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Modelling Fatigue Crack Growth from Micro-Scale Discontinuities in Additively Manufactured Components

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zentech.co.uk

Durability and Damage Tolerance (DADT) of AM components

- Use of AM components, cold spray AM materials, cold spray repairs and fibre polymer matrix composites is on the increase in the defence industry, particularly since March 2019 (1)
  - To enable the transformation of maintenance operations and supply chains, increase logistics resiliency, and improve self-sustainment and readiness of defence forces
- These AM processes, however, may leave micron-sized discontinuities (i.e. small cracks) in components
  - Thus affecting the fatigue life
- US MIL-STD-1530D (2) and NASA Fracture Control Handbook NASA-HDBK-5010 (3) mandate qualification, certification, and risk/safety evaluation must be carried out by an appropriate engineering support activities based on Linear Elastic Fracture Mechanics (LEFM) principles including 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

Introduction

Modelling Fatigue Crack Growth from Micro-Scale Discontinuities in Additively Manufactured Components

- Why is this required?
  - Clearly the use of AM components in safety critical environments requires an understanding of the durability of the component
  - One industry example:
    - US MIL-STD-1530D (2) and NASA Fracture Control Handbook NASA-HDBK-5010 (3) mandate qualification, certification, and risk/safety evaluation must be carried out by an appropriate engineering support activities based on Linear Elastic Fracture Mechanics (LEFM) principles including predictive durability and damage tolerance (DADT) assessment for all applications of AM parts/repair patches
    - However, the United States Air Force (USAF) Structures Bulletin EZ-SB-19-01 (4) stated that one of the most difficult challenges facing the certification of AM parts is the ability to predict their durability and damage tolerance (DADT)

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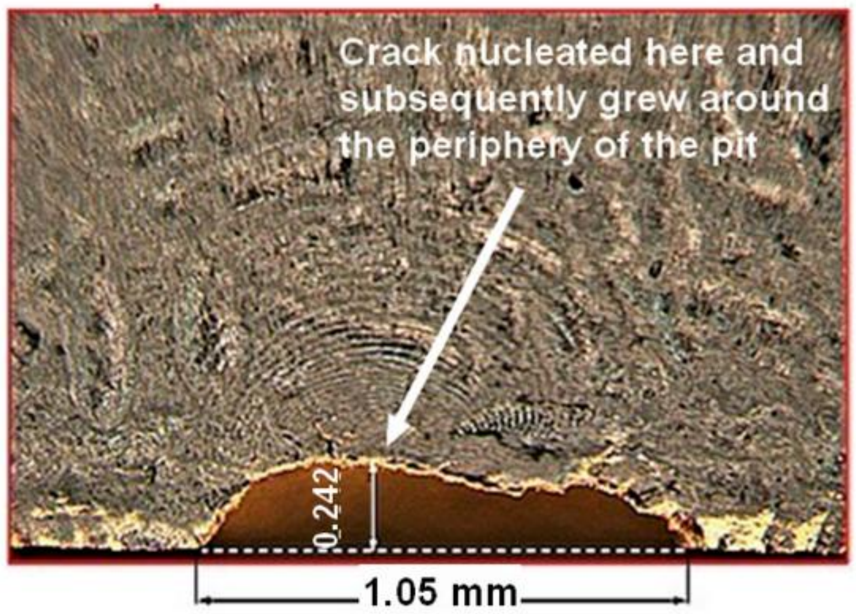
4. Structures Bulletin EZ-SB-19-01, Durability and Damage Tolerance Certification for Additive Manufacturing of Aircraft Structural Metallic Parts; Wright Patterson Air Force Base: Dayton, OH, USA, 2019. Available online: https://daytonaero.com/usaf-structures-bulletins-library/

Introduction

Modelling Fatigue Crack Growth from Micro-Scale Discontinuities in Additively Manufactured Components

- What are some of the issues for a predictive capability?
  - Definition of a suitable crack growth law
    - Variability in crack growth curves obtained from testing under different AM processes
    - Combining data for short cracks and long crack regimes
  - Modelling naturally arising 3D cracks that nucleate from small surface-breaking or near-surface manufacturing defects
    - Porosity
    - Lack of fusion
    - Corrosion pits
  - Modelling delamination in composites
- Recent publication by Jones et al (5) reviews some of these issues in detail

Figure 7. An example of how a 3D crack can nucleate at the bottom of a surface defect/pit before evolving into a near semi-elliptical shape, all dimensions are in mm. In this instance, the specimen was a Boeing Space, Intelligence, and Weapon Systems laser-powder-built (LPBF) Scalmalloy® part.



Example taken from (5)

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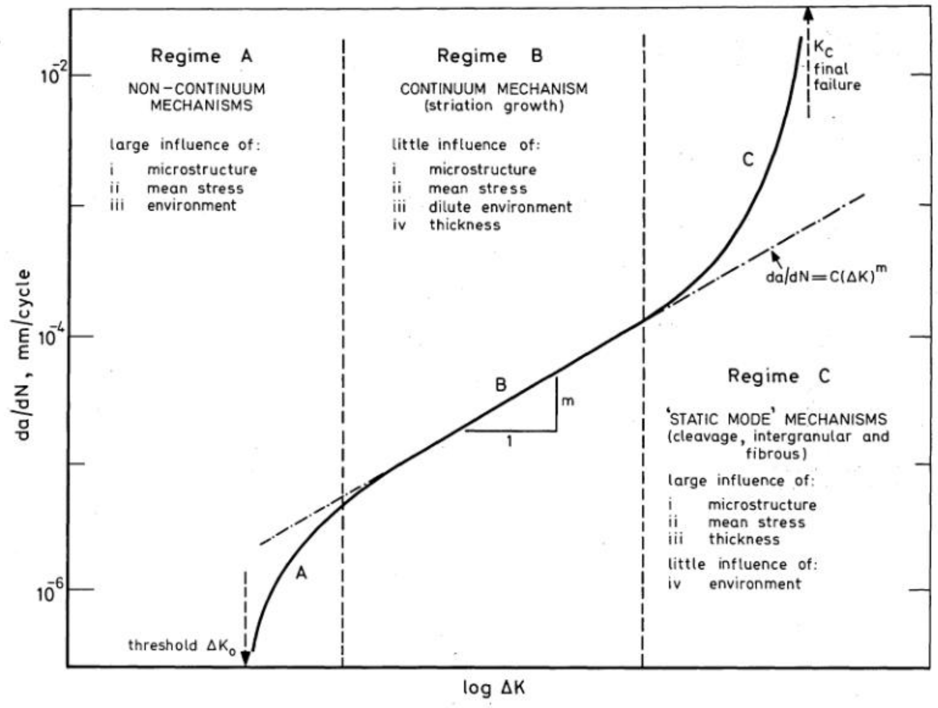
5. A Review of the Parameters Controlling Crack Growth in AM Steels and Its Implications for Limited-Life AM and CSAM Parts, Jones et al, Materials 2026, 19(2), 372. Available online: https://www.mdpi.com/1996-1944/19/2/372

Definition of a suitable crack growth law

- It has long been understood, for example (6), that the simple Paris law defining fatigue crack growth is not appropriate near threshold and near failure regimes
- In particular for AM components and the inherent micron sized defects they may contain, the near threshold regime is important
- Multiple publications have shown that representing the x-axis by an alternative parameter in place of ΔK can yield improved representation of test data e.g. (7, 8)

Fatigue crack growth regimes and the Paris law
(from a paper by Ritchie dated 1977 (6))



1 **Primary fracture mechanisms in steels associated with sigmoidal variation of fatigue crack propagation rate (*da/dN*) with alternating stress intensity (Δ*K*).**

6. Ritchie, R.O. Influence of microstructure on near-threshold fatigue-crack propagation in ultra-high strength steel. Met. Sci. 1977, 11, 368–381.MIL-STD-1530D (W/ CHANGE-1), Department Of Defense Standard Practice: Aircraft Structural Integrity Program (ASIP) (13 Oct 2016).
   Available online: https://www.tandfonline.com/doi/abs/10.1179/msc.1977.11.8-9.368
7. A Review of the Parameters Controlling Crack Growth in AM Steels and Its Implications for Limited-Life AM and CSAM Parts, Jones et al, Materials 2026, 19(2), 372.
   Available online: https://www.mdpi.com/1996-1944/19/2/372
8. Further Studies into the Growth of Small Naturally Occurring Three-Dimensional Cracks in Additively Manufactured and Conventionally Built Materials, Chan et al, Crystals 2025, 15(6), 544.
   Available online: https://www.mdpi.com/2073-4352/15/6/544

Definition of a suitable crack growth law

- These studies 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:

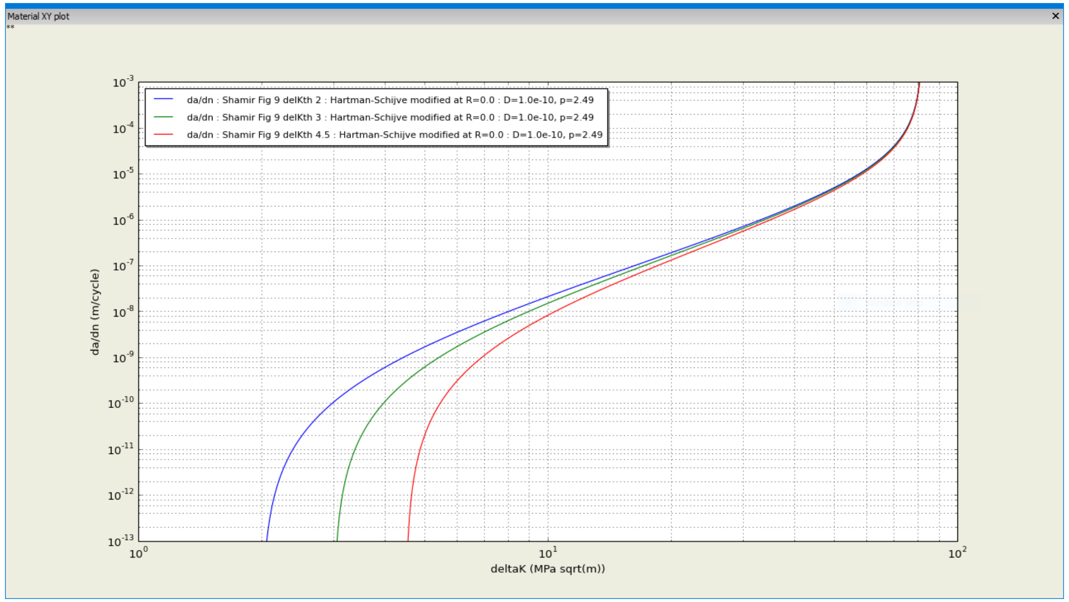
$$da/dN = D\,(\Delta\kappa)^p$$

N is cycle number, a is crack length

D and p are material constants

Similitude constant $\Delta\kappa$ as defined by Schwalbe (9):

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



Example of Hartman-Schijve da/dN vs ΔK plots

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9. 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.

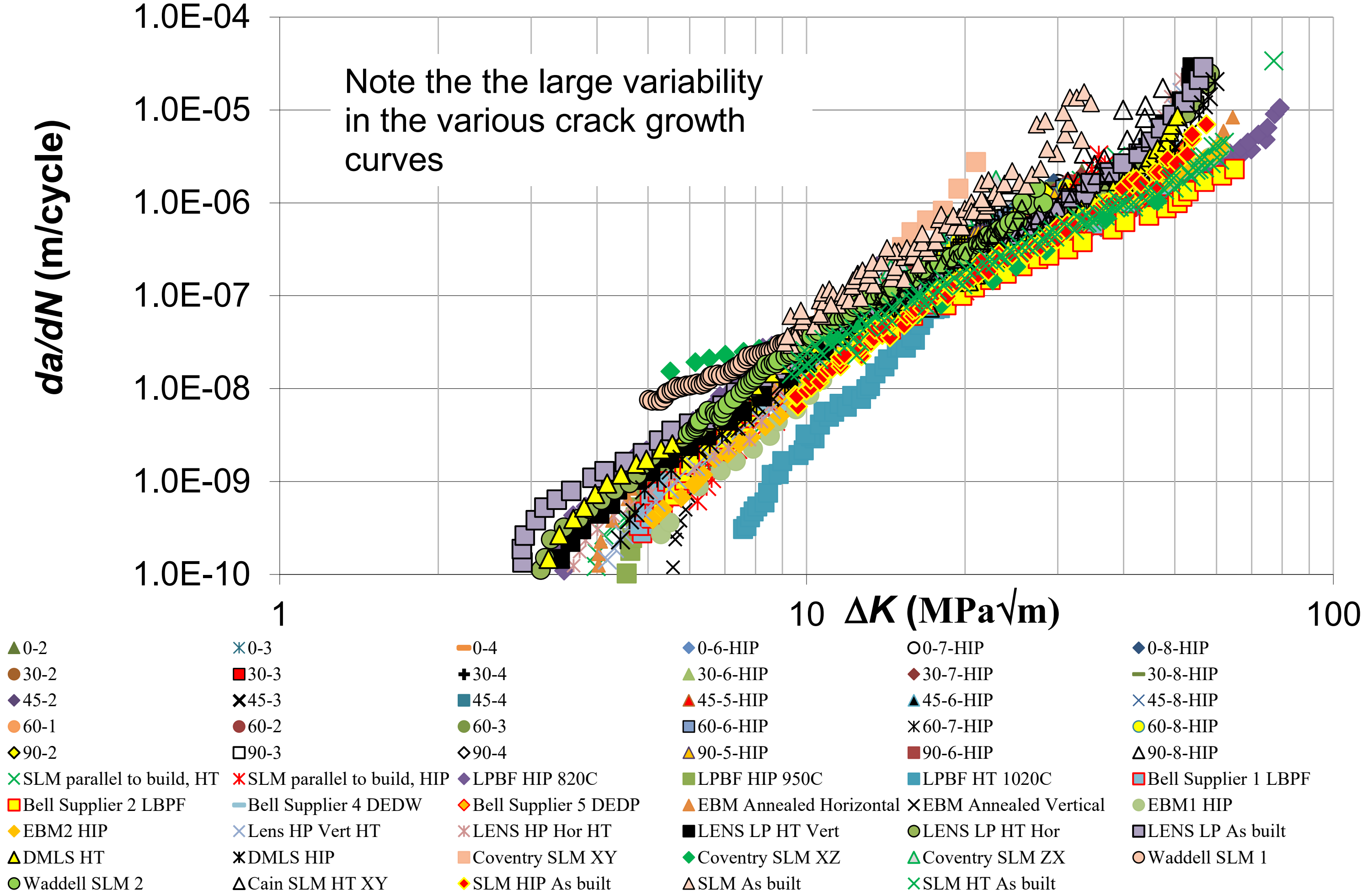
Material variability - an example: AM Ti-6Al-4V

Plot of 58 R=0.1 da/dN versus ΔK curves for tests on AM Ti-6Al-4V reported in (10)

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.



10. 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.

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

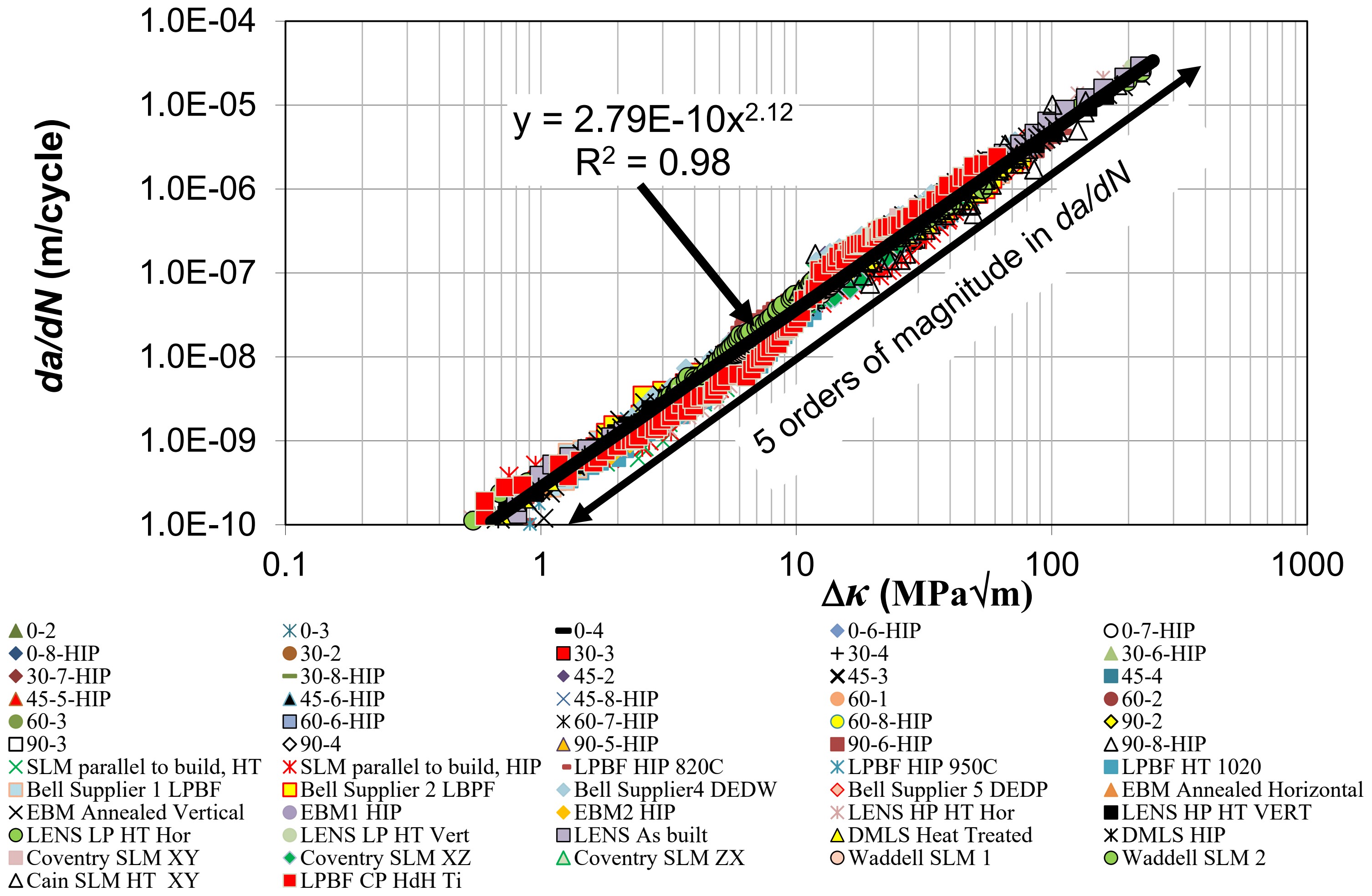
When allowance is made for the effect of the different build processes on the variability in the *two parameters* ΔK_{thr} and A, then (allowing for experimental error) **each of these 57 curves essentially collapse onto a single curve** (10).

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

Δ*κ* is the crack tip (*similitude*) parameter as defined by Schwalbe (9):

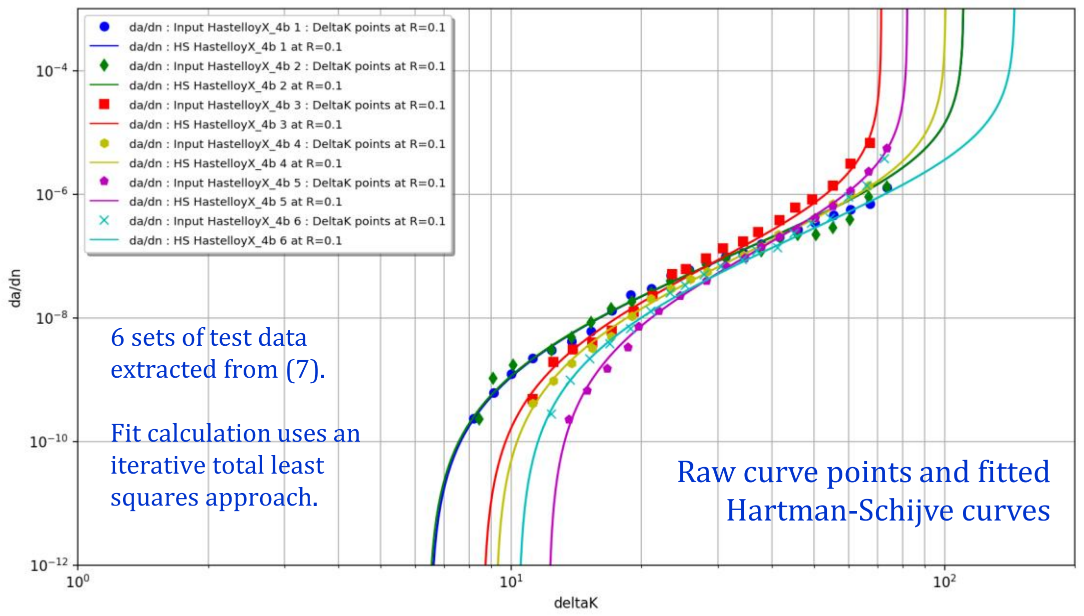
$\Delta\kappa = (\Delta K - \Delta K_{thr}) / (1-(K_{max}/A))^{1/2}$

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



Fitting process – example with 6 sets of test data

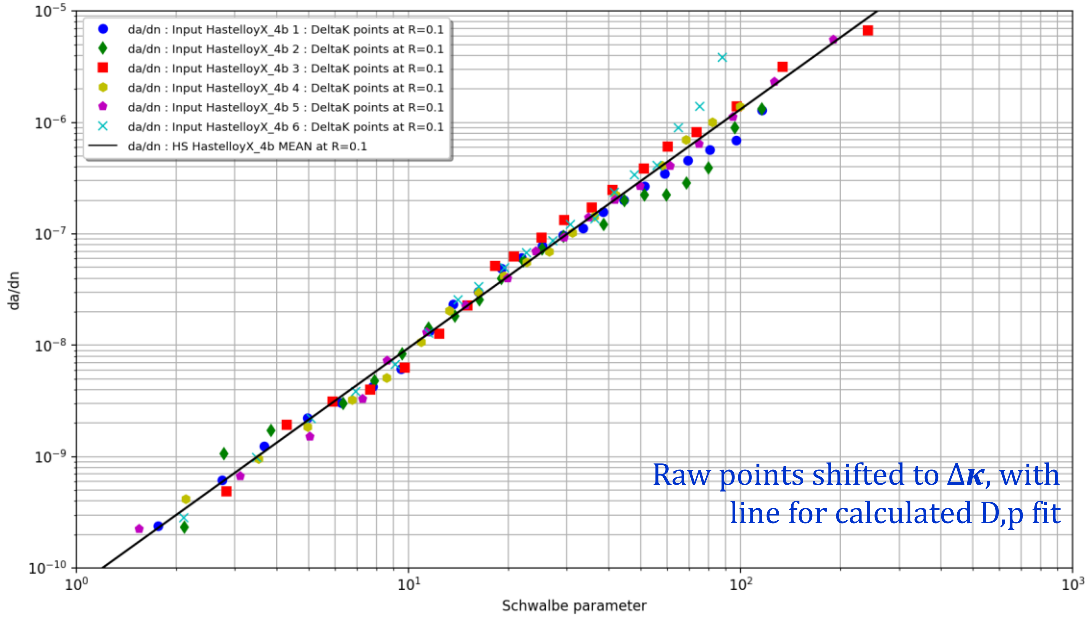
- A fitting process is used to calculate the necessary four parameters of the Hartman-Schijve equation
  - Calculate ΔK_{thr} and A to fit each curve while calculating D and p in the shifted $\Delta\kappa$ form for all curves:
    - General case makes no assumption about ΔK_{thr} and A values
    - Fitting process adopts a total least squares approach
  - 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
  - This example shows a fit generated for six test curves (test data is from (11))



6 sets of test data extracted from (7).

Fit calculation uses an iterative total least squares approach.

Raw curve points and fitted Hartman-Schijve curves

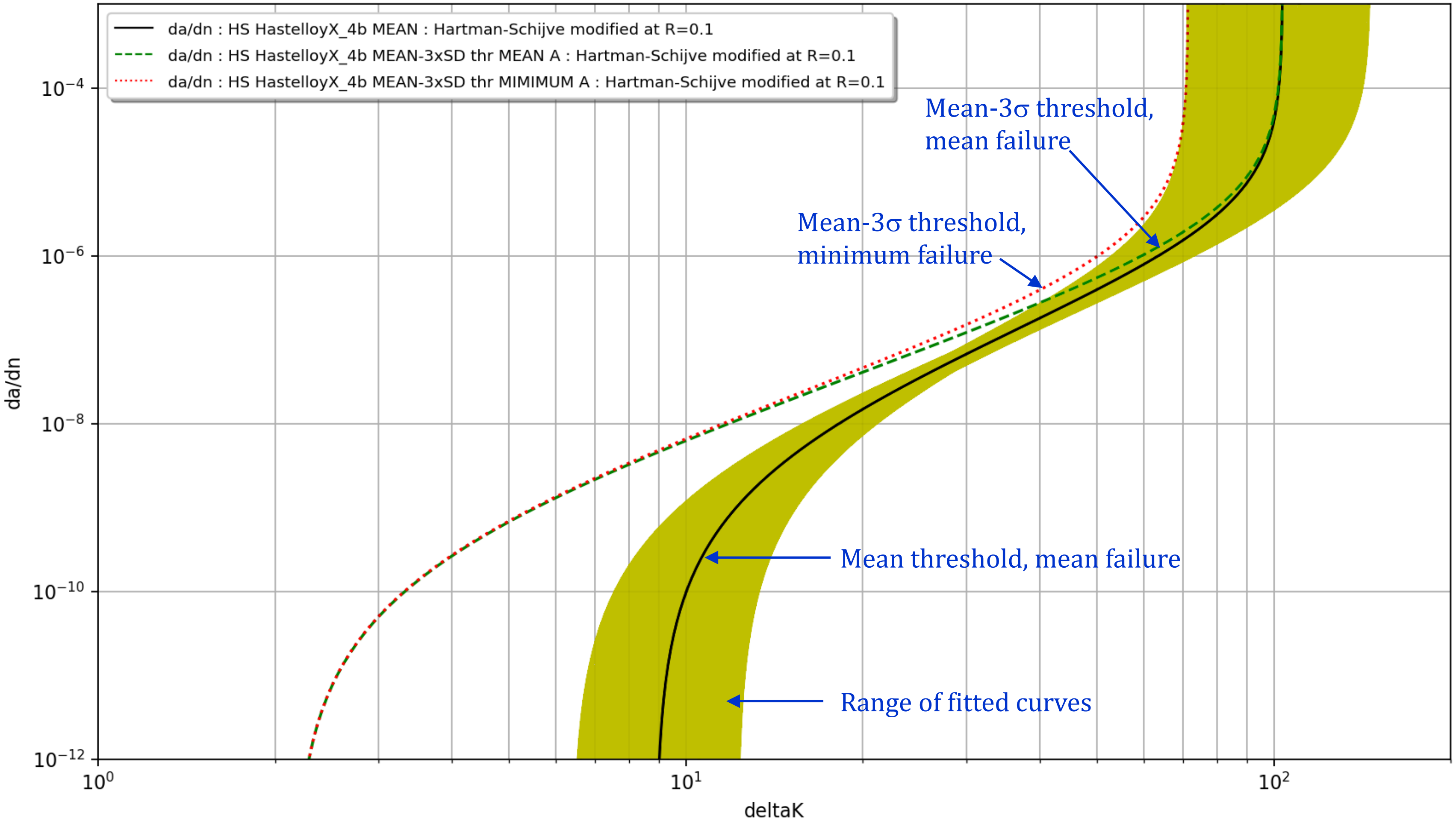


Raw points shifted to $\Delta\boldsymbol{\kappa}$, with line for calculated D,p fit

11. 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

- 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
- 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.



Mean-3σ threshold, mean failure

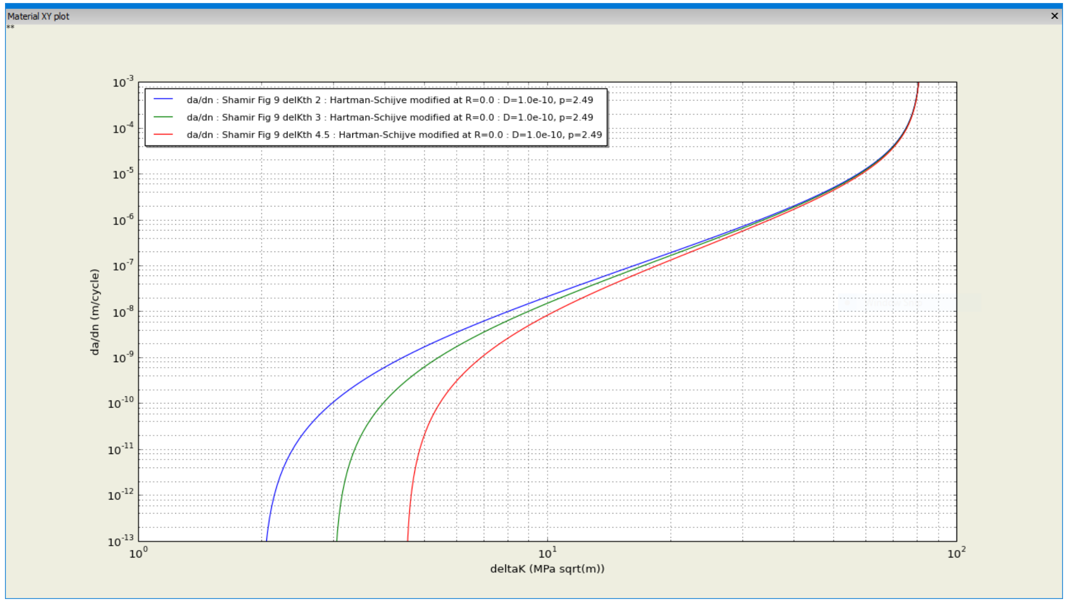
Mean-3σ threshold, minimum failure

Mean threshold, mean failure

Range of fitted curves

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



da/dn : Shamir Fig 9 delKth 2 : Hartman-Schijve modified at R=0.0 : D=1.0e-10, p=2.49
da/dn : Shamir Fig 9 delKth 3 : Hartman-Schijve modified at R=0.0 : D=1.0e-10, p=2.49
da/dn : Shamir Fig 9 delKth 4.5 : Hartman-Schijve modified at R=0.0 : D=1.0e-10, p=2.49

Example of Hartman-Schijve da/dN vs ΔK plots

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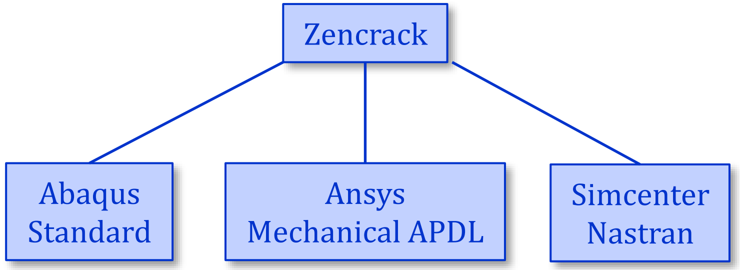
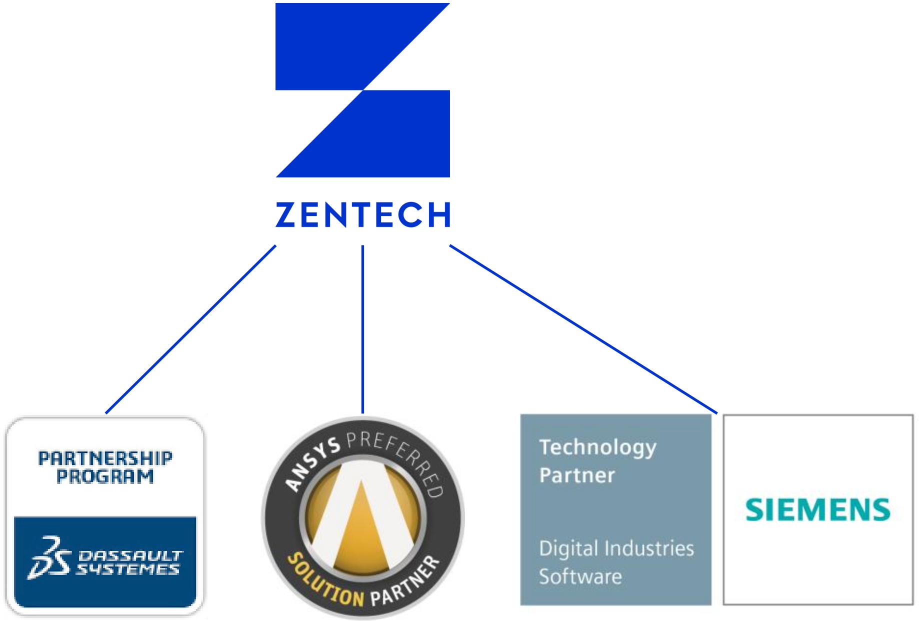
* Centre of Expertise for Structural Mechanics, Department of Mechanical and Aerospace Engineering, Monash University, Victoria, Australia;
ARC Industrial Transformation Training Centre on Surface Engineering for Advanced Materials, Swinburne University of Technology, Victoria, Australia.

The solution available from Zentech: Zencrack

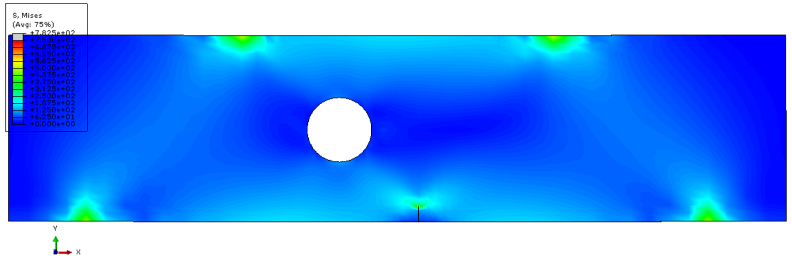
- Zencrack:
  - Is a powerful tool for fracture mechanics analyses
  - Uses commercially available finite element codes as the solution engine to help calculate fracture mechanics parameters:
    - Abaqus/Standard
    - Ansys/Mechanical APDL
    - Simcenter Nastran (previously NX Nastran)
  - Has meshing 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

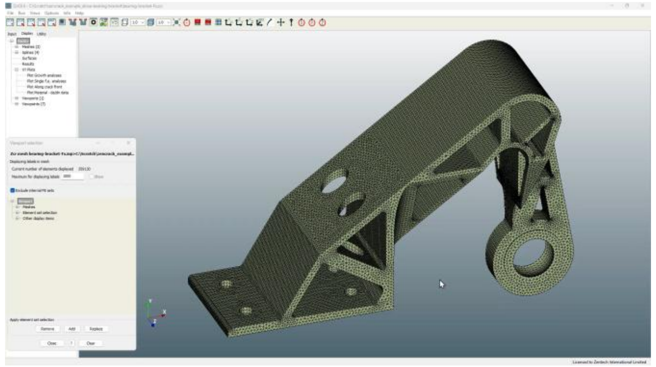


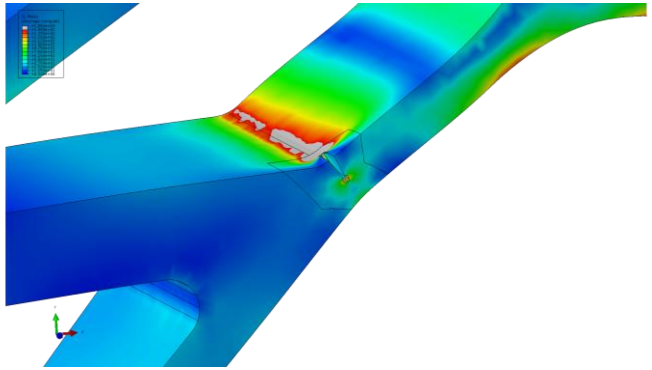


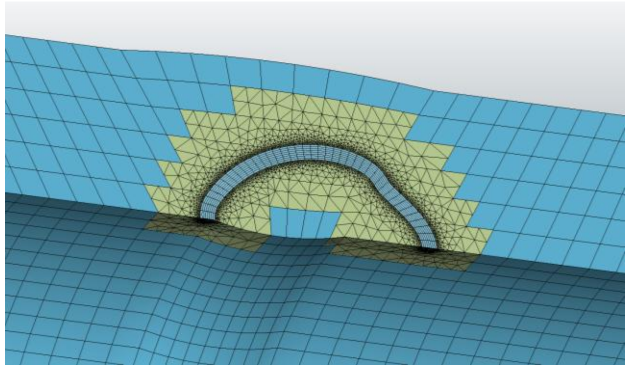
Life extension, durability & damage tolerance assessment

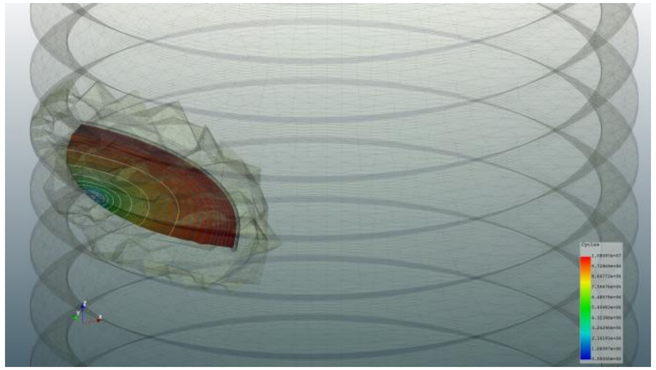
- Engine disks, blades and their dovetail connections
- Power generation components
- Pipeline defects
- Welded connections
- Stiffened panels (integral & riveted)
- Adhesive bonded joints / patch repairs
- Additive manufactured components

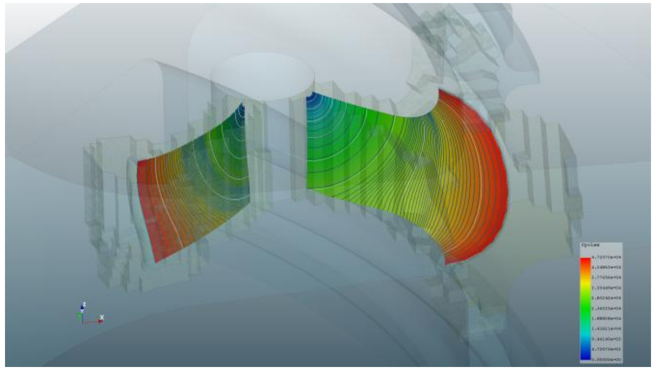




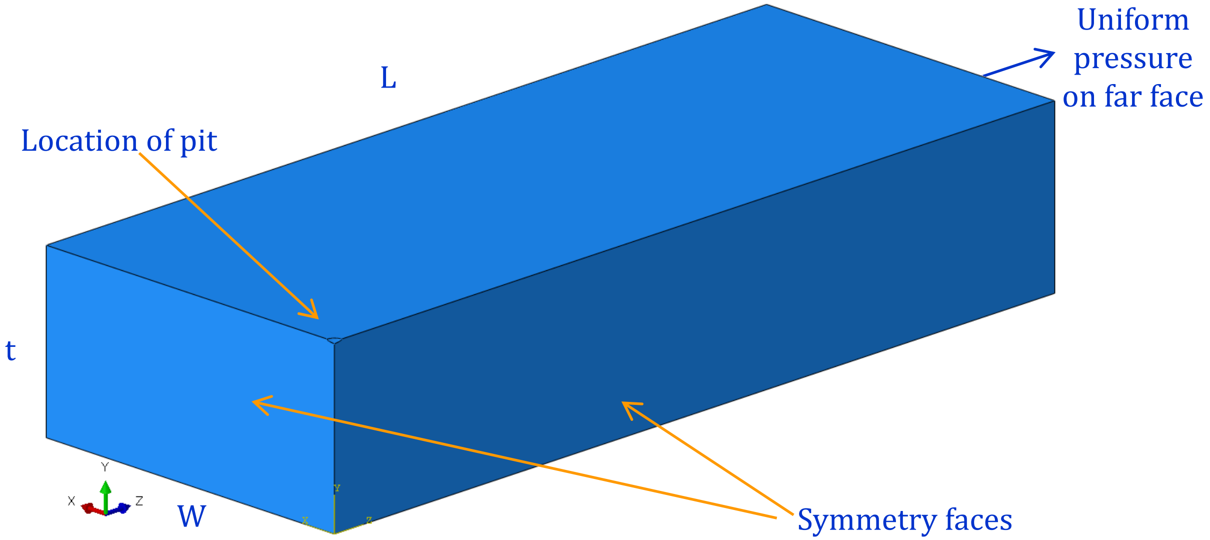


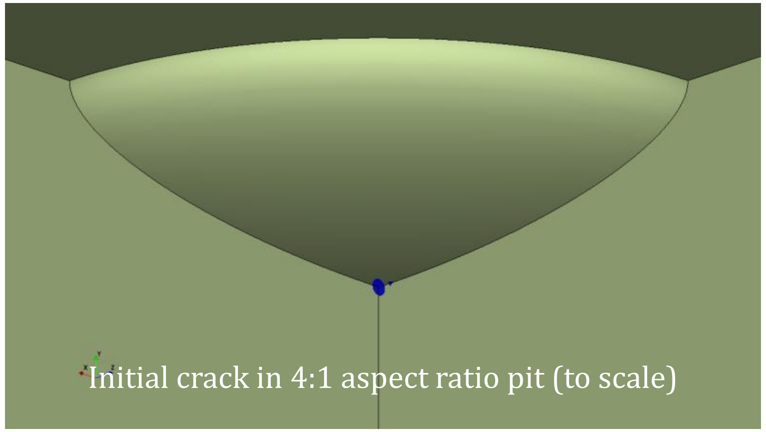






Example – Crack at root of surface pit – variation of pit ratio

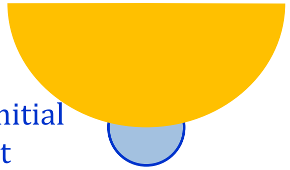



Initial crack in 4:1 aspect ratio pit (to scale)

Pit radius is 0.5mm on the surface.

Variations are made to the pit depth.

In each analysis the initial crack is circular with radius 0.01mm.
The centre of the circle is located at the deepest point of the pit (or on the surface for the plain block).


Schematic of initial crack in pit (not to scale)

Rectangular block modelled with symmetry in width and length directions:
W=20mm, t=10mm, L=50mm
i.e. full block size 40mm x 10mm x 100mm

The analysis model and extracted results are in mm and MPa units.

Uniform pressure load is applied on the far face. The loaded face has unconstrained nodes i.e. axial displacements differ across the loaded face.

Maximum remote stress of 300 MPa, constant amplitude stress ratio R = 0.1

E =73,000MPa, $\nu = 0.37$

Modified Hartman Schijve K-law:

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

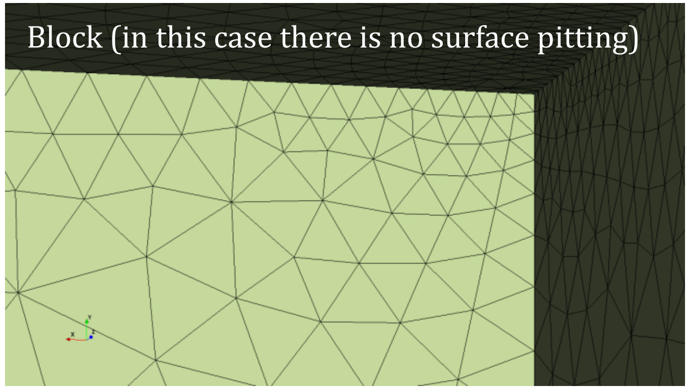
N is cycle number, a is crack length

Similitude constant $\Delta\kappa$:

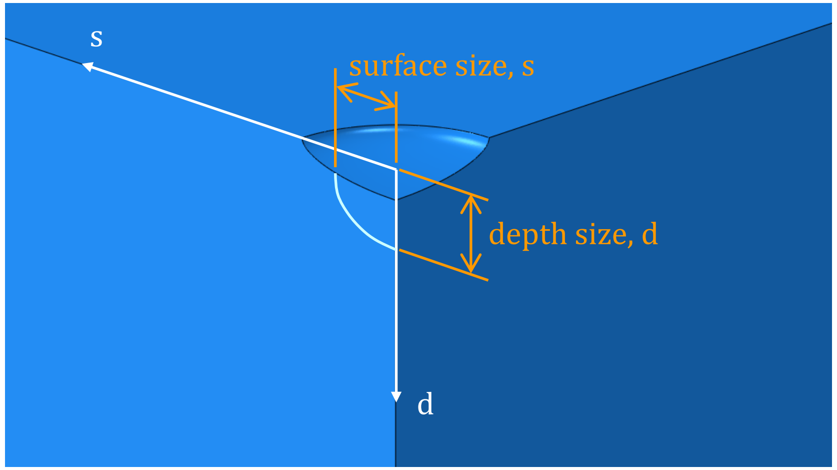
$$\Delta\kappa = \frac{\Delta K - \Delta K_{thr}}{\sqrt{1 - \frac{K_{max}}{A}}}$$

material constants D =7e-10, p = 2
threshold, $\Delta K_{thr} = 0.1$
toughness, $A = 39$
(these values are for da/dn in m/cycle and K terms in MPa sqrt(m))

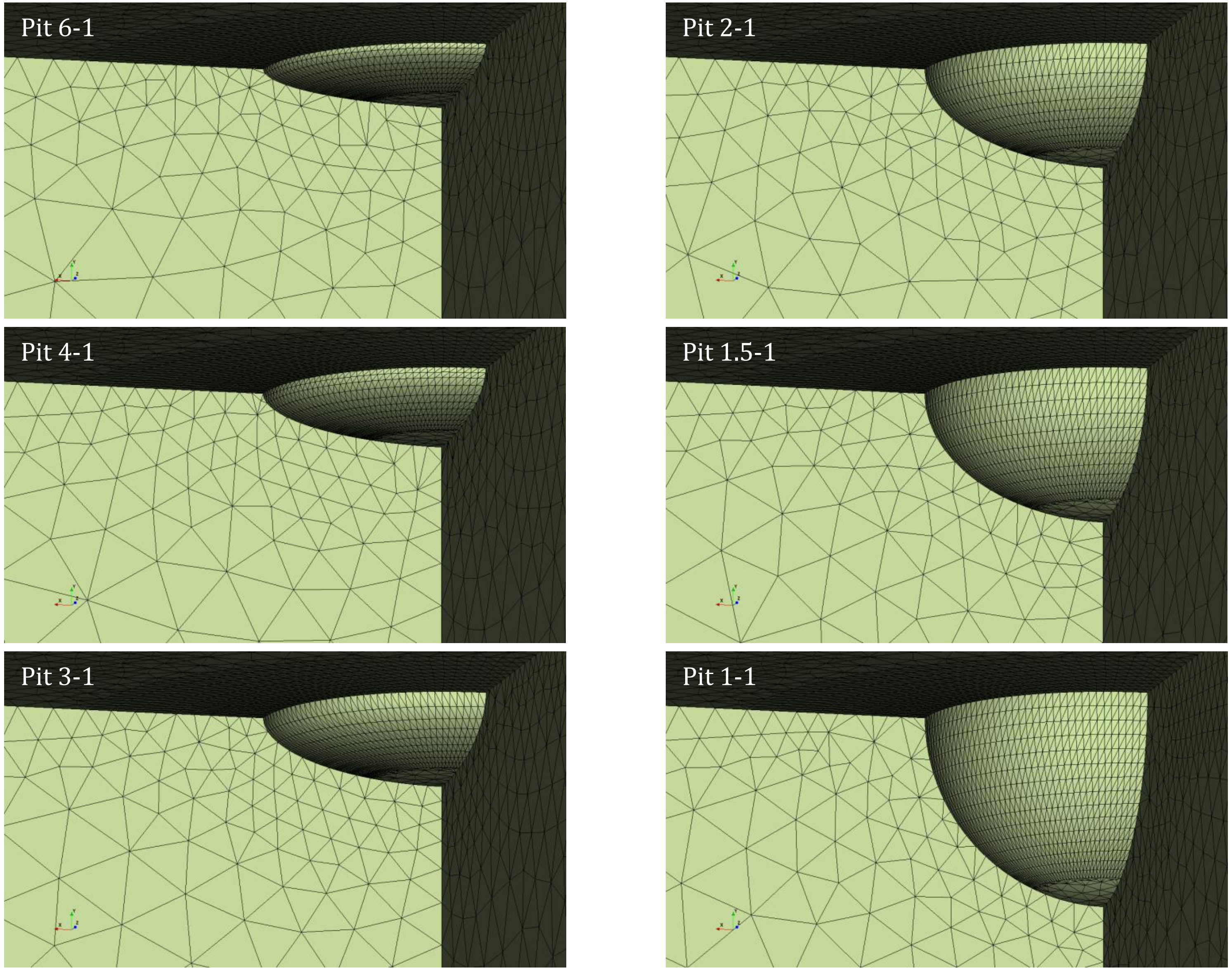
Example – Crack at root of surface pit – variation of pit ratio

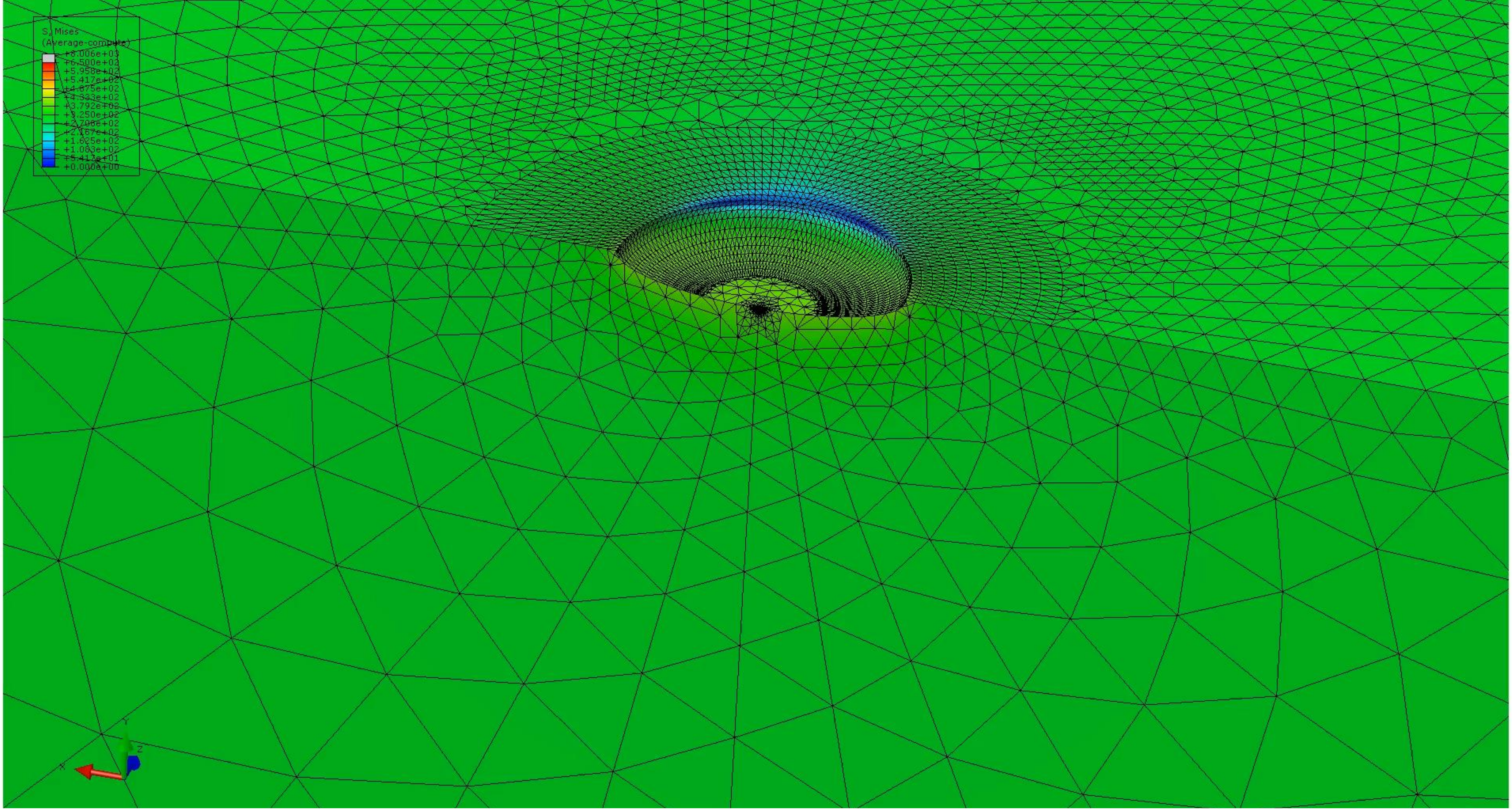


Uncracked meshes for plain block and different pits

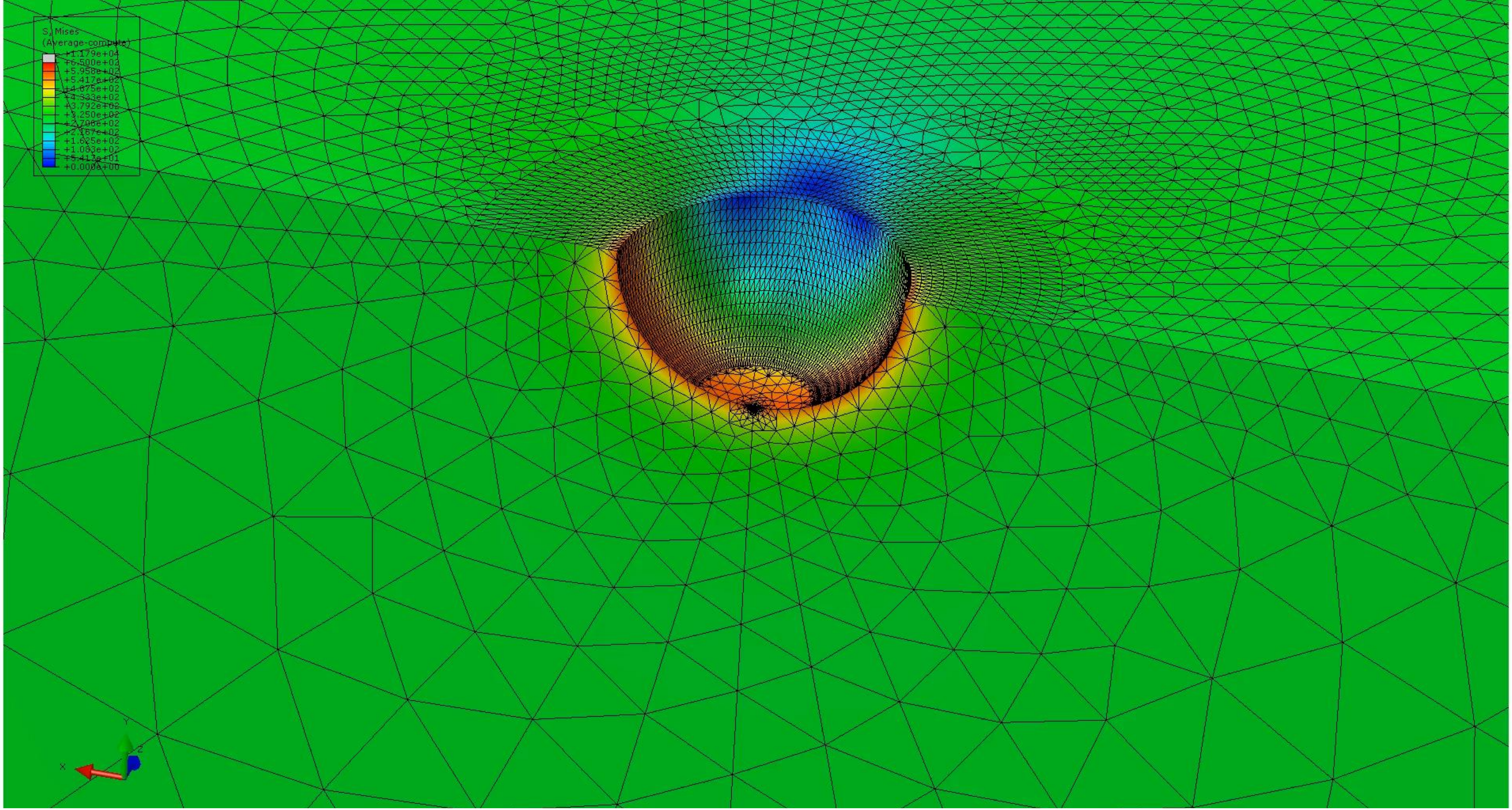


Results are extracted as “surface size” and “depth size” via the X and Y coordinates of the end points of the crack.
i.e. “size” values are with respect to the local s-d axis shown above.



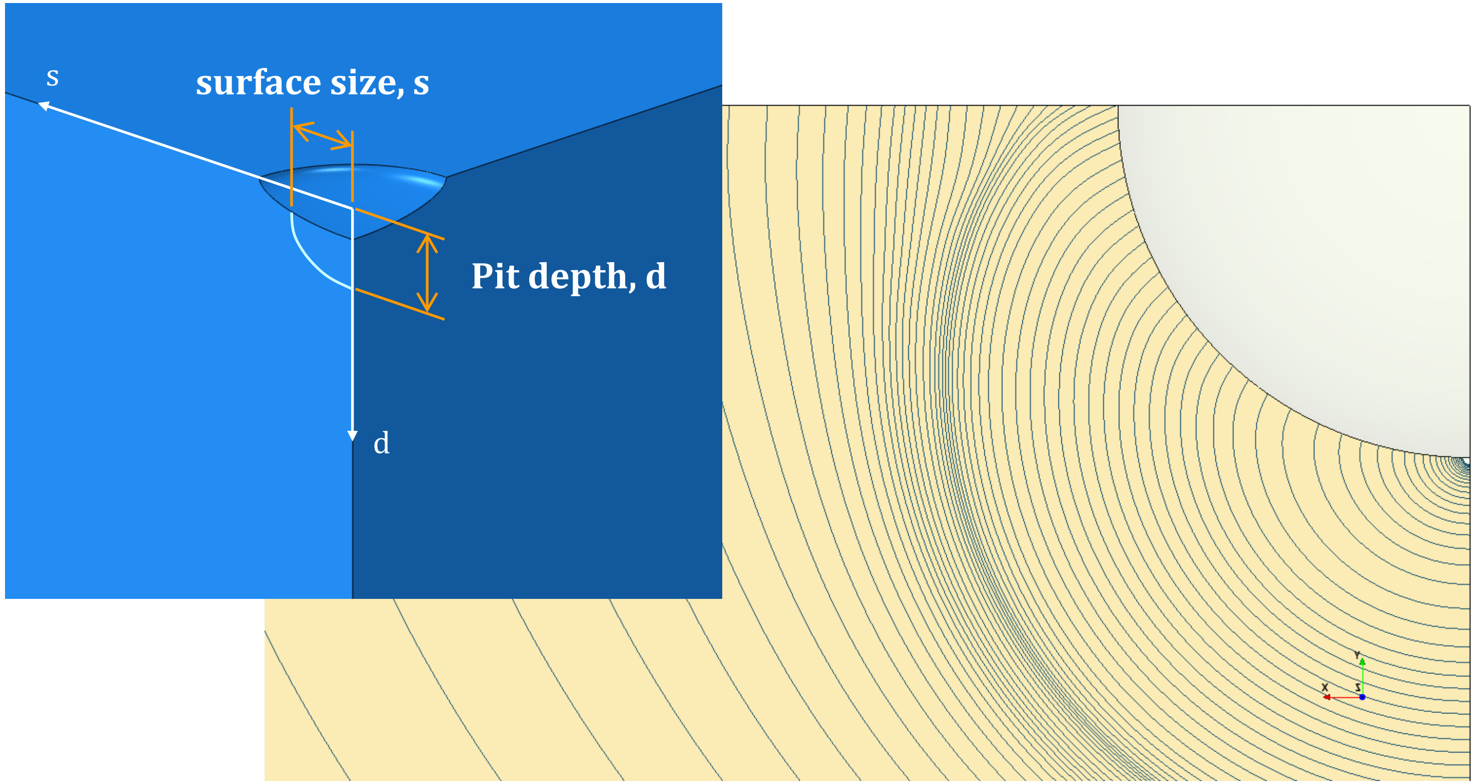


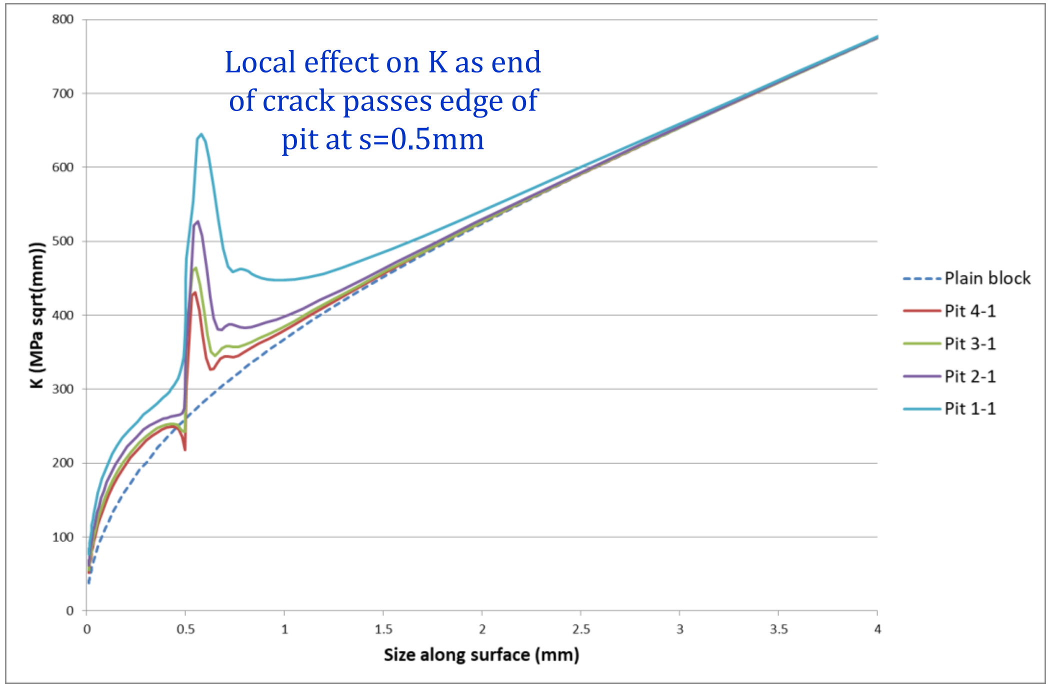
Pit aspect ratio 4:1

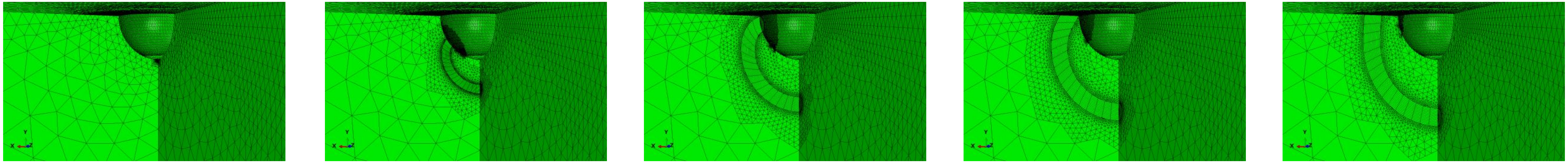


Pit aspect ratio 1:1

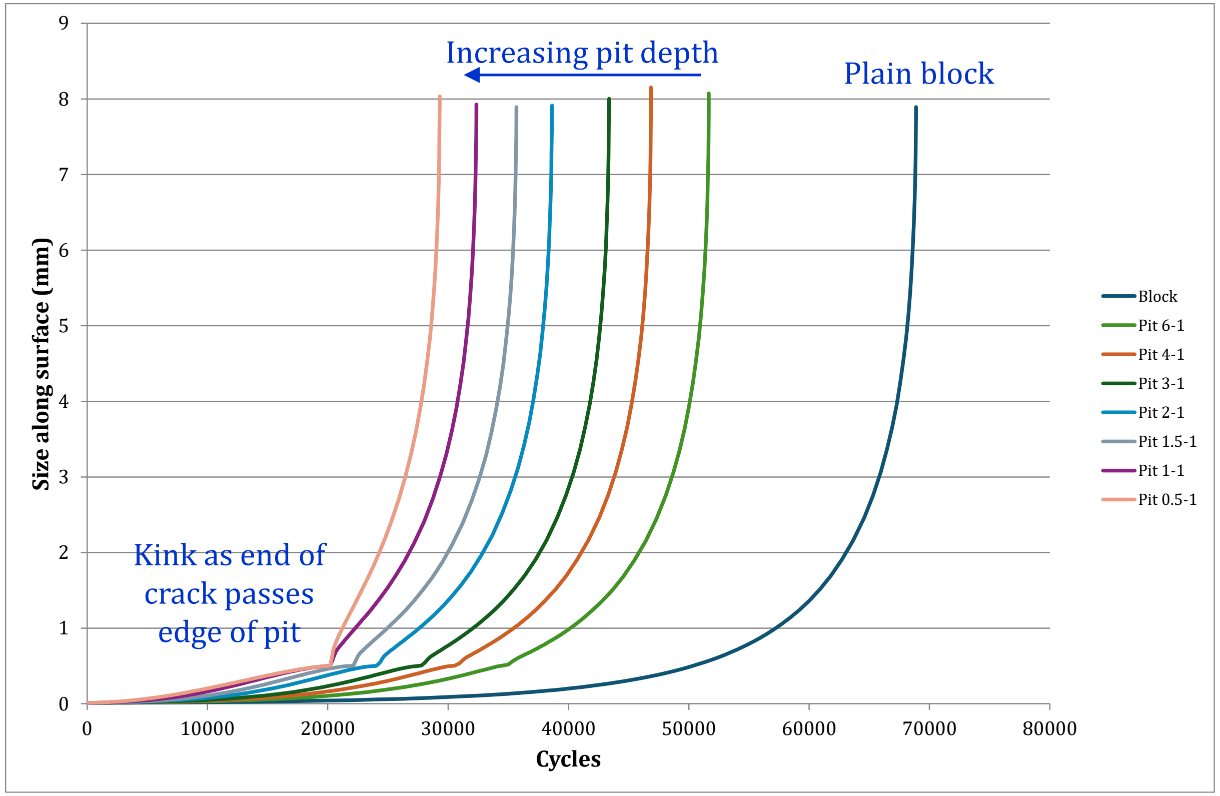
Effect of pit on surface value of K

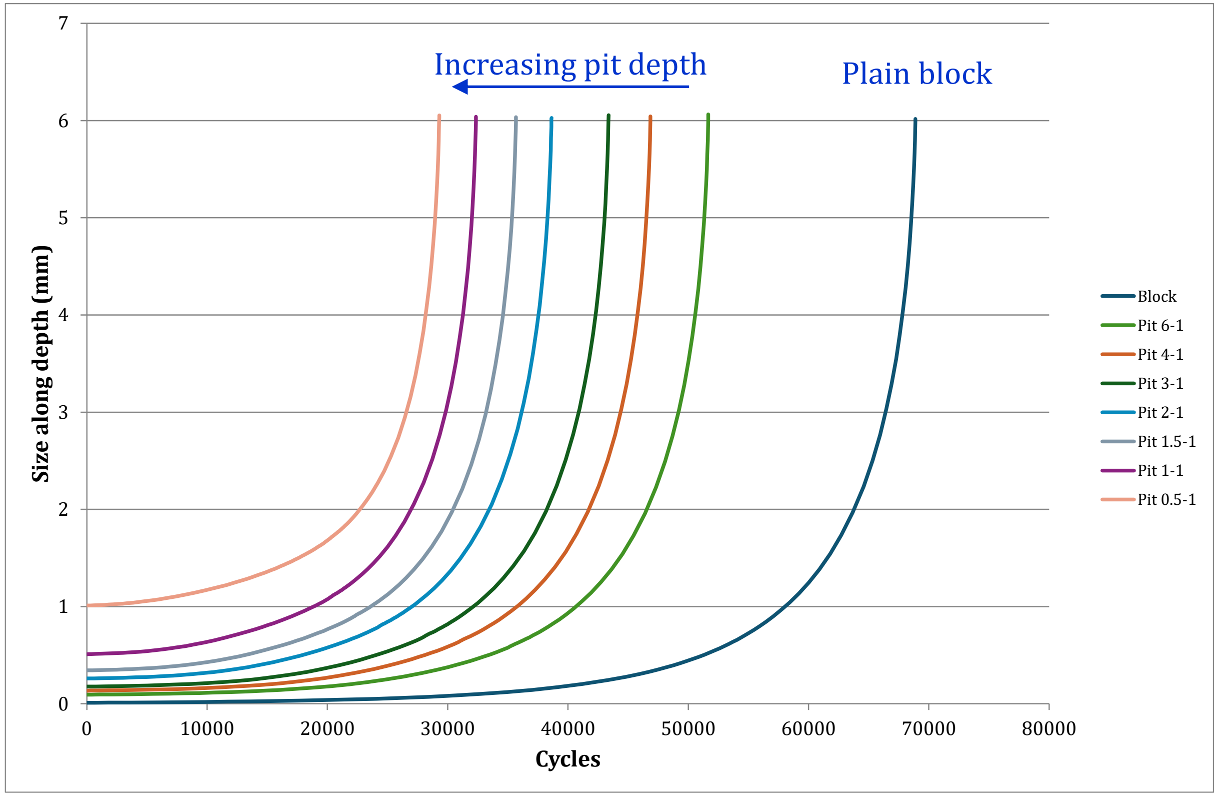



Local effect on K as end of crack passes edge of pit at s=0.5mm



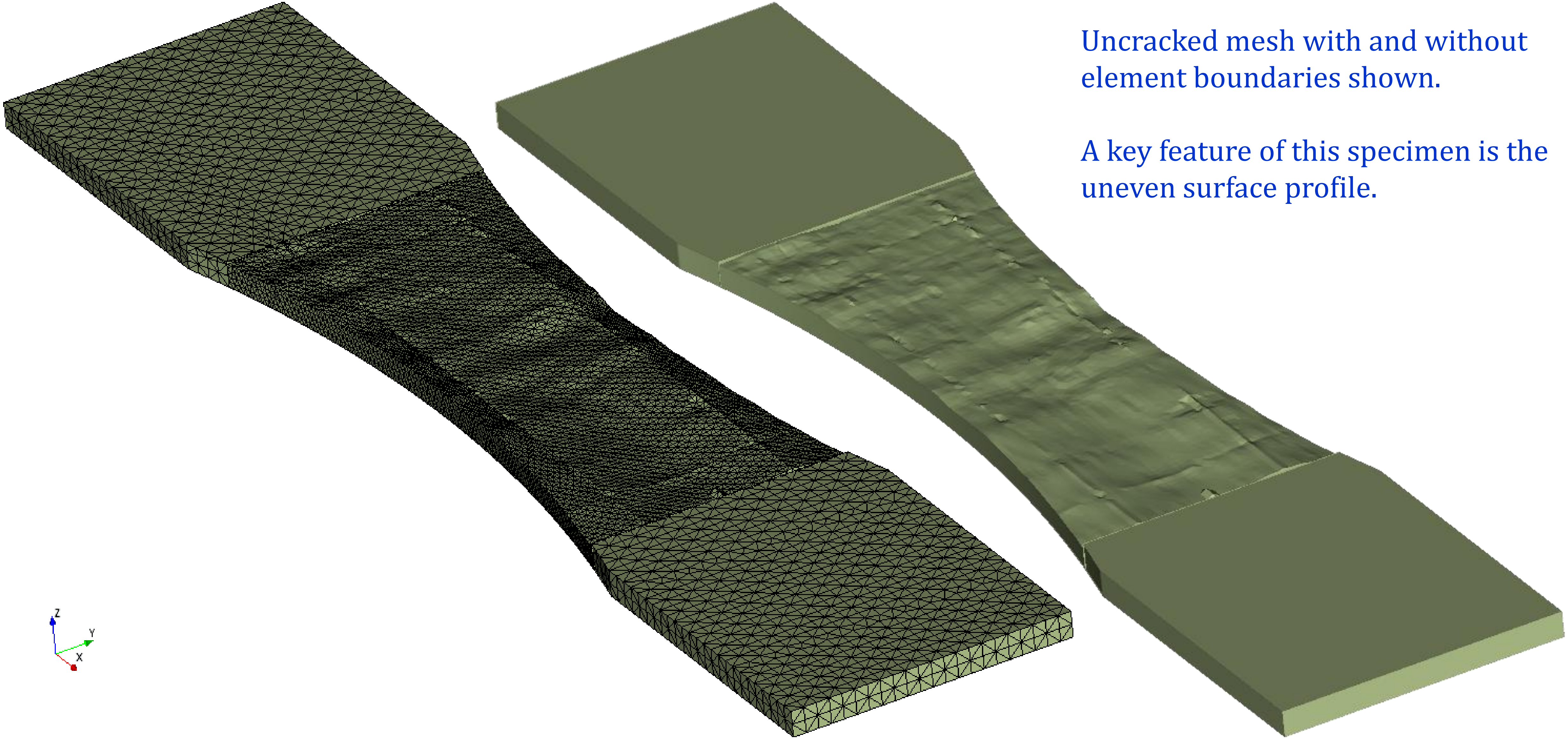
Effect of pit on cycle count





Cycle count reduces dramatically
compared to a plain block

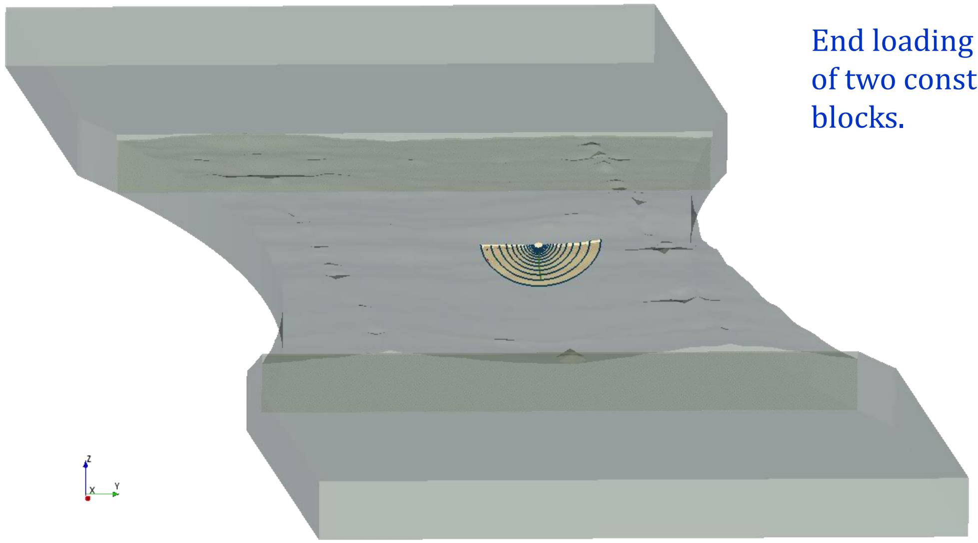
Example – Additive manufacturing



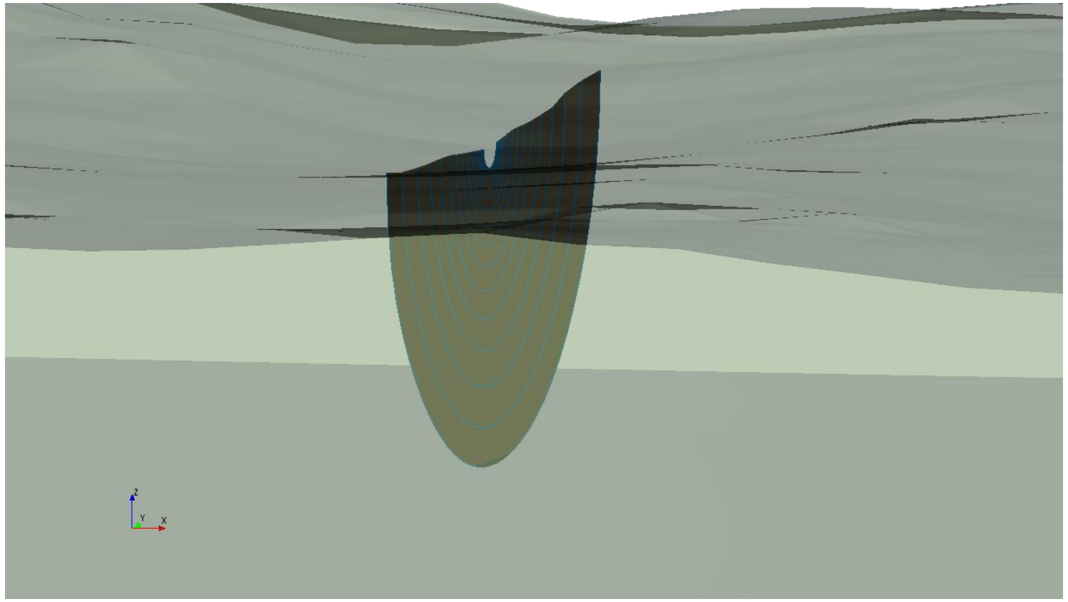
Uncracked mesh with and without element boundaries shown.

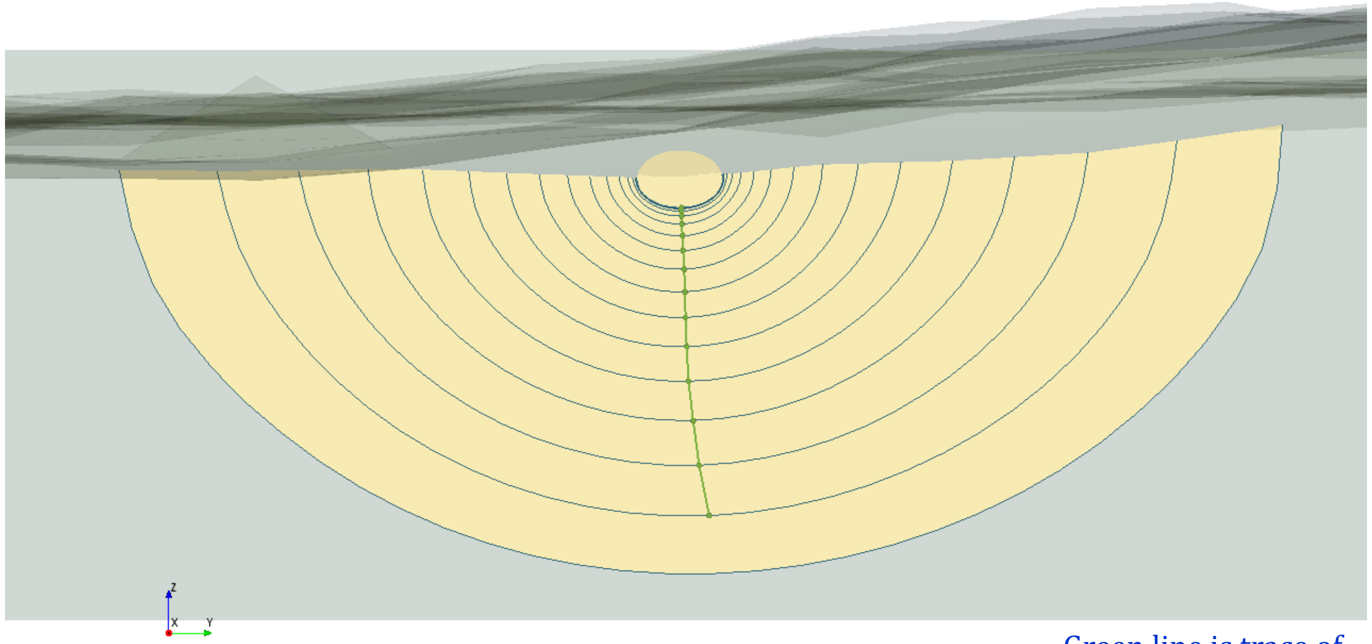
A key feature of this specimen is the uneven surface profile.

Example – Additive manufacturing



End loading is a sequence of two constant amplitude blocks.

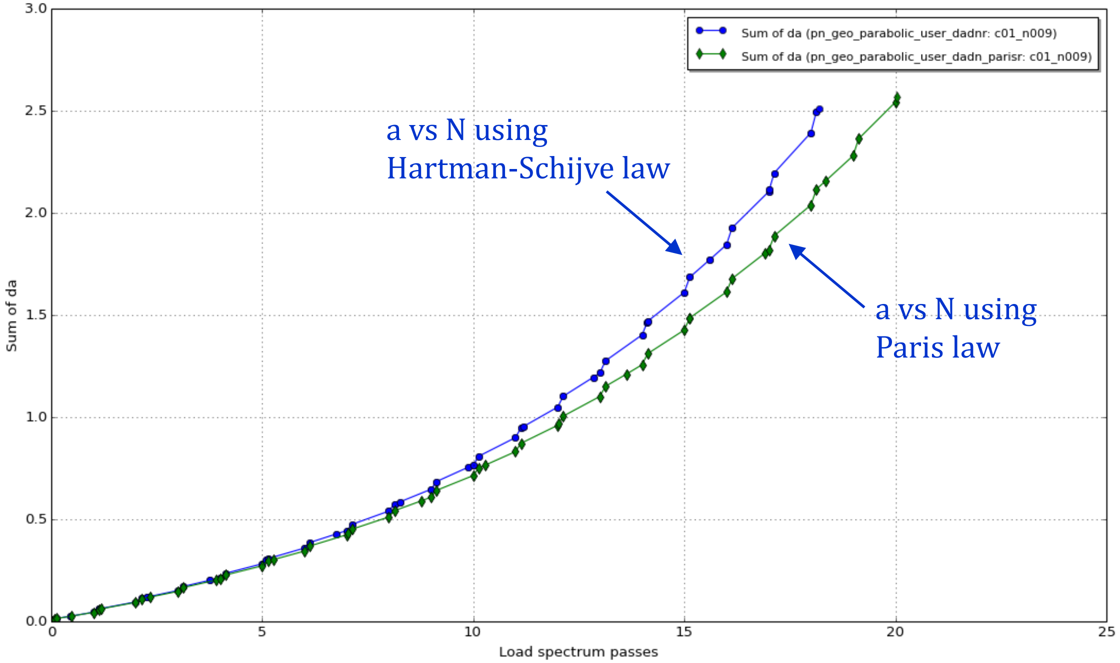




Green line is trace of middle point of the crack front used for xy plots (next slide)

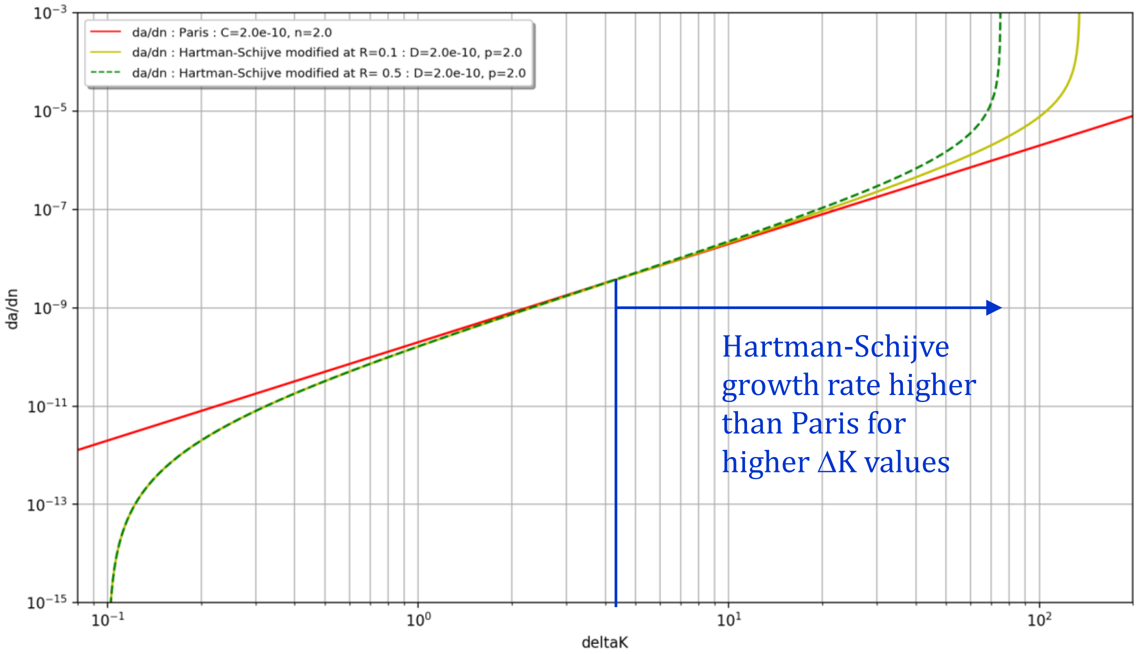
Example – Additive manufacturing

- 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



a vs N using Hartman-Schijve law

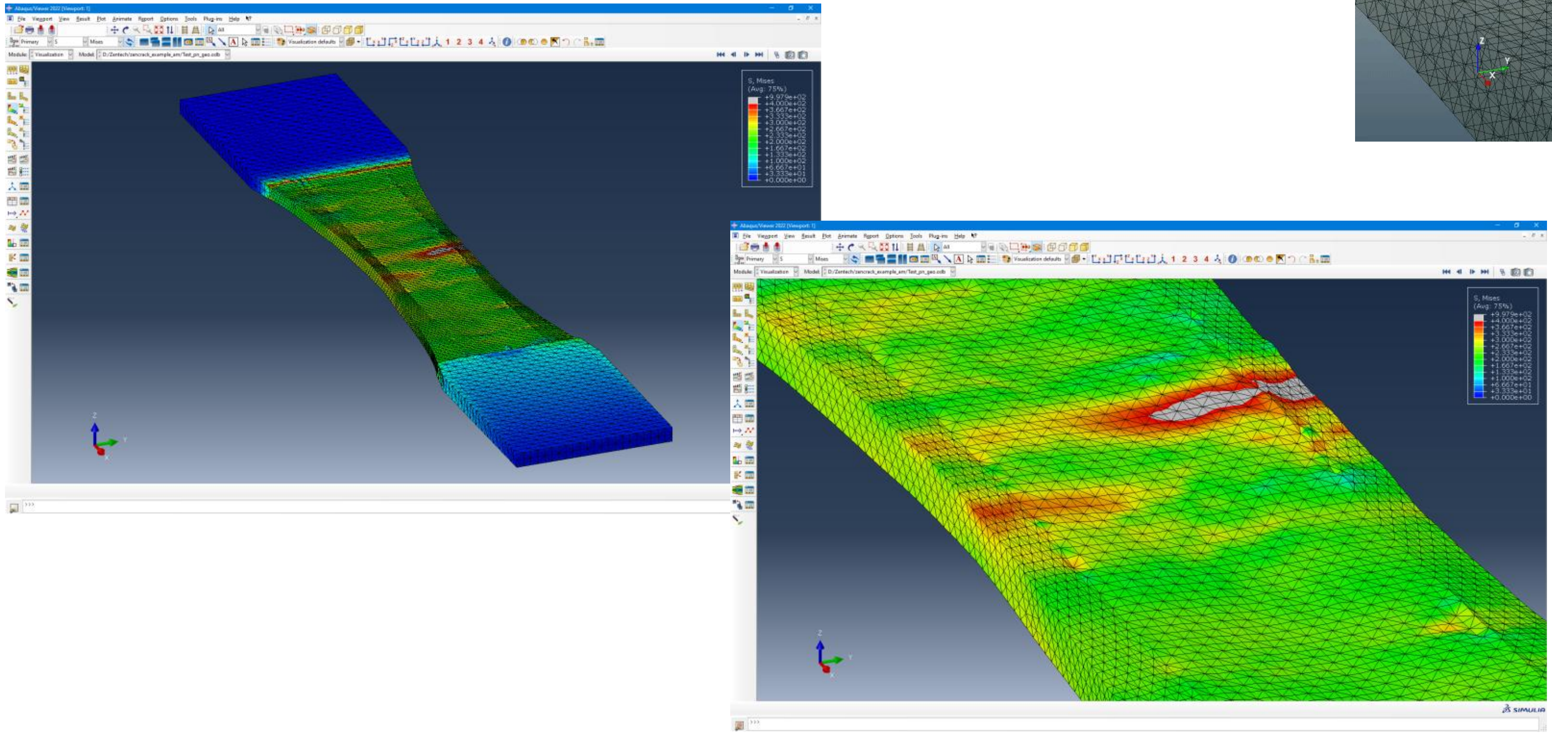
a vs N using Paris law

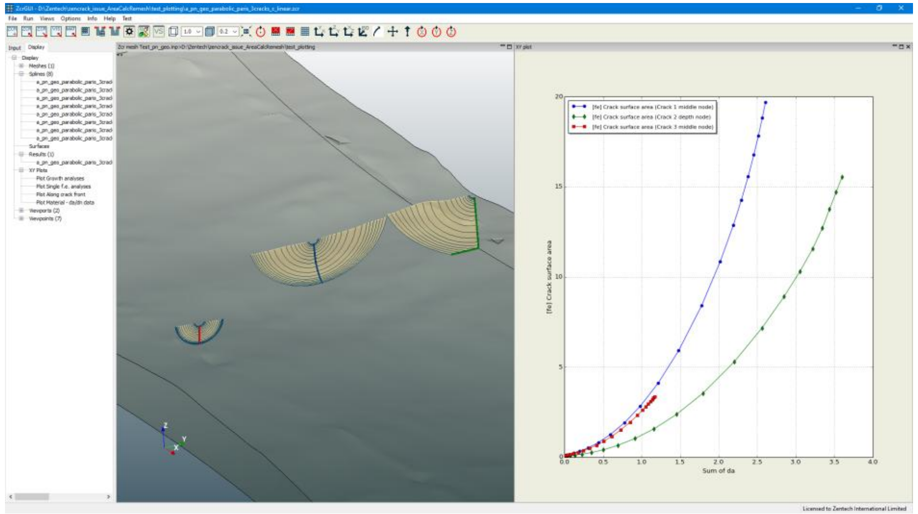


Hartman-Schijve growth rate higher than Paris for higher ΔK values

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





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):

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

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  - 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

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Thank you.
For more information and to download an evaluation copy of Zencrack:

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