Durability And Damage Tolerance (DADT) of AM Components

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Three key areas for crack simulation

Fracture mechanics parameters

K, G, J

Closed form

Numerical evaluation - BEM, FEM

Crack simulation

Certification requires a fracture mechanics approach

Topology issues

Initial crack

Mixed mode / non-planar growth

Crack shape development

Multiple cracks

Loading and crack growth integration

Cycle-by-cycle

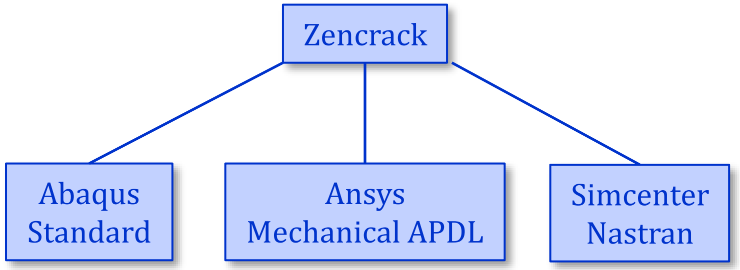
Finite evaluations of fracture parameters

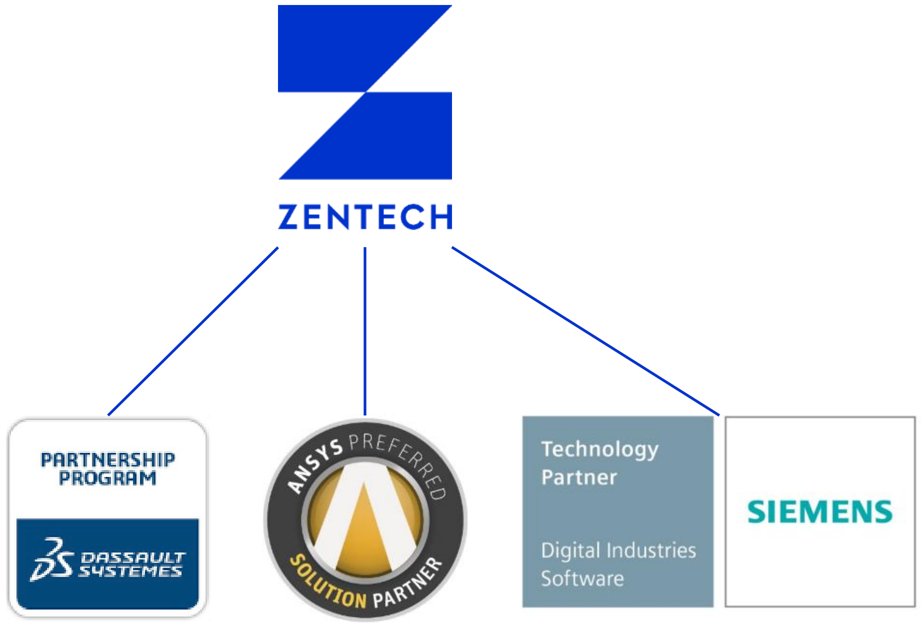
Crack growth data, threshold effects

Load spectrum, flight cycles

The solution provided by Zencrack

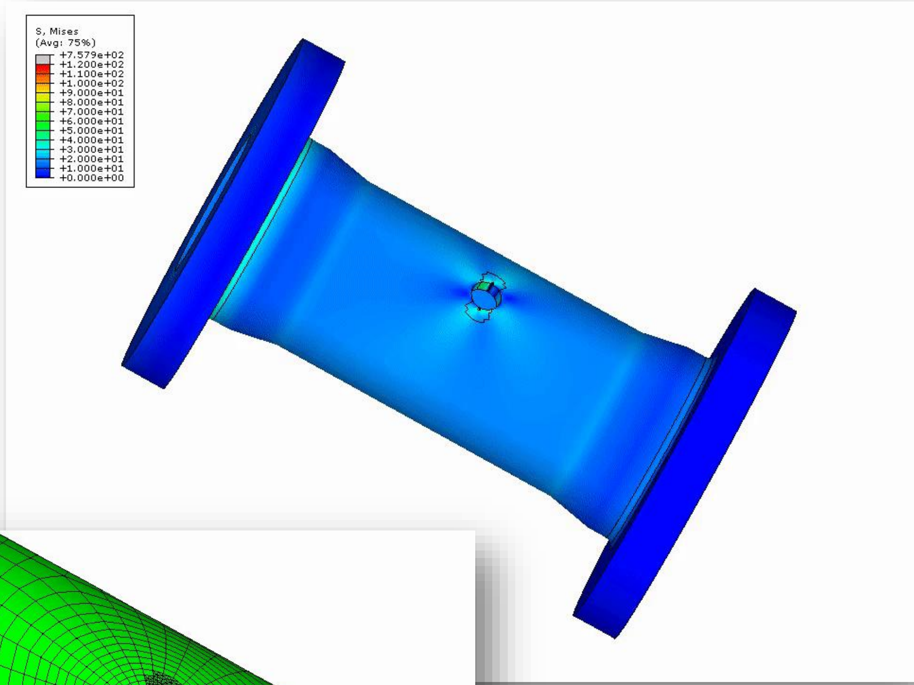
- Zencrack:
  - Is a powerful tool for fracture mechanics analyses
  - Uses commercially available finite element codes as the solution engine to help calculate fracture mechanics parameters:
    - » Abaqus/Standard
    - » Ansys/Mechanical APDL
    - » Simcenter Nastran (previously NX Nastran)
  - Has meshing algorithms and generalised approaches for modelling crack fronts to help minimise topology related issues
  - Has a crack growth integration scheme to allow generalised non-planar crack growth prediction

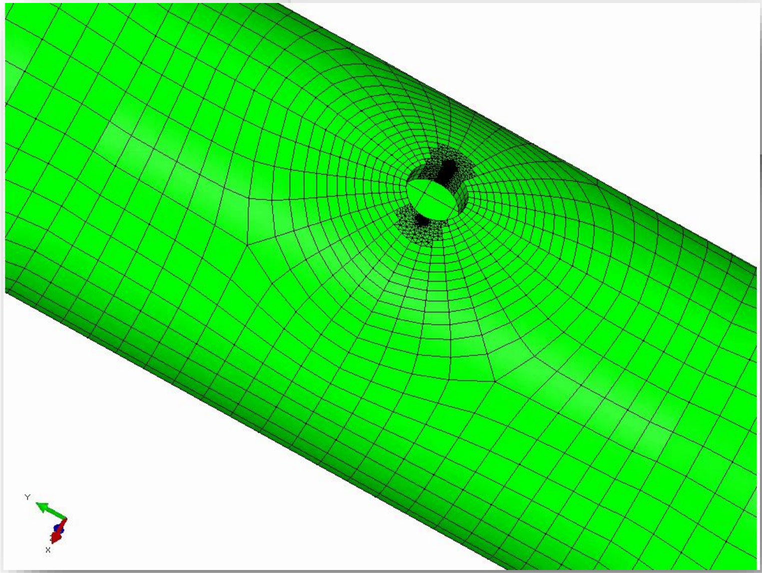




The solution provided by Zencrack

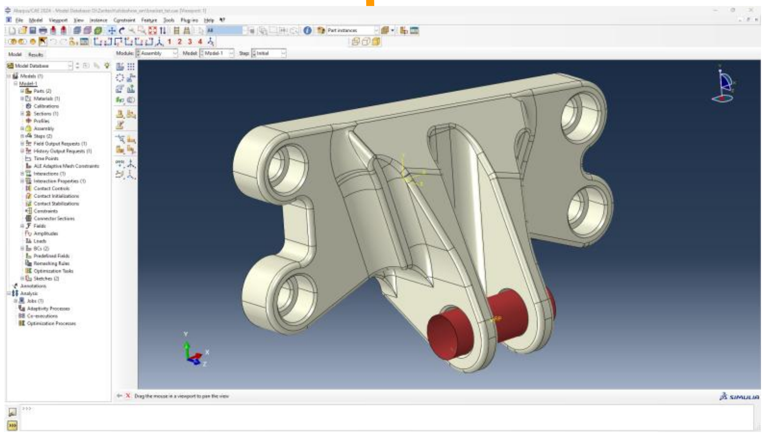
- A fast and easy means of analysing cracks in 3D components under arbitrary loading
  - Static load cases
  - Thermal transients
  - Thermo-mechanical time-varying loads
  - Multiple cracks
- A general purpose 3D crack growth simulation capability
  - Non-planar crack growth
  - Fatigue loading
    - Constant amplitude to complex thermo-mechanical load cycles
  - Time dependent loading



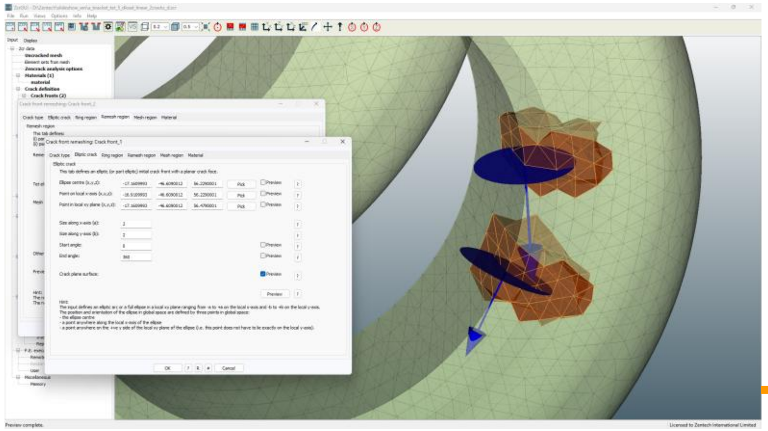


Example:
Two cracks growing from a hole.
Loaded by constant amplitude tension-torsion cycles.

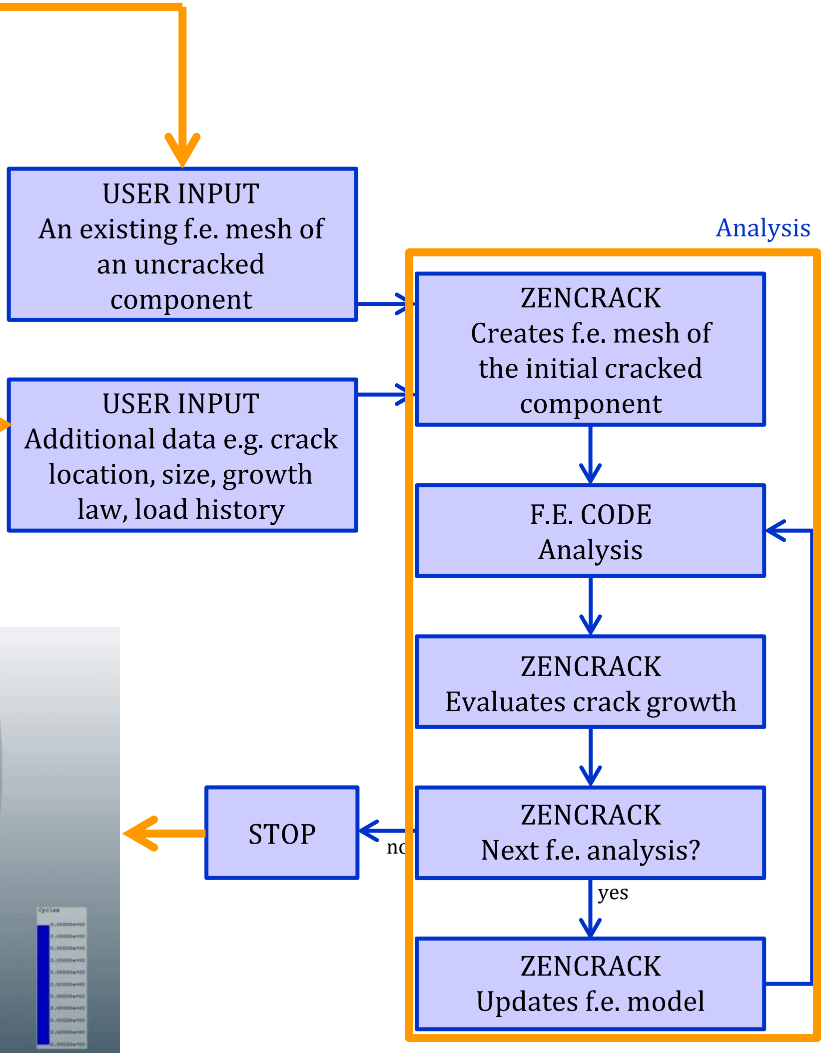
Summary of workflow

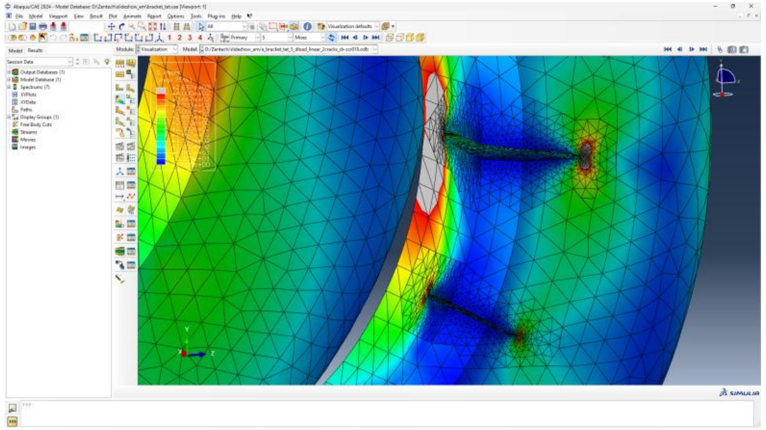


F.E. pre-processing

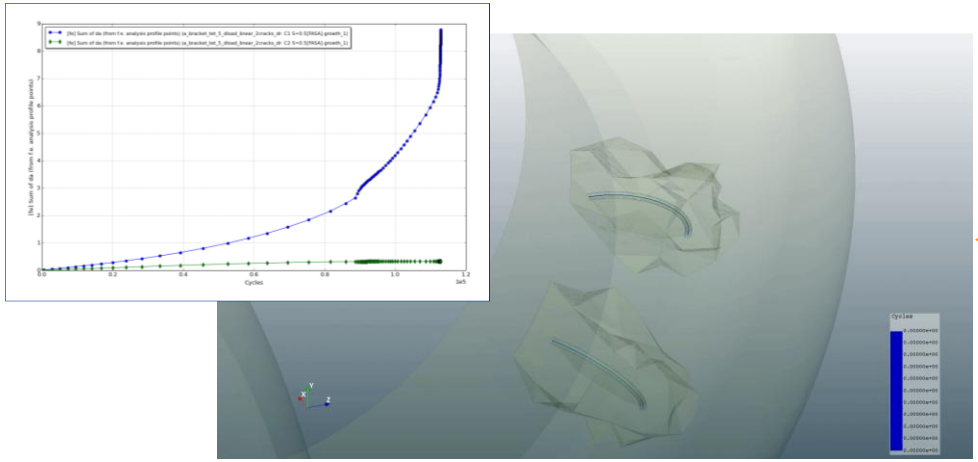


Zencrack pre-processing



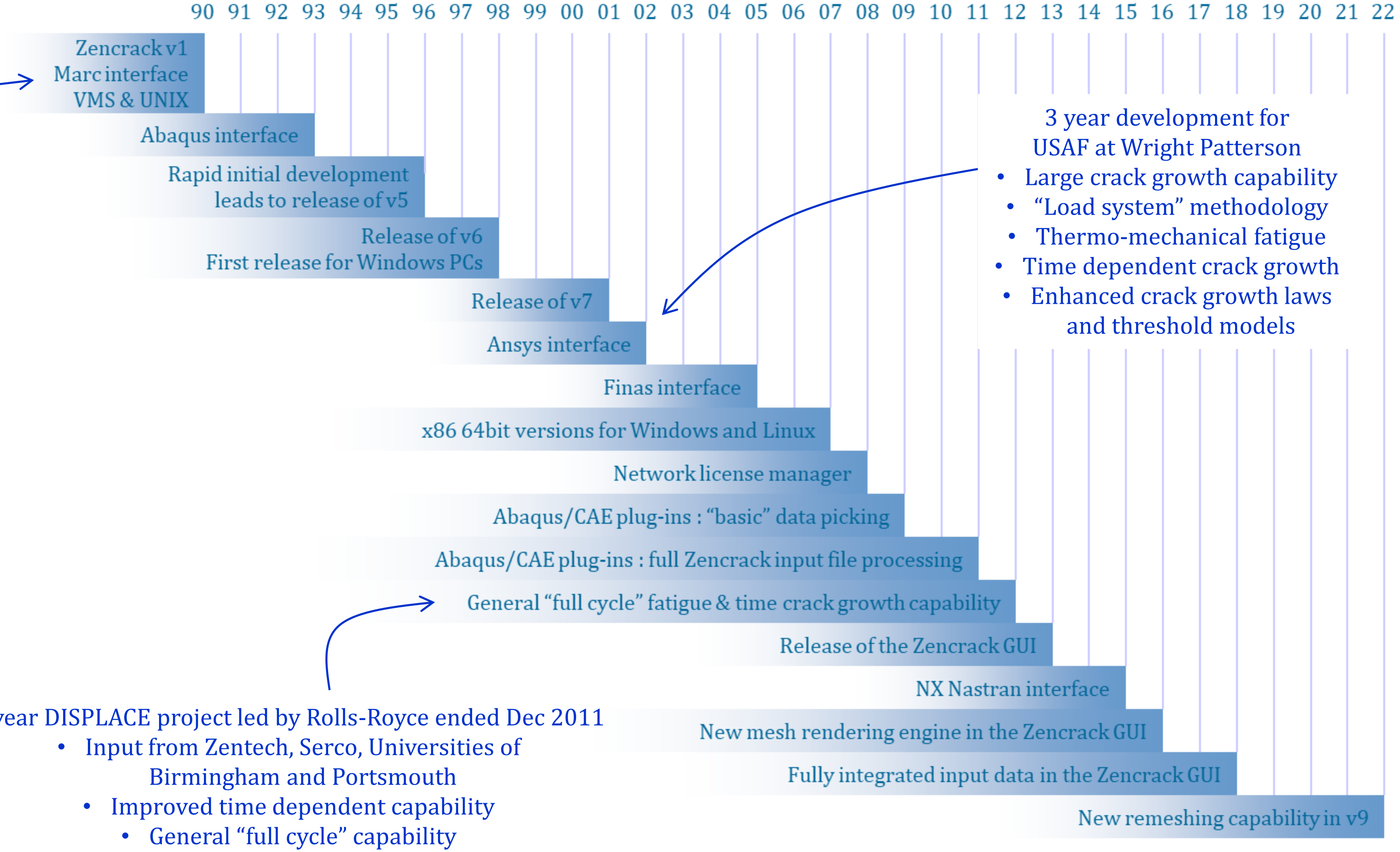


F.E. post-processing



Zencrack post-processing

Zencrack historical perspective



3 year development for
USAF at Wright Patterson

- Large crack growth capability
- "Load system" methodology
- Thermo-mechanical fatigue
- Time dependent crack growth
- Enhanced crack growth laws and threshold models

Initiated by consultancy for George Harrison at RAE Pyestock

- Parametric studies of elliptic cracks
- Re-meshing routines to simulate crack growth
- 2D and then 3D geometries

3 year DISPLACE project led by Rolls-Royce ended Dec 2011

- Input from Zentech, Serco, Universities of Birmingham and Portsmouth
- Improved time dependent capability
- General "full cycle" capability

Durability and Damage Tolerance of AM components

- Use of AM Components, Cold Spray AM materials and Cold Spray Repairs is on the increase in Defence industry specially since March 2019 (1), to enable the transformation of maintenance operations and supply chains, increase logistics resiliency, and improve self-sustainment and readiness for DoD forces.
- These processes, however, may leave micro-sized discontinuities (small cracks) affecting the fatigue life.
- US MIL-STD-1530D (2) and NASA Fracture Control Handbook NASA-HDBK-5010 (3) also mandate that requisite level of qualification, certification, and risk/safety evaluation must be carried out by an appropriate engineering support activity based on Linear Elastic Fracture Mechanics (LEFM) principles and perform predictive Durability and Damage Tolerance (DADT) assessment for all applications of AM parts/repair patches.
- Both MIL and NASA standards mandate a minimum EIDS (equivalent initial damage size) of 0.01 inch (0.254 mm) for performing durability analysis.
- The predictive assessment requires crack growth data for small and large crack regimes.

1. Under Secretary, Acquisition and Sustainment, Directive-type Memorandum (DTM)-19-006 – "Interim Policy and Guidance for the Use of Additive Manufacturing (AM) in Support of Materiel Sustainment", Pentagon, Washington DC, March 21st, 2019.
2. MIL-STD-1530D (W/ CHANGE-1), Department Of Defense Standard Practice: Aircraft Structural Integrity Program (ASIP) (13 Oct 2016). Available online: http://everyspec.com/MIL-STD/MIL-STD-1500-1599/MIL-STD-1530D_CHG-1_55391
3. NASA-HDBK-5010, Fracture Control Handbook For Payloads, Handbook For Payloads, Experiments, And Similar Hardware (19 Oct 2017). Available online : https://standards.nasa.gov/standard/nasa/nasa-hdbk-5010

Additive Manufacturing Is Coming of Age: BAe Systems and the Global Combat Aircraft

"BAe Systems initiative forms part of the Tempest project and will lean on additive manufacturing technologies to produce 'significant structural parts' of the aircraft. This demonstrator aircraft will be used to generate data that can be harnessed to support the development of the Tempest combat aircraft.

BAE Systems made the announcement at Farnborough International Airshow, detailing how the demonstrator aircraft is a 'significant advancement' in crewed supersonic aircraft and will boast 'stealth features.' The collaborators are aiming to have the demonstrator ready for flight by 2027, with a new combat aircraft set to be ready by 2035.

Harnessing 3D printing and Hot Isostatic Press (HIP) technology, BAE is hoping to produce structural parts of the demonstrator aircraft 'efficiently and cost-effectively.' The UK Defence Journal reports that test pilots from BAE Systems, Rolls-Royce and the Royal Air Force have conducted over 215 hours of simulation flights, which has generated information that can be leveraged to support aircraft design and future flight trials."

By Sam Davies, 25 July 2024

Reference: https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/latest-additive-manufacturing-3d-printing-news/bae-systems-utilise-3d-printing-manufacture-tempest-demonstrator/

Image: https://www.baesystems.com/en-uk/product/combat-air-demonstrator

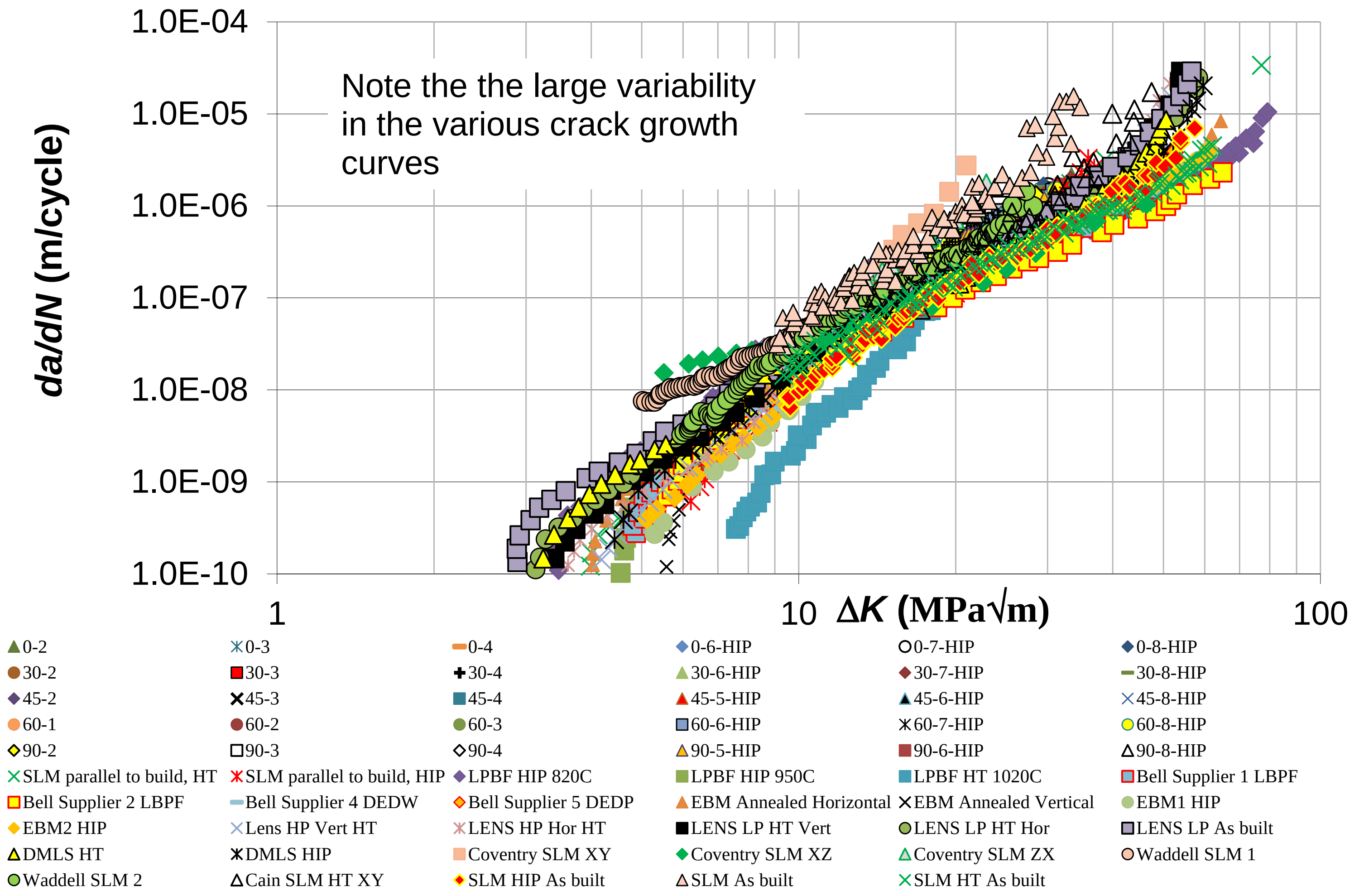
Material Variability an Example: AM Ti-6Al-4V

Plot of 58 R=0.1 da/dN versus ΔK curves for tests on AM Ti-6Al-4V reported in (5)

Material: AM Ti-6Al-4V

LENS = Laser Engineered Net Surface
EBM = Electron Beam Melt
SLM = Selective Laser Melt
LPBF = Laser Powder Bed Fusion
DED = Directed Energy Deposition
DMLS = Directed Metal Laser Sintering
WAAM = Wire arc additively manufactured

Specimens labelled x-n refer to heat treated SLM built specimens with the crack at an angle x to the build direction, n is the specimen number, i.e. 45-2 has the crack at 45° to the build direction. Specimens with the suffix HIP, i.e. 0-6-HIP, have been hipped.



Durability And Damage Tolerance (DADT) Assessment

- A number of studies performed by US DoD and Boeing Space Agency have shown that Durability of AM, Cold Spray AM (CSAM) Materials and Cold Spray repairs appear to be controlled by only TWO Fracture Mechanics parameters for a material:

  - A — the cyclic fracture toughness parameter
  - ΔK_{thr} — the cyclic fatigue threshold

- The Hartman-Schijve crack growth law, a variant of NASGRO crack growth law, which is applicable to both small and long cracks is used:

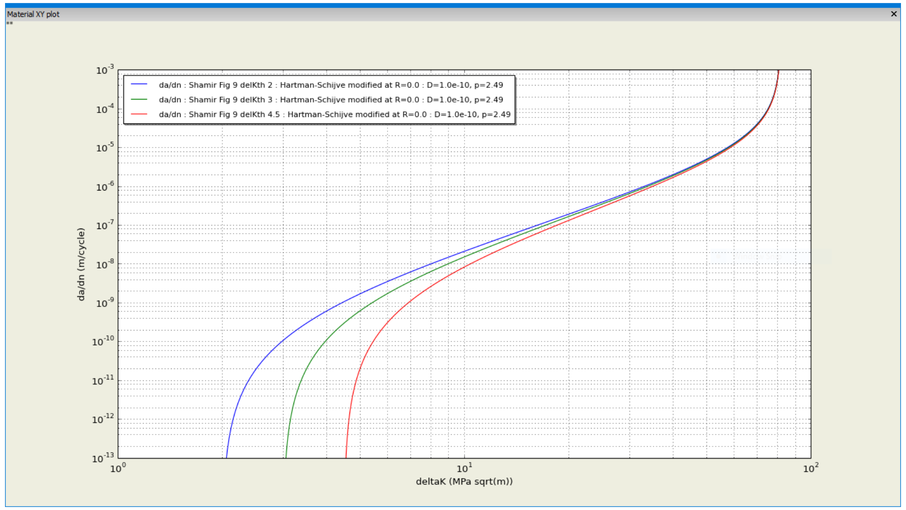
$$da/dN = D\,(\Delta\kappa)^{p}$$

N is cycle number, a is crack length

D and p are material constants

Similitude constant $\Delta\kappa$ as defined by Schwalbe (4):

$$\Delta\kappa = (\Delta K - \Delta K_{thr})\,/(1-(K_{max}/A))^{1/2}$$



Example of Hartman-Schijve da/dN vs ΔK plots

4. Schwalbe K.H., On the beauty of analytical models for fatigue crack propagation and fracture - a personal historical review. In Fatigue and Fracture Mechanics: 2011, 37, 3-73, doi:10.1520/JAI102713.

The da/dN versus Δκ relationship for Ti-6Al-4V (5)

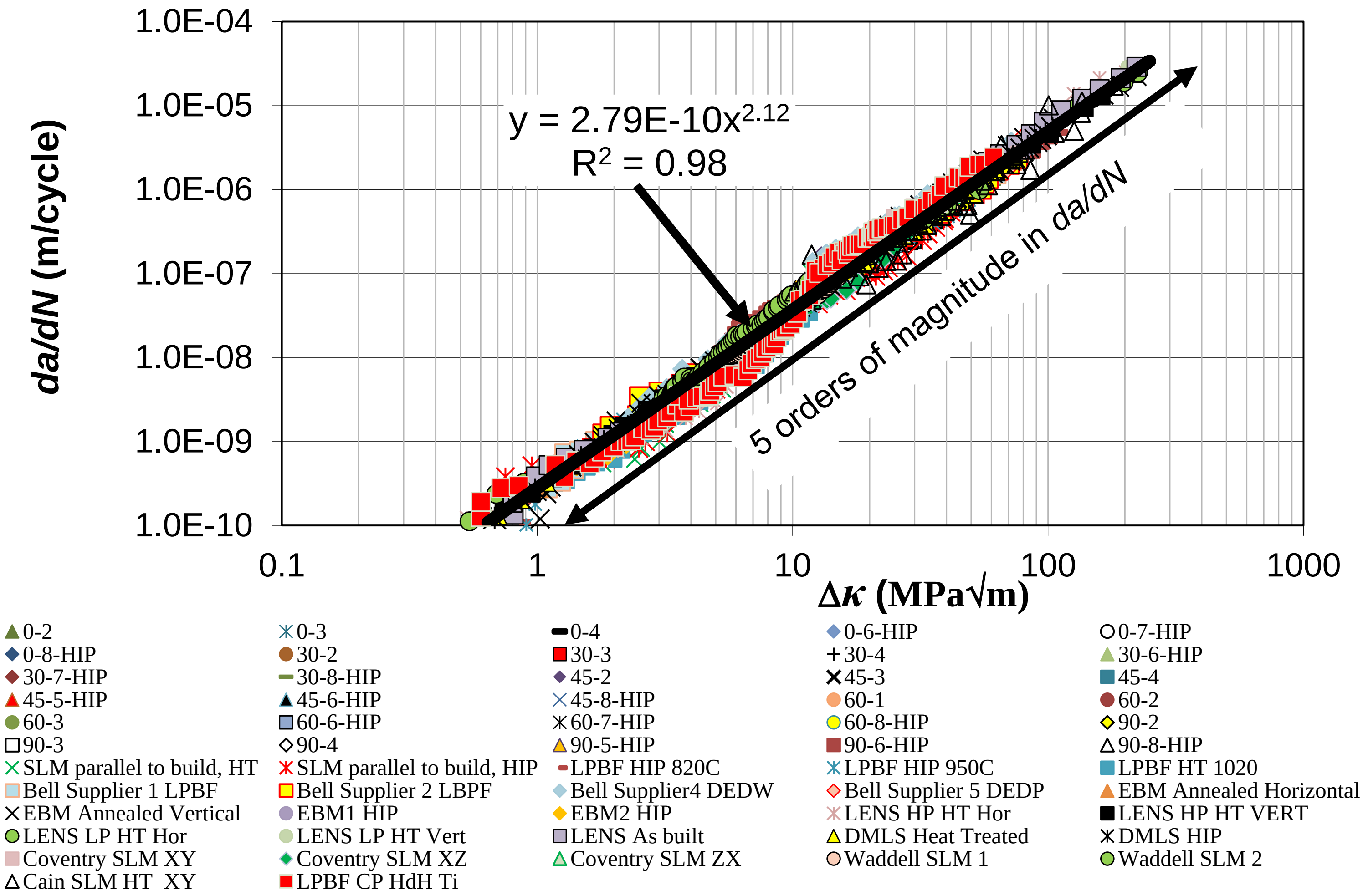
When allowance is made for the effect of the different build processes on the variability in the *two parameters* ΔK_{thr} and A, then (allowing for experimental error) **each of these 57 curves essentially collapse onto a single curve**.

Plot da/dN vs Δκ rather than da/dN vs ΔK,

where $\Delta\kappa$ is the crack tip (*similitude*) parameter as defined by Schwalbe (4):

$\Delta\kappa = (\Delta K - \Delta K_{thr}) / (1-(K_{max}/A))^{1/2}$

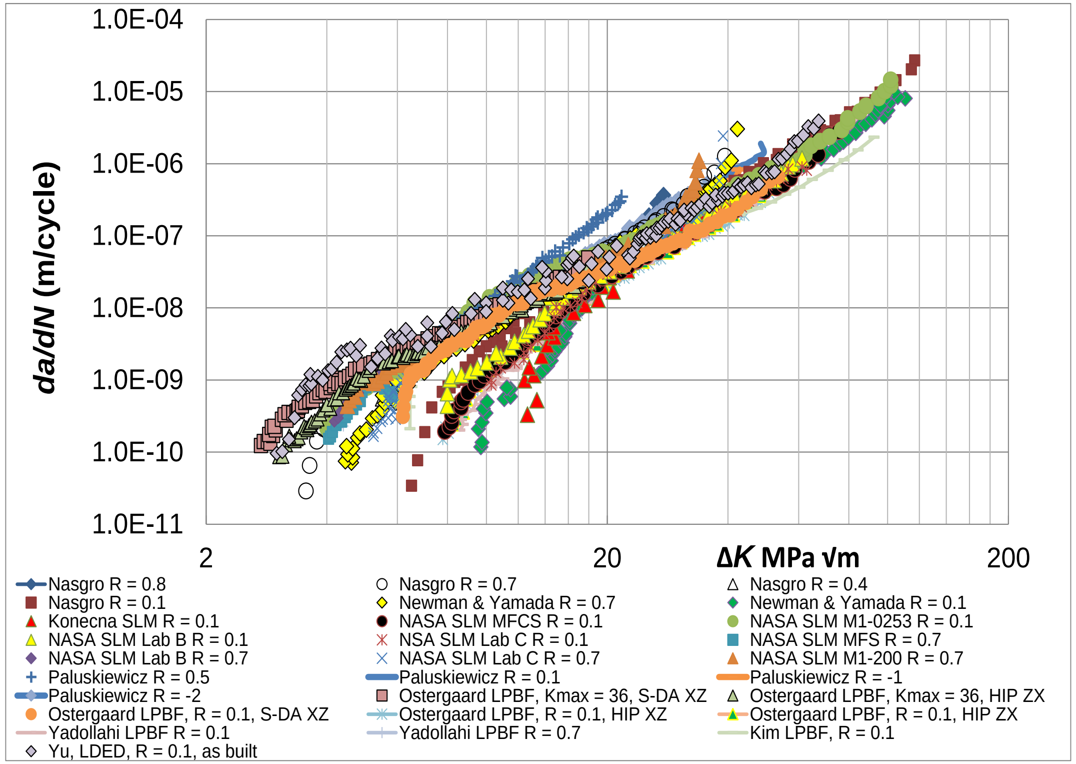
ΔK is the range of the stress intensity factor seen in a cycle and K_{max} is the maximum stress intensity factor in the cycle



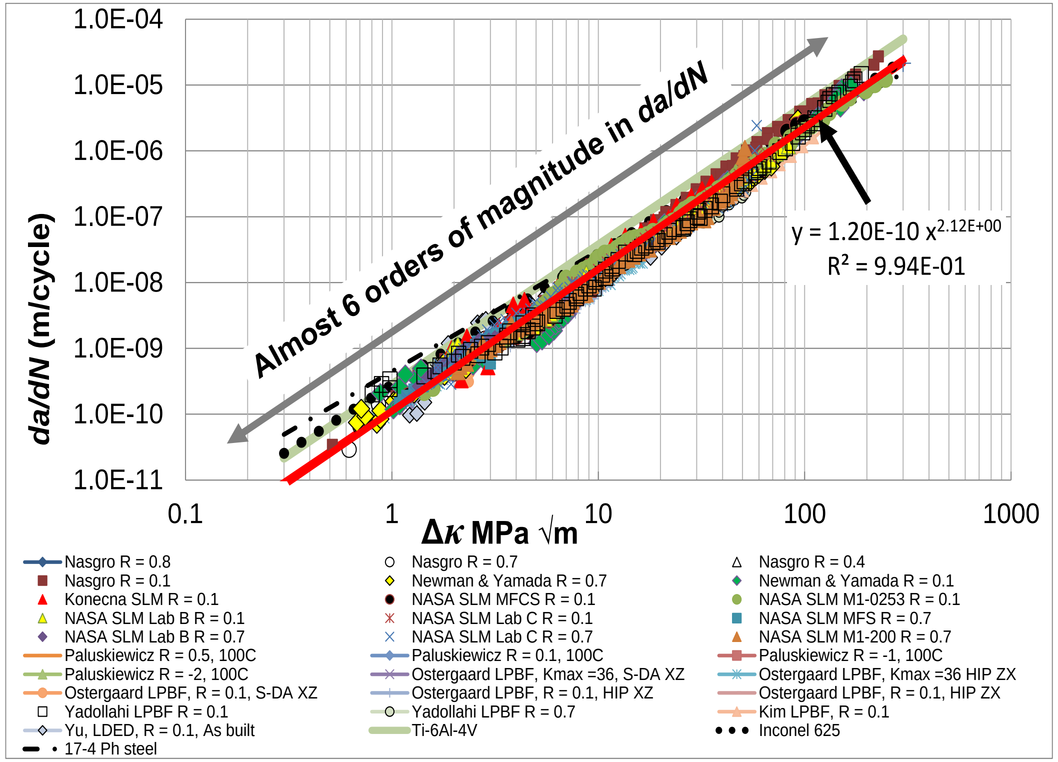
5. Jones R., Peng D., A Building Block Approach to Sustainment and Durability Assessment: Experiment and Analysis, In: Aliabadi, Ferri M H and Soboyejo, Winston (eds.), Comprehensive Structural Integrity, 2nd Edition, vol. 7, pp. 73–101, 2023. Oxford, UK. Elsevier, ISBN 978-0-12-822944-6.

Further example - Conventionally Built & AM Inconel 718 (6)

- Twenty eight da/dN versus ΔK curves covering a wide range of R ratios, build processes, and with the crack at different angles to the build direction.



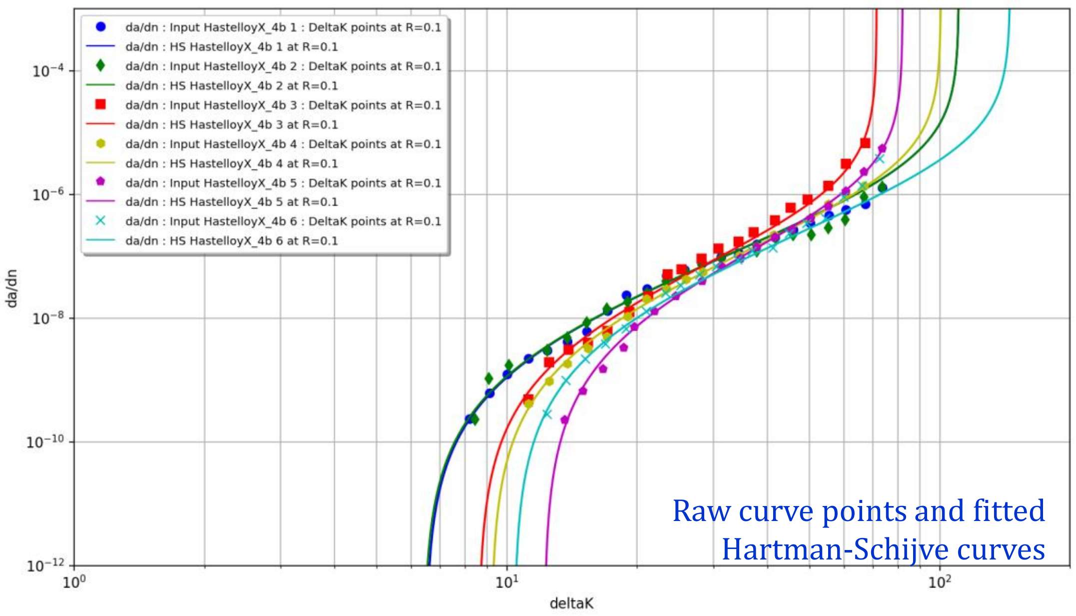
- When da/dN is expressed as a function of Δκ, then all curves, which cover a wide range of R ratios, collapse onto the same da/dN versus Δκ curve. *Over 5 orders of magnitude in da/dN.*

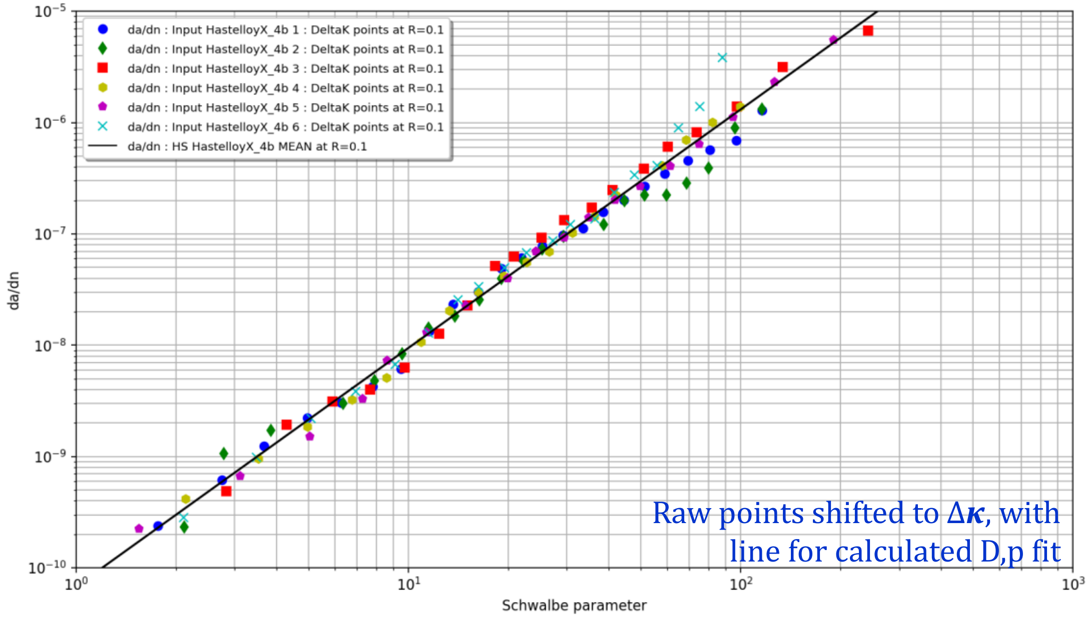


6. Jones R, Ang A, Peng D, Champagne VK, Michelson A, Birt A. Modelling Crack Growth in Additively Manufactured Inconel 718 and Inconel 625. Metals. 2023; 13(7):1300. https://doi.org/10.3390/met13071300 (A US Army funded study)

Fitting process – example with 6 sets of test data (7)

- Calculate ΔK_{thr} and A to fit each curve while calculating D and p in the shifted $\Delta\kappa$ form for all curves:
  - General case makes no assumption about ΔK_{thr} and A values
  - Alternative approach could specify the same A for all curve fits
- Take mean of the individual curve ΔK_{thr} and A values to give final ΔK_{thr} and A
- Result is a “mean” 4-parameter curve representing all original data: ΔK_{thr} , A, D, p

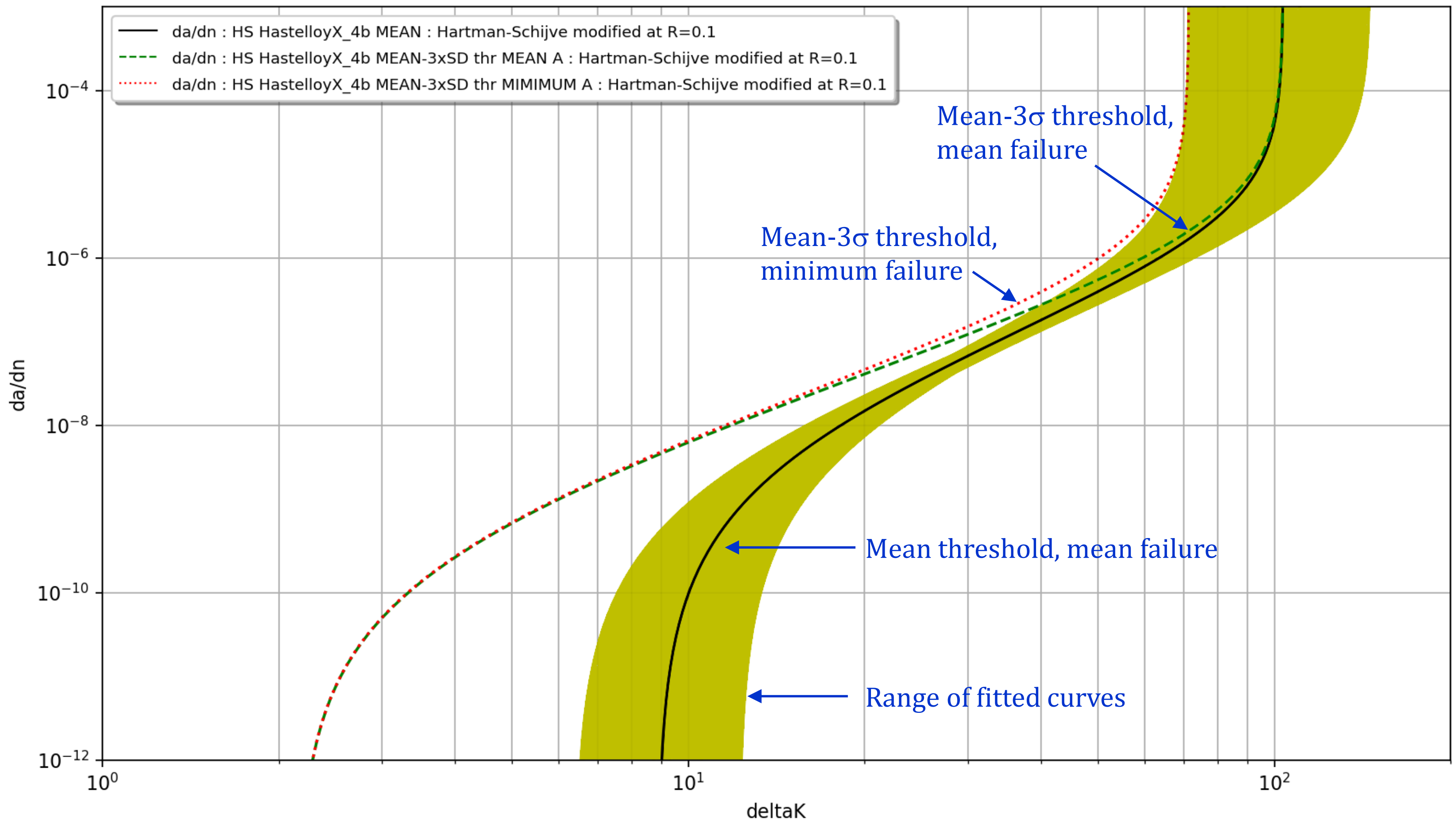




7. Fatigue crack growth in additively manufactured Hastelloy X - Influences of crack orientation and post-fabrication treatments, Karapuzha et al, Materials Science & Engineering A 854 (2022) 143773, https://doi.org/10.1016/j.msea.2022.143773

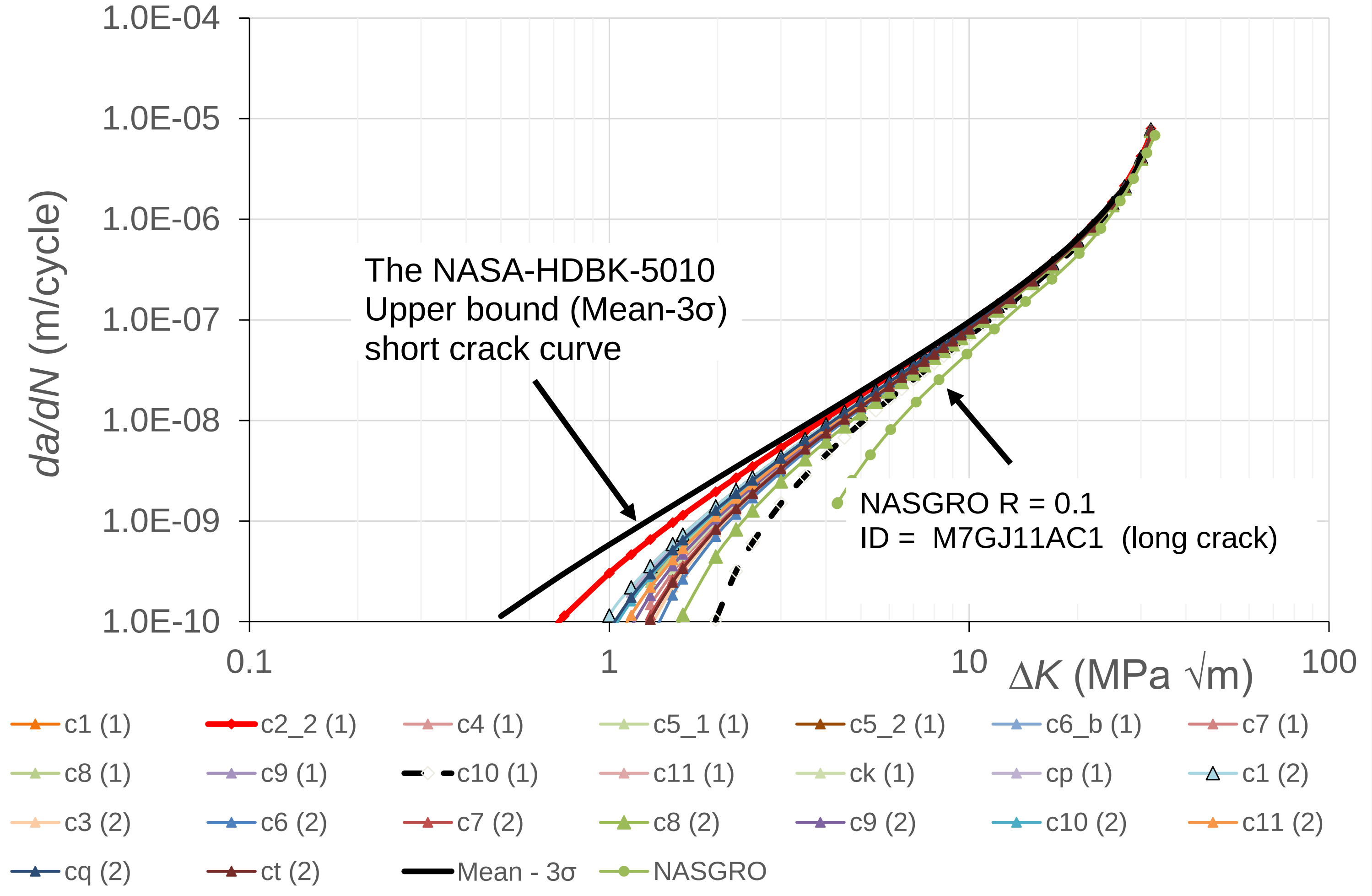
Fitting process – example with 6 sets of test data (7)

- The mean curve can be further processed using the standard deviation of threshold
- The plot shows curves at R=0.1 on a ΔK x-axis with three possible combinations of threshold and failure



The NASA-HDBK-5010 approach

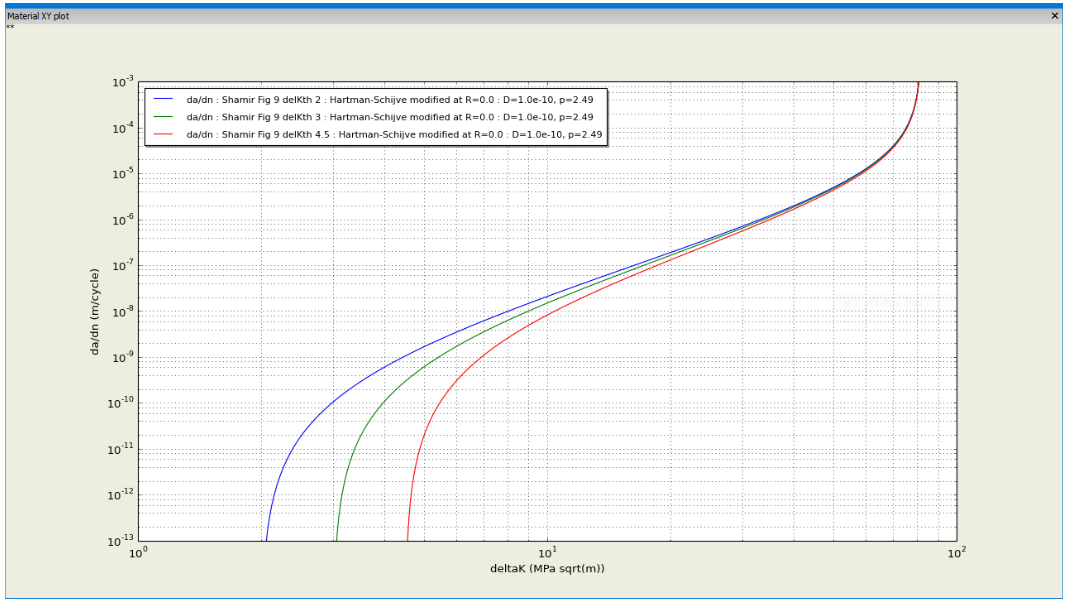
- By definition the “mean” curve does not provide the worst-case scenario in terms of performing life prediction
- NASA-HDBK-5010 (3) mandates using the worst-case (mean-3σ) da/dN v ΔK crack growth curve.
- Example of the NASA-HDBK-5010 approach for short cracks in conventionally manufactured 7050-T7451, from (8).
- 7050-T7451 is widely used in both the F/A-18 Super Hornet and the F-35.



8. R. Jones , C. Rans, A.P. Iliopoulos, J.G. Michopoulos, N. Phan, D. Peng, Modelling the Variability and the Anisotropic Behaviour of Crack Growth in SLM Ti-6Al-4V, Materials 2021, 14, 1400. https://doi.org/10.3390/ma14061400.

Durability And Damage Tolerance (DADT) Assessment

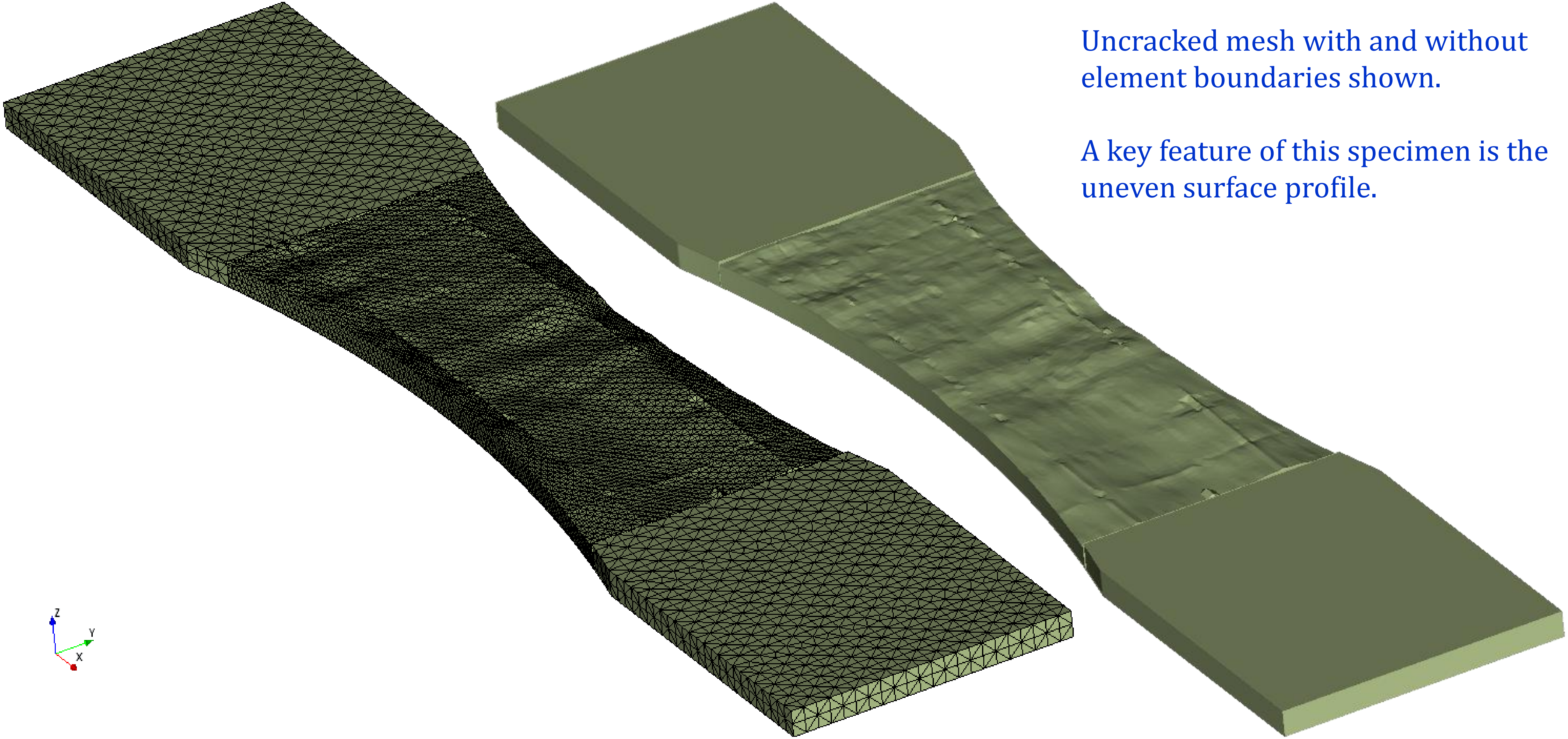
- In collaboration with Prof. Dr Rhys Jones*, Zentech became involved in DADT assessment of AM components and adhesive connections using the Hartman-Schijve crack growth law described on the previous slides
- The implementation of the Hartman-Schijve crack growth law, which is applicable to both long and small crack, includes:
  - Curve fitting to calculate curve parameters from test data
  - Stress intensity and energy formulation of the law
- The law is used with the general capabilities in Zencrack to alongside calculation of stress intensity factors and energy release rates which, coupled with cyclic loading history, are used in crack growth calculations



Example of Hartman-Schijve da/dN vs ΔK plots

* Centre of Expertise for Structural Mechanics, Department of Mechanical and Aerospace Engineering, Monash University, Victoria, Australia;
ARC Industrial Transformation Training Centre on Surface Engineering for Advanced Materials, Swinburne University of Technology, Victoria, Australia.

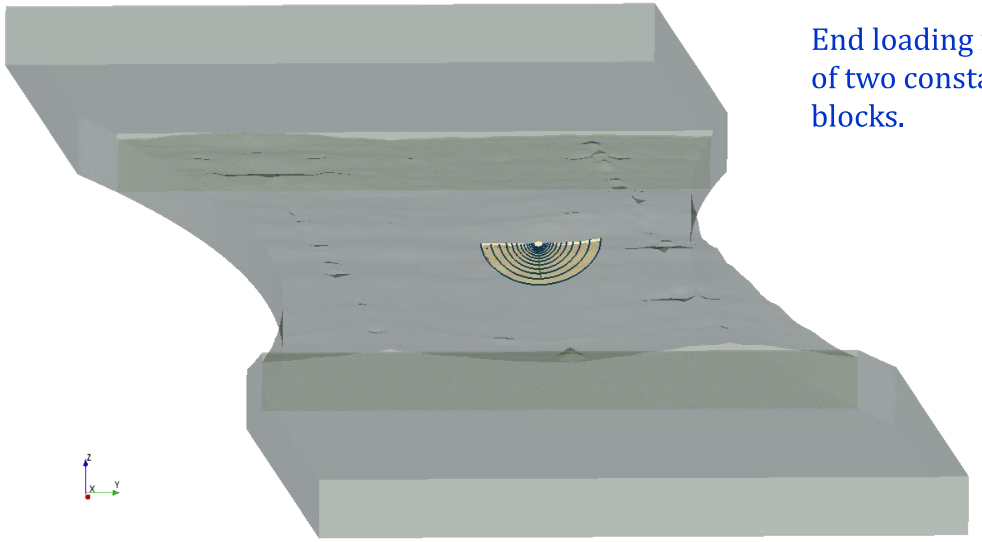
Example – Additive manufacturing



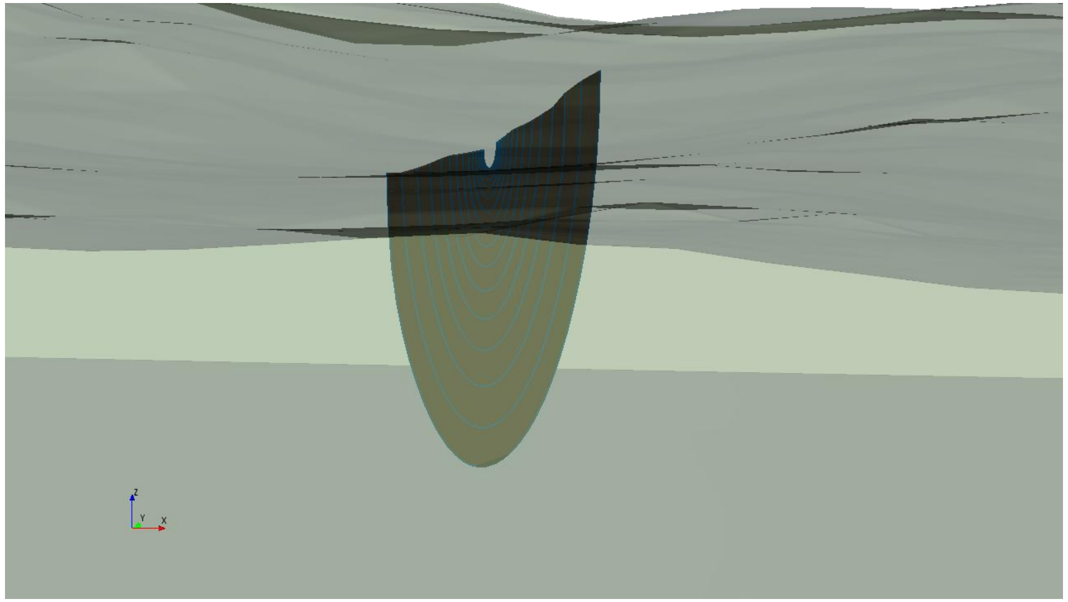
Uncracked mesh with and without element boundaries shown.

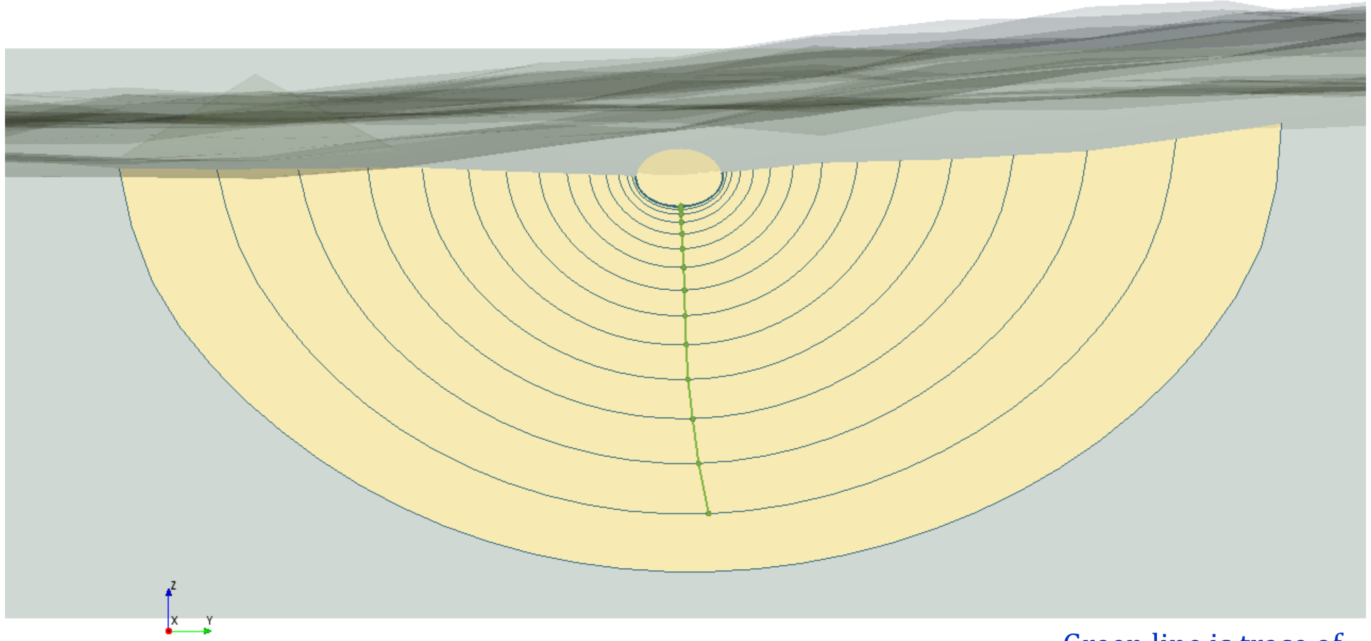
A key feature of this specimen is the uneven surface profile.

Example – Additive manufacturing



End loading is a sequence of two constant amplitude blocks.

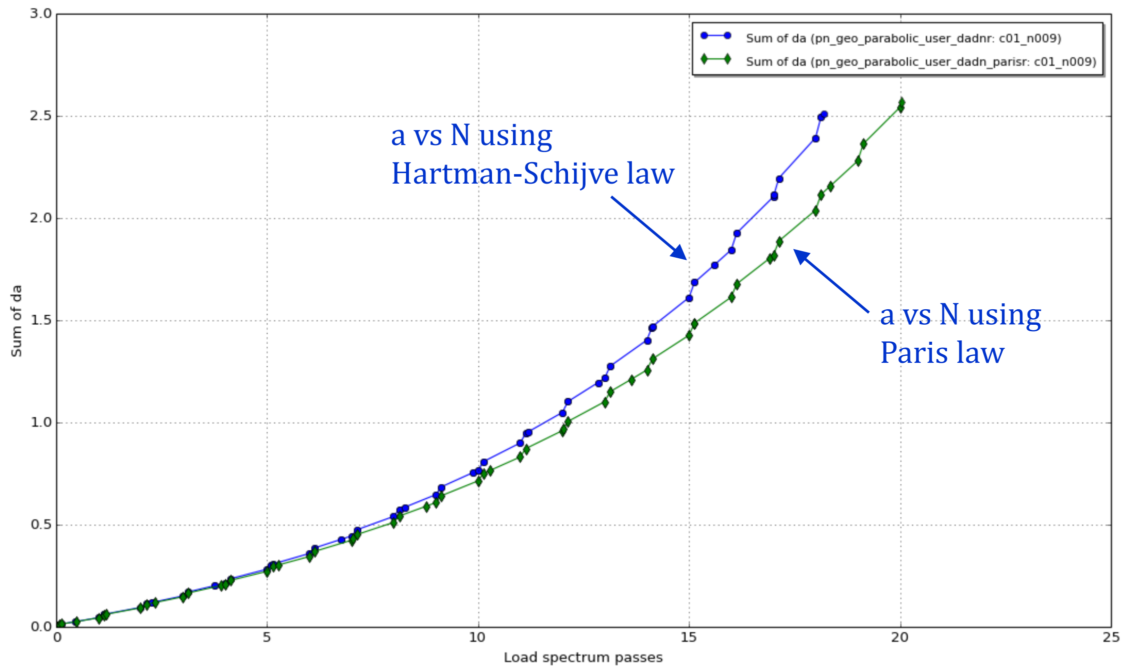


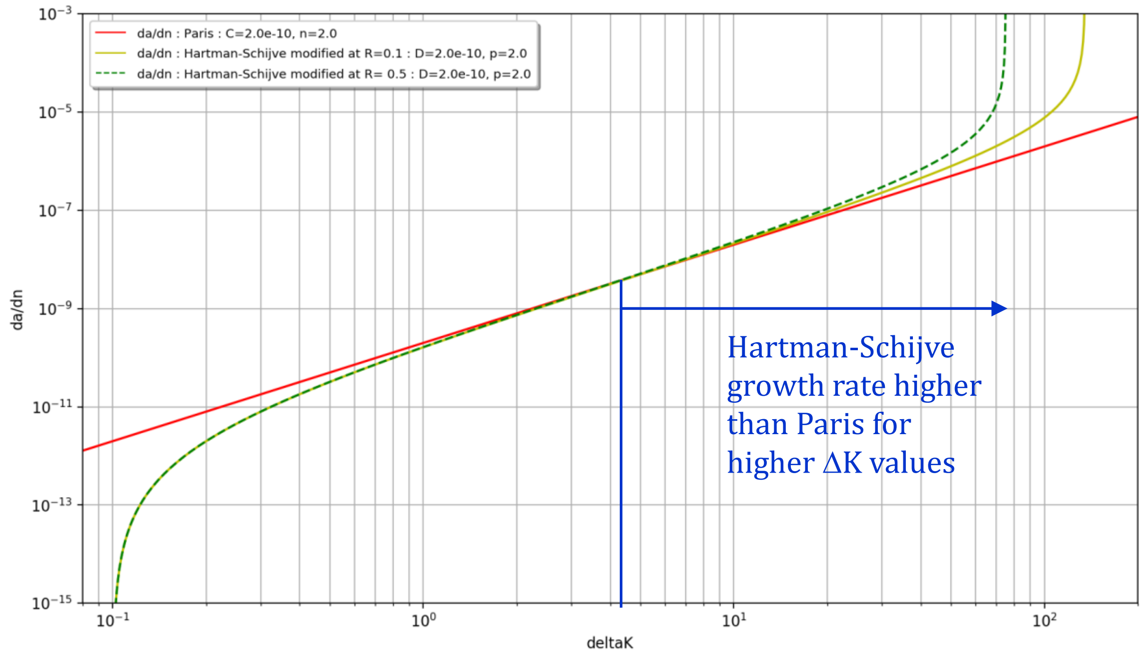


Green line is trace of middle point of the crack front used for xy plots (next slide)

Example – Additive manufacturing

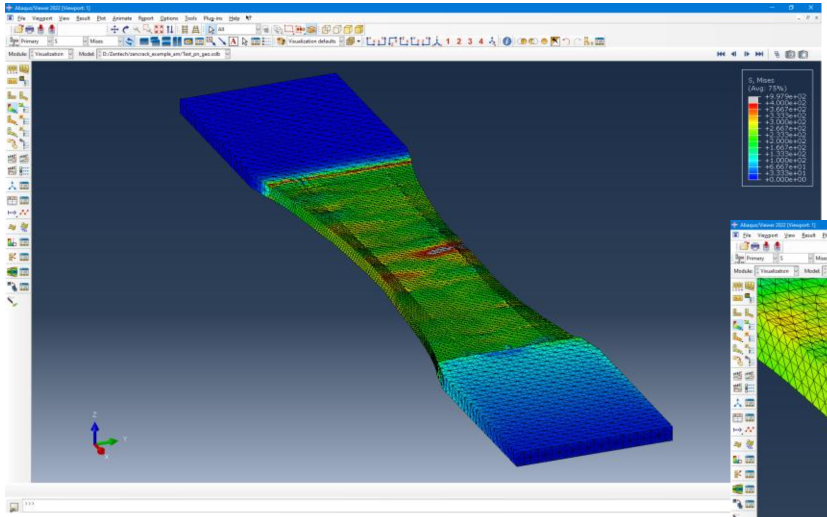
- Left-hand plot shows growth vs the number of load spectrum passes
  - plot shows comparison of Paris and modified Hartman-Schijve growth laws
  - Same C,n and D,p coefficients for the two laws
- Whether the instantaneous growth rate for Paris is higher or lower than the Hartman-Schijve growth rate depends upon the ΔK value

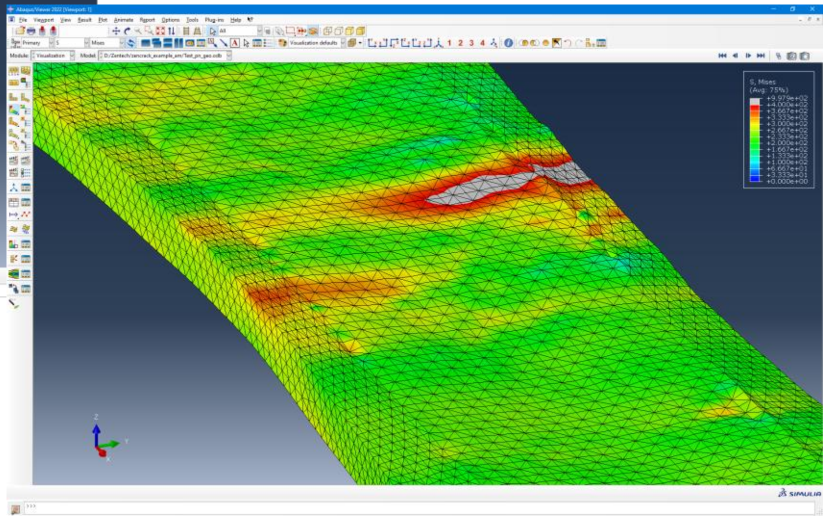


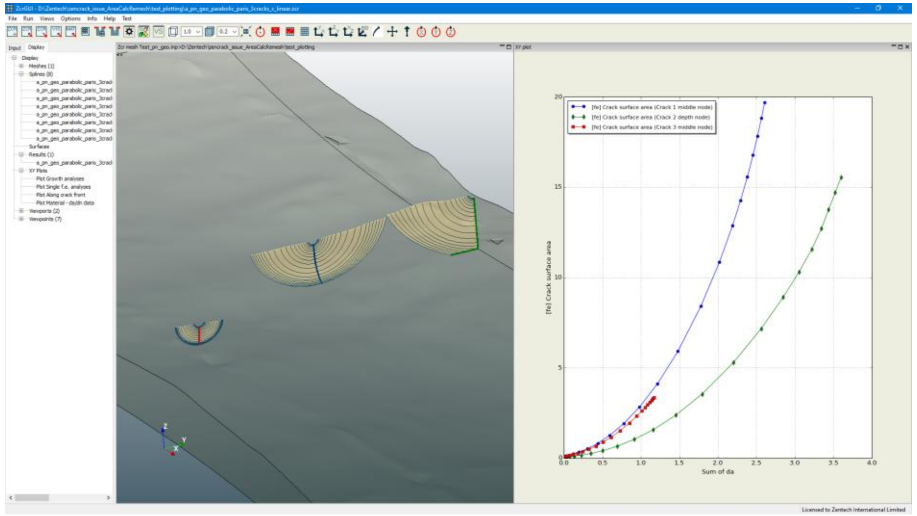


Example – Additive manufacturing – 3 cracks

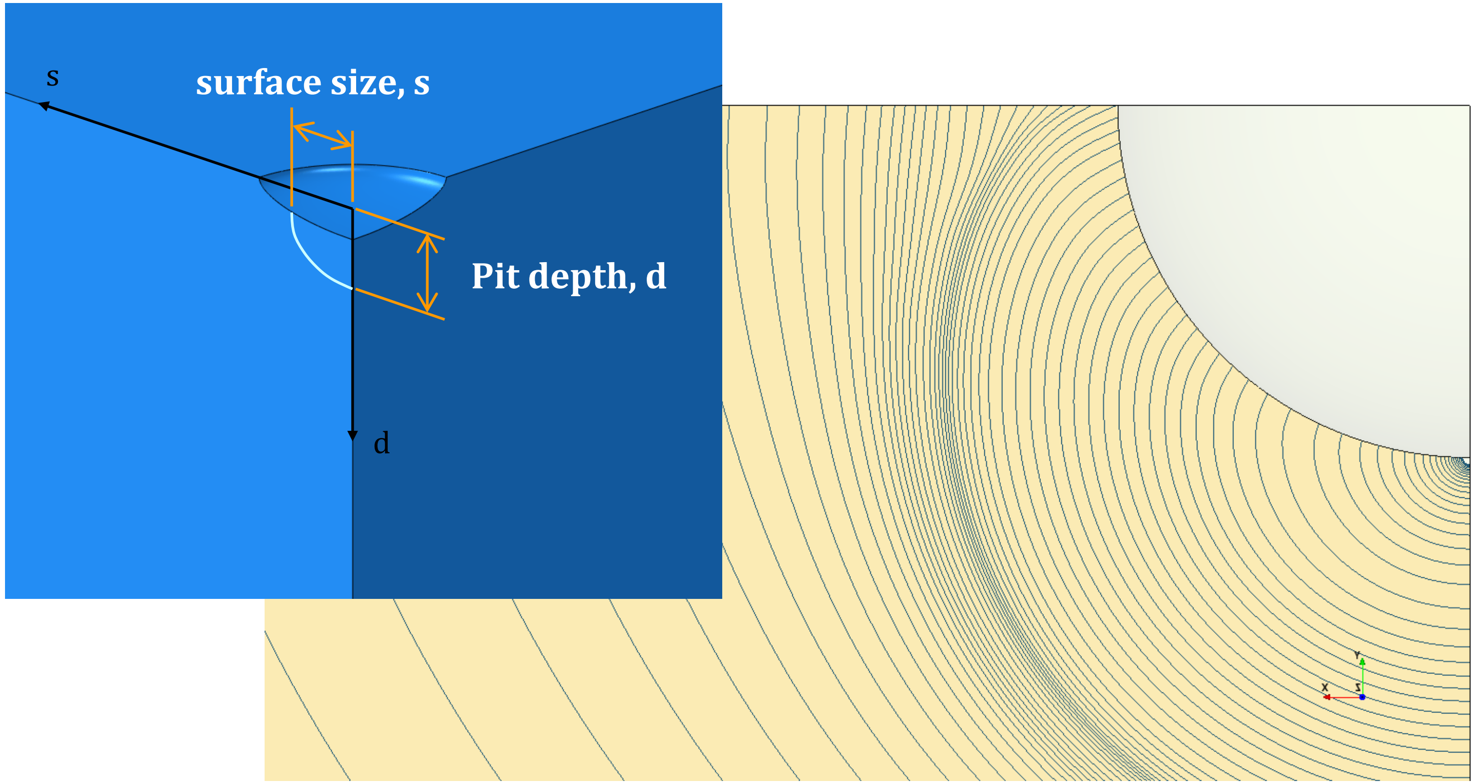
- Additive manufacturing example with three cracks
- Initial cracks located near high stress regions of the uncracked component
- Modified Hartman-Schijve crack growth law

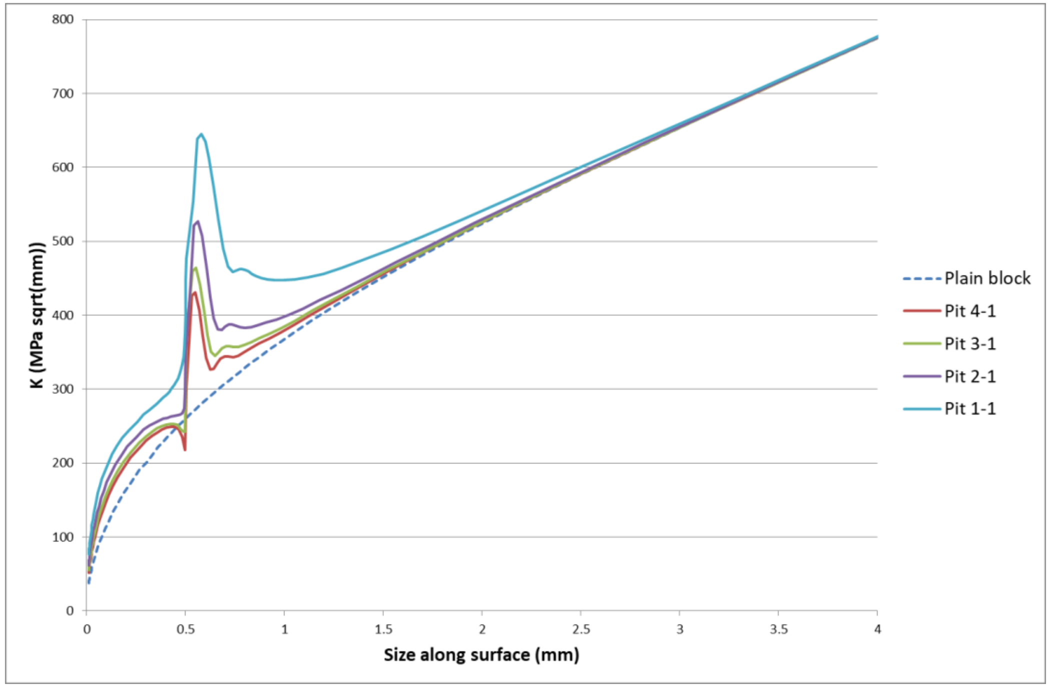


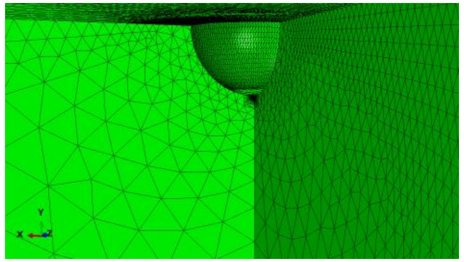


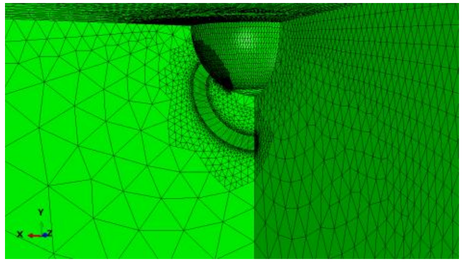


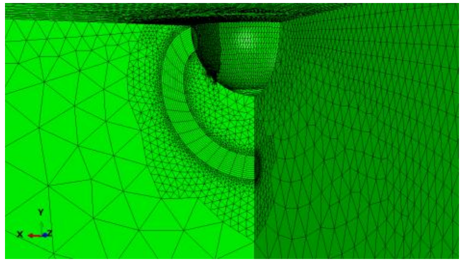
Example – Crack at root of surface pit – variation of pit ratio

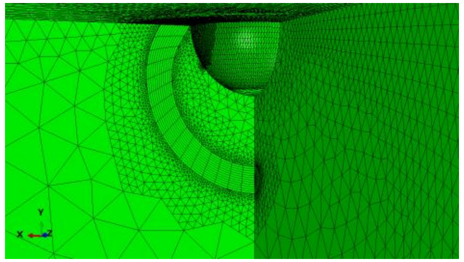


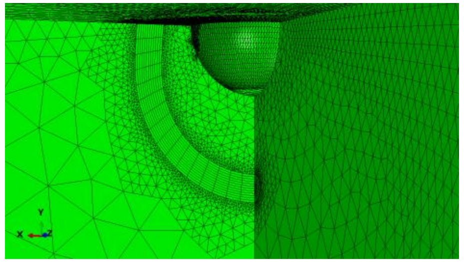












Summary

- With increased usage of AM components, Cold Spray AM materials and Cold Spray Repair Patches in Defence and Aerospace Industries, MIL and NASA Standards mandate the LEFM based Durability Analysis for the Certification to cater for small discontinuities inherent in these processes.
- It has been shown that in small crack region only two material properties matter, irrespective of the AM procedure used:
  - the cyclic fatigue threshold (ΔK_{thr}) and the cyclic fracture toughness (A).
- To achieve this, a crack growth law based on the Hartman-Schijve equation (a variant of the NASGRO equation) is proposed:

$$\frac{da}{dN} = D(\Delta\kappa)^p$$

N is cycle number, a is crack length; D and p are material constants

Similitude constant Δκ as defined by Schwalbe (2) in terms of stress intensity factors (K) or energy release rate (G):

$$\Delta\kappa = \frac{\Delta K - \Delta K_{thr}}{\sqrt{1-\frac{K_{max}}{A}}} \qquad \Delta\kappa = \frac{\Delta\sqrt{G} - \Delta\sqrt{G_{thr}}}{\sqrt{1-\frac{\sqrt{G_{max}}}{\sqrt{A}}}}$$

Additional References

ZENTECH

- Application of the Hartman–Schijve equation to represent Mode I and Mode II fatigue delamination growth in composites
  - R. Jones, S. Pitt, A.J. Bunner, D. Hui
  - Composite Structures, 2012, 94, 1343-1351
  - https://doi.org/10.1016/j.compstruct.2011.11.030
- Thoughts on the Importance of Similitude and Multi-Axial Loads When Assessing the Durability and Damage Tolerance of Adhesively-Bonded Doublers and Repairs
  - R. Jones, R. Chandwani, C. Timbrell , A.J. Kinloch, D. Peng
  - Aerospace 2023, 10(11), 946.
  - https://www.mdpi.com/2226-4310/10/11/946
- A framework for automating the parameter determination of crack growth models
  - A. Iliopoulos, J.G. Michopoulos, R. Jones, A.J. Kinloch, D. Peng
  - International Journal of Fatigue, 169, April 2023, 107490
  - https://doi.org/10.1016/j.ijfatigue.2022.107490

- This durability assessment capability is now commercially available in Abaqus, Simcenter Nastran and Ansys via Zencrack:
  - https://zentech.co.uk/software/zencrack