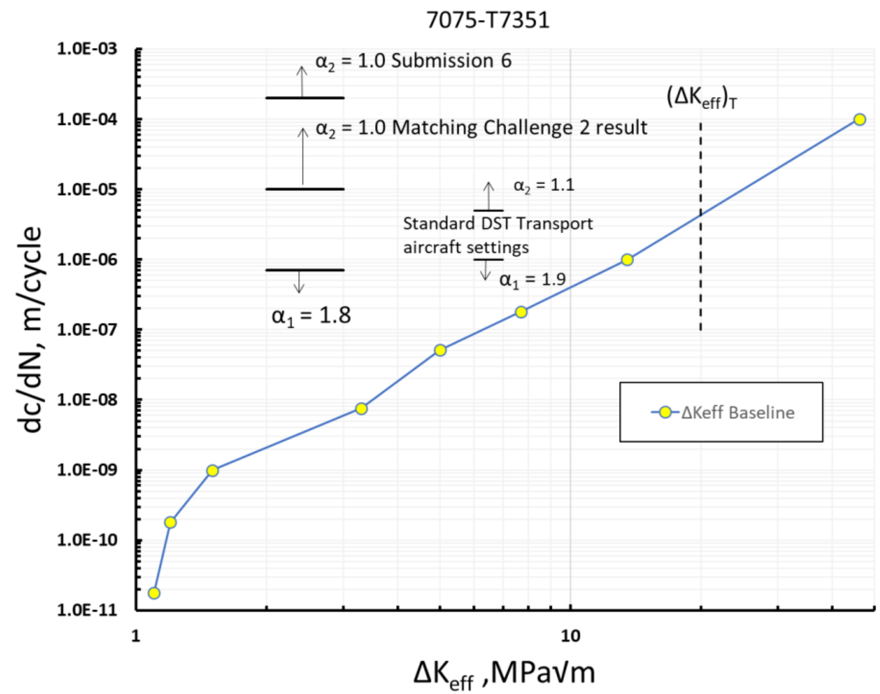


(a) Maximum stress. (b) Minimum stress.



Investigation using FASTRAN – Constraint Loss

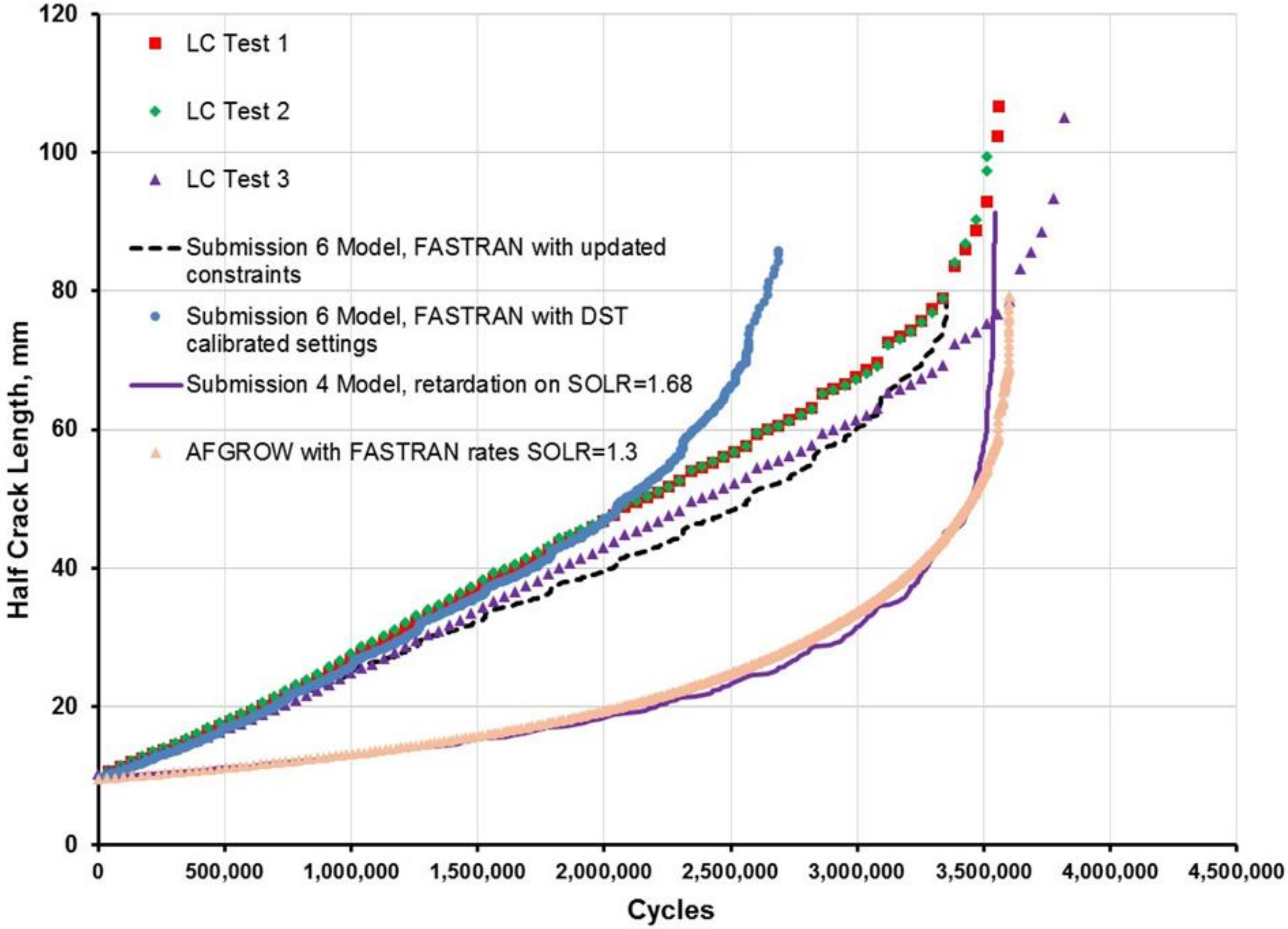




$$(\Delta K_{eff})_T = 0.5\sigma_0\sqrt{B}$$

Source: Newman , J.C., Jr., Crews, J.H., Bigelow, C.A., and Dawicke, D.S., Variations of a global constraint factor in cracked bodies under tension and bending loads, in Constrain effects in fracture: Theory and applications, ASTM STP 1244, M. Kirk and A. Bakker, Editors. 1995, ASTM. p. 21-42.

Further investigations with calibrated analyses



Conclusions

- All predictions were conservative, some excessively so
- Spectrum contained a significant overload, so retardation played a major role here
- Analytical method needs to account for retardation
- Equivalent energy approach (Submission 1) produced the best results
- Strip-yield analytical crack closure model worked well
- BAMF model seemed to somewhat over-predict the SIF
- Variations in crack growth rate data and SIF solution did not seem to have a significant effect here (apart from BAMF SIF difference)
- Variability in threshold region for rate data did not seem to impact on the results here, but it may in other cases
- Long crack case here, combined with spectrum filter level, means threshold region not activated. But that will be very different in other cases where the threshold can play a critical role

Recommendations

- Engage with the author of Submission 1 to consider the merits of that approach and application to other cases
- Conduct further tests and analyses to identify if further improvements can be made for the FASTRAN strip-yield analytical closure model, particularly around constraint-loss regime for M(T) type configurations
- Conduct CA testing on wide panels to characterise the constraint-loss regime, and consider collaboration with DLR Germany who are conducting research into wide, thin M(T) specimens (950 mm wide, 1.6 mm thick)
- Encourage possible investigation into why the Willenborg retardation model seems to promote an unrealistic crack growth curve shape
- Investigate the source of the variability in rate data in the threshold region
- Share the results from this review with all participants and invite them to collaborate on follow on work (including these recommendations)

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1. QinetiQ Australia – Melbourne, Australia
2. Defence Science and Technology Group – Melbourne, Australia

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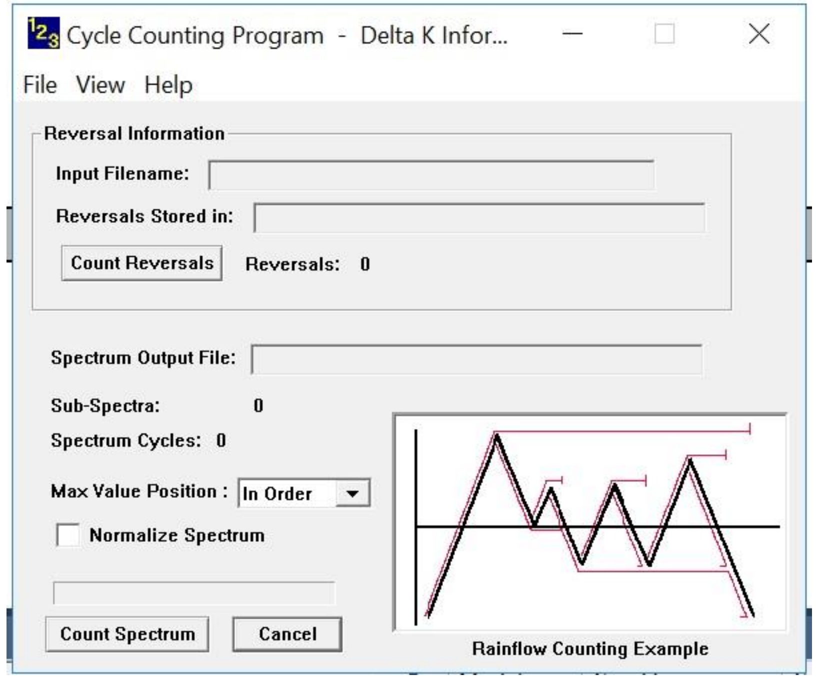
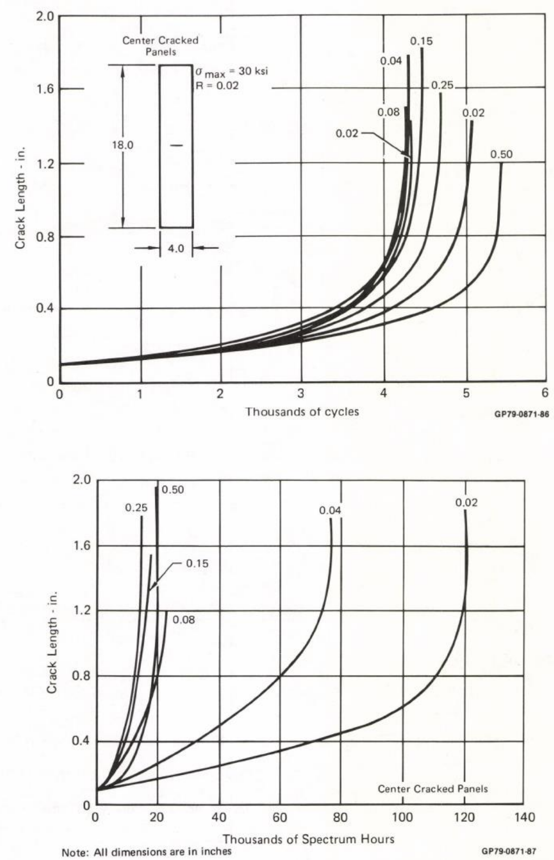
Backup Slides

AFGROW RPC Tool



Charley Saff McDonnell Douglas 1978 Example



Note: All dimensions are in inches

Figure 74. Sheet Thickness Tests - Constant Amplitude and Spectrum Test Results