The Use Of Fracture Mechanics For Fatigue Life Assessment

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Overview

- Why use fracture mechanics for fatigue life assessment
- Processes involved in fatigue
- Design approaches
- Examples

Fatigue Process

- The fatigue process is formed of two phases:
  - Crack initiation
  - Crack propagation
- Initiation occurs at the grain boundary level until a crack is large enough to form a geometric stress concentration
- A local plastic zone is then formed ahead of the crack as it propagates through the structure

Design Approaches

- Total-Life Design
  - Design life span
  - Durability, etc.
- Defect-Tolerant Design
  - Advancement in Material Science
  - Manufacturing

http://www.afmc.af.mil/news/story.asp?id=123138571

- Example:
  - U.S.A.F. Engine Rotor Life Extension (ERLE) program
  - "The overall ERLE objective is to safely double the life of fracture-critical turbine engine components, resulting in projected cost avoidances in excess of $1B through 2020 when fully implemented."

http://www.saffm.hq.af.mil/shared/media/document/AFD-070221-113.pdf

Fatigue – Initiation / Nucleation

- Depends on grain size, grain boundaries
- Micron size crack growth rate law is still ‘work in progress’
- Not suited to fracture mechanics techniques yet
- Classical fatigue analysis used to evaluate this phase of life

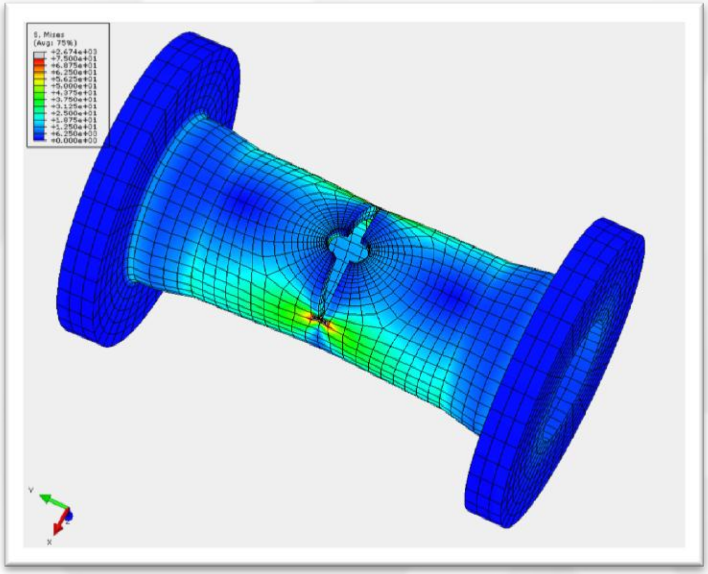
Use of Finite Element methods

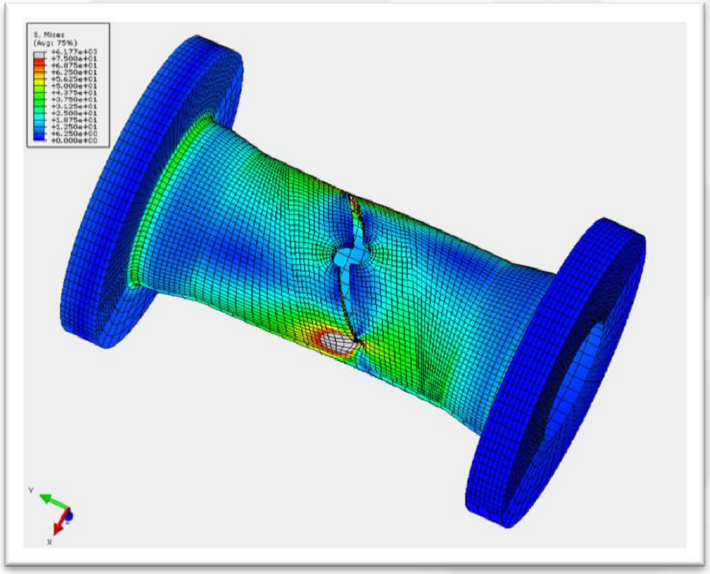
- Finite element methods greatly help both crack initiation and crack growth phases:
  - Multi-axial loads
  - Thermo mechanical
  - Creep fatigue
  - Welded joints
  - Residual stress effects
  - Random and multi-spectral loading effects
  - Stresses and other results through the load history
  - Effect of variability of load and material

Use of Finite Element methods

- Simulation of different scenarios
- Replace spreadsheet fatigue calculations
- Replace expensive prototype testing
- Produce a durable design
- Identify onset of failure from different loading
- Design of new materials

Fatigue – Propagation





- Fracture mechanics can provide post-initiation modelling:
  - Crack growth paths
  - Crack shape development
- Fracture mechanics approach has:
  - Similarities with traditional fatigue because the underlying load scenario has not changed
    - Combine stress solution(s) for “base” load case(s) with load history(ies) and material fatigue data

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Fatigue – Propagation

Fracture mechanics parameters
K, G, J.
Closed form or
numerical evaluation (BEM, FEM).

Crack propagation

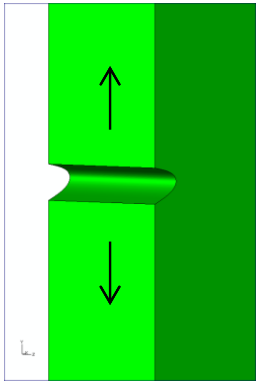
Topology issues
Initial crack.
Mixed mode.
Non-planar growth.
Crack shape development.
Multiple cracks.

Crack growth integration
Cycle-by-cycle or finite evaluations of fracture parameters.
Crack growth data, threshold effects.
Load spectrum, flight cycles, general thermo-mechanical cycles.

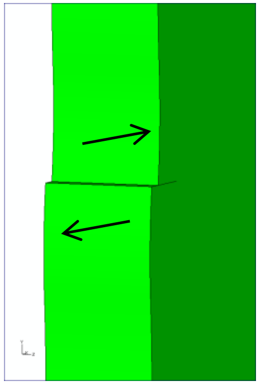
Fatigue – Propagation

- Explicit inclusion of crack(s) in the analysis
  - Fracture mechanics approach quantifies conditions local to defined crack front(s)
  - Usually described in terms of stress intensity factors, K_i, K_{ii} and K_{iii}
  - Energy release rate and j-integral can also be used

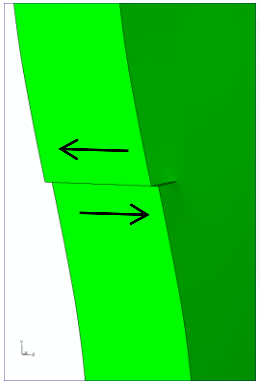
Mode I
opening



Mode II
sliding

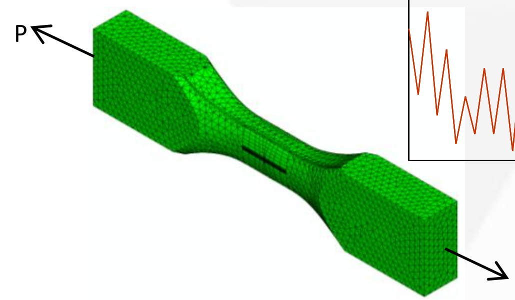


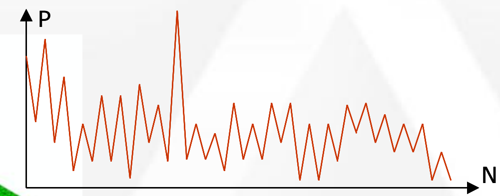
Mode III
tearing



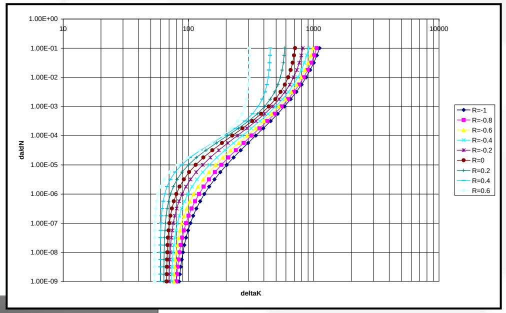
Fatigue – Propagation

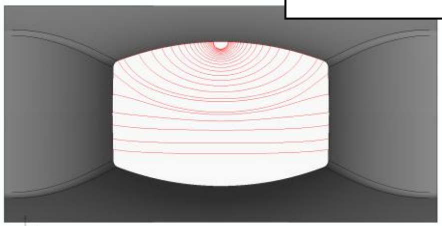
- A "linear elastic fracture mechanics" approach is most often used for crack propagation
  - Loading & history
    - Calculate Ki range, ΔK
  - Crack growth law
    - Relates ΔK to the growth rate, da/dn
  - Advance the crack by da over the next dn cycles





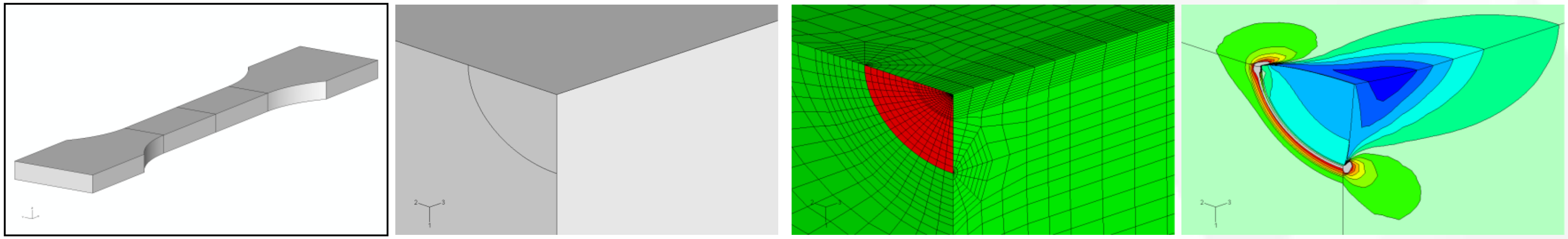
$$\frac{da}{dN} = f(\Delta K, R, T, f \ldots)$$



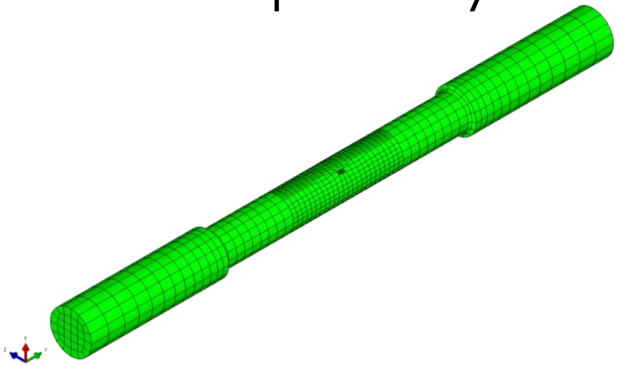


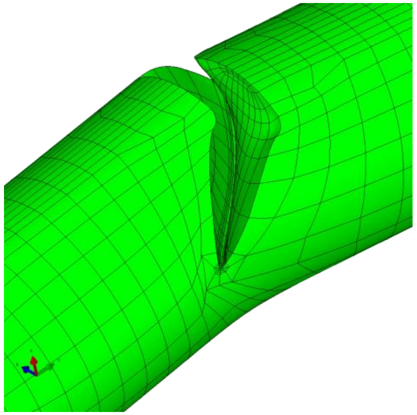
Fatigue – Propagation

- Evaluation of K is critical in this process
  - Handbook methods provide limited solutions



  - Finite element analysis provides a general solution capability





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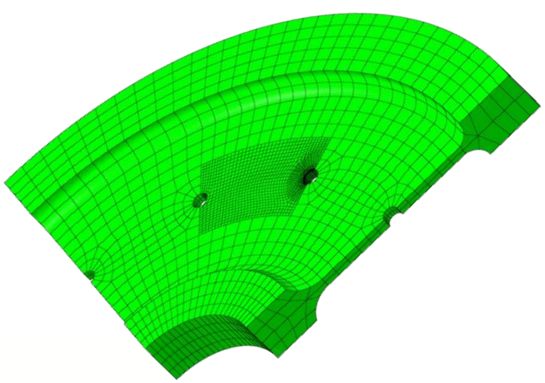
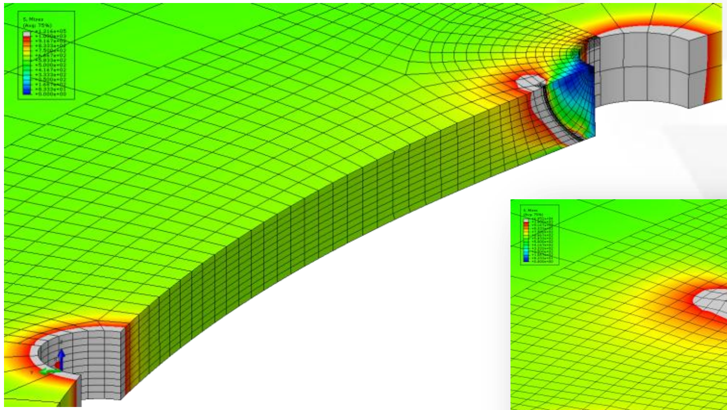
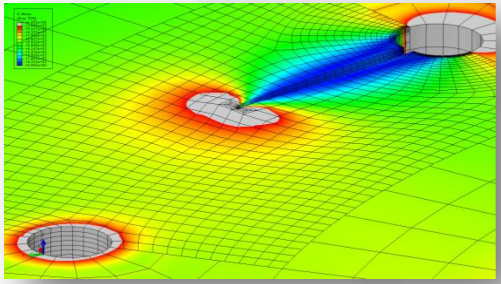
Fatigue – Propagation

- Aims include:
  - Determine remaining life of existing defects
  - Forensic investigation of failures
  - Determine inspection / maintenance schedules
  - Allow continued safe operation with known defect sizes







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Example: Post failure investigation

- Roller bearings installed during refurbishment in 1996 had split in two by 2002
  - Replace all 148 bearings
- Considerable implications:
  - bridge over a mile long, more than 100 feet high, weighing over 58,000 tons
  - carries 160,000+ vehicles per day
  - 35 bridge piers
  - 320km of scaffolding required
  - £52 million for all repair work

LIVE BBC NEWS CHANNEL

Last Updated: Thursday, 3 April, 2003, 08:33 GMT 09:33 UK

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M6 motorists face more delays

Roadworks on one of the busiest stretches of motorway in the North West could be extended by two years.

The motorway carries about 150,000 vehicles a day

Repairs to the Thelwall Viaduct on the M6 in Cheshire were meant to be finished by Easter, but now engineers have found further problems.

The two bridges carry traffic over the Manchester Ship Canal and are used by about 150,000 cars a day.

The northbound bridge was closed in July last year when cracks were discovered in its rollers.

Traffic was diverted on to the southbound bridge and speed limits were put in place.

Now the Highways Agency has admitted that the work is more extensive than it first thought.

Testing has revealed more faults in the 136 roller bearings which support the carriageway and the engineers say the only safe option is to replace all of them.

Ref: http://news.bbc.co.uk/1/hi/england/2912343.stm

Example: Post failure investigation

- The bearings allow for expansion and contraction due to changes in temperature and also to allow for movement of the viaduct as it carries traffic
- Analysis undertaken to investigate possible failure modes and cracking mechanisms

Programme of Repairs

M6 Thelwall Viaduct, Cheshire

M6 Thelwall Viaduct, Cheshire

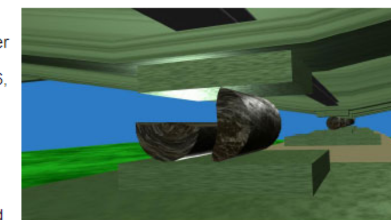
Programme of Major repairs

Works Complete

Works were completed in February 2005 and Thelwall Viaduct was fully reopened.

Background

The northbound viaduct was partially closed to traffic in July 2002, after it was discovered a roller bearing, which was installed when the viaduct was refurbished in 1996, had split in two.



Bridge bearings are positioned between the bridge deck and its supporting columns. They allow thermal expansion and contraction of the viaduct between summer and winter as well as flexing due to traffic.

Initially it was hoped repair work could be carried out quickly but an extensive study of all the support bearings revealed serious problems. After it was realised that all the roller bearings would fail in the short to medium term the decision was taken to replace all 148 of them. This decision was made in the interest of public safety and to prevent further damage to the viaduct.

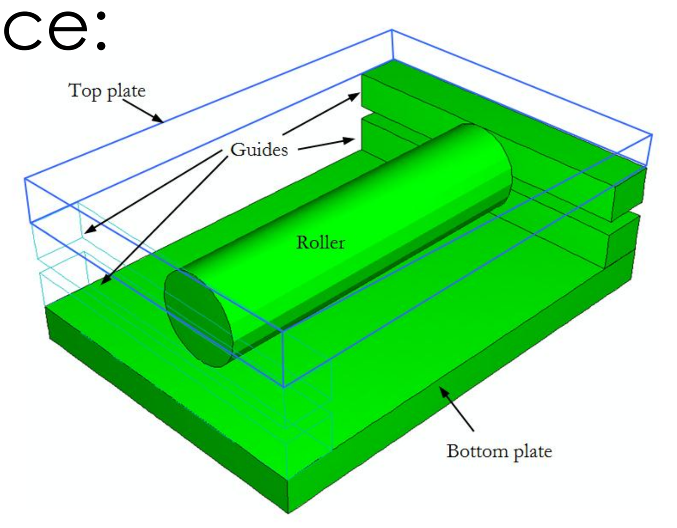
In order to gain access to the bearings scaffolding was erected around each of the 35 piers and 2 abutments that support the viaduct. In total 320 kilometres of scaffolding poles was used, which if laid out end to end would stretch from London to Carlisle.

When replacing a bearing it was necessary to jack up the viaduct to allow the old bearing to be removed and a new one installed. This was a complex operation which first required the strengthening of the beam above the bearing (step 1 in the diagram below). Temporary jacking brackets could then be bolted to the beam (step 2), and the bridge jacked up using four 300 ton jacks (step 3). Once the failed roller bearing had been replaced with a new slider bearing the bridge could be lowered and the jacks and brackets removed and used elsewhere on the bridge.

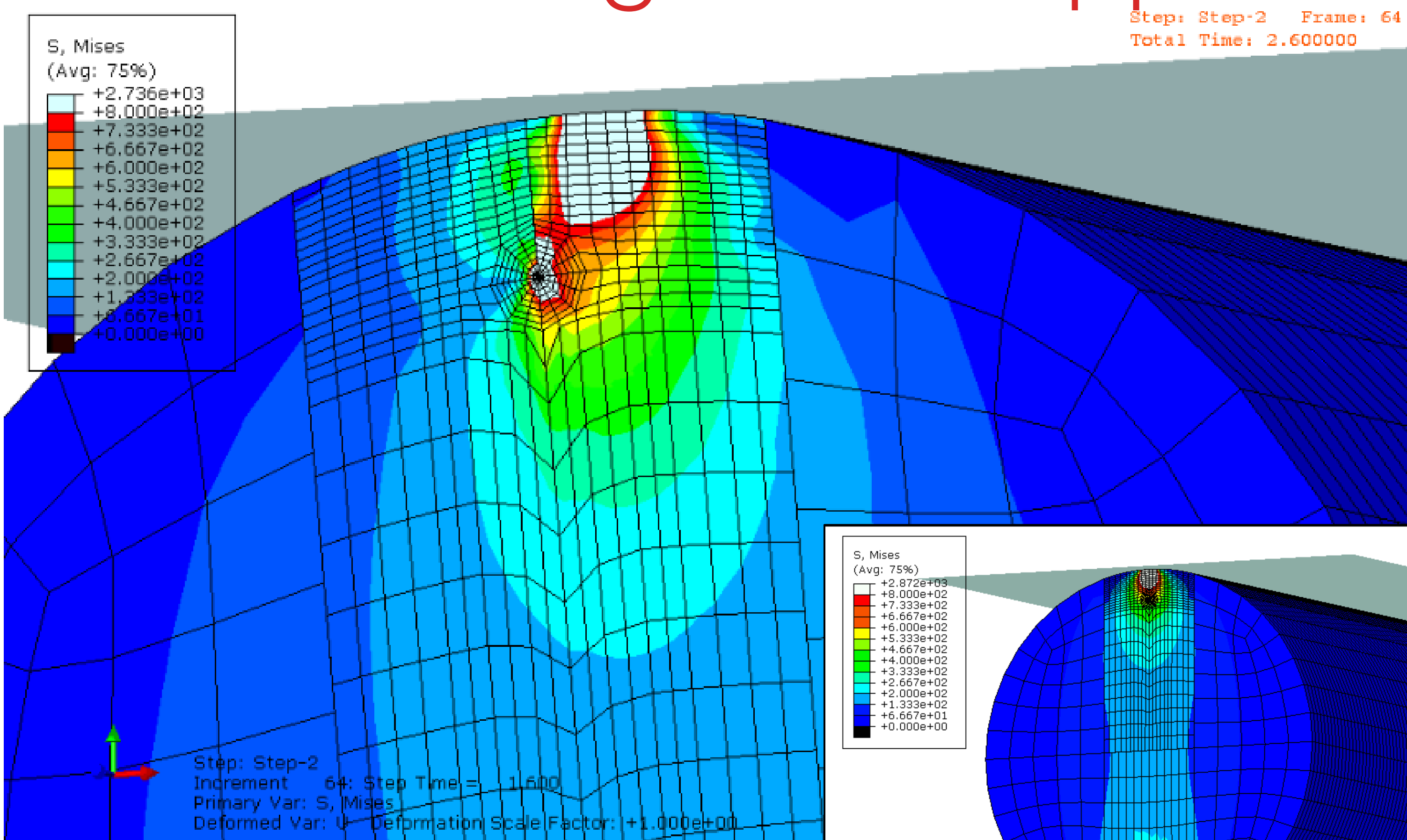
Ref: http://www.highways.gov.uk/roads/projects/4858.aspx

Cracked bridge roller supports

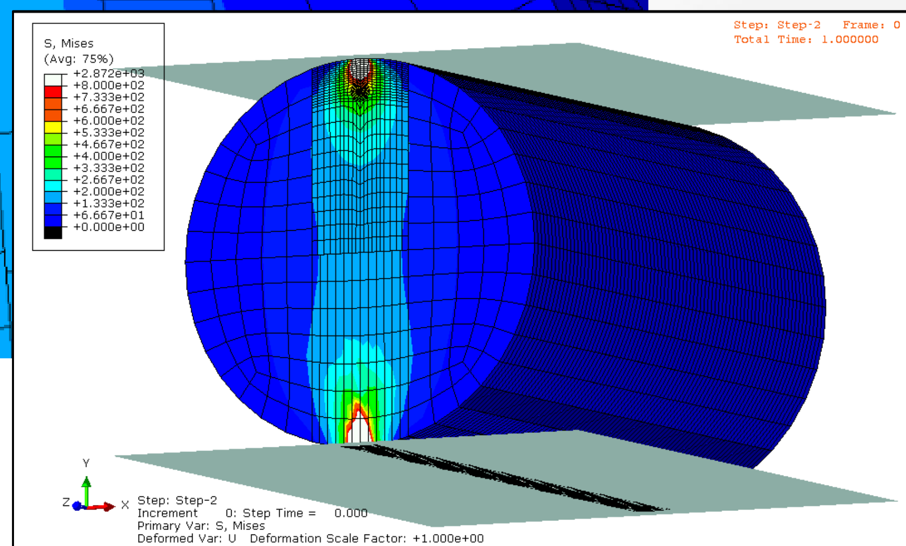
- Analysis includes:
  - contact between the roller and the surrounding plates and also between the crack faces where there is potential for mode II and mode III effects
  - weight of the bridge deck
  - a full roll cycle representing deck expansion & contraction
- The analysis was able to produce:
  - crack growth profiles matching those seen in failed rollers
  - predicted failure time consistent with the actual failure time of the rollers



Cracked bridge roller supports



The model shown has a single defect.
The "real" analysis has multiple defects, starting as corner cracks, at the contact positions with the plates.



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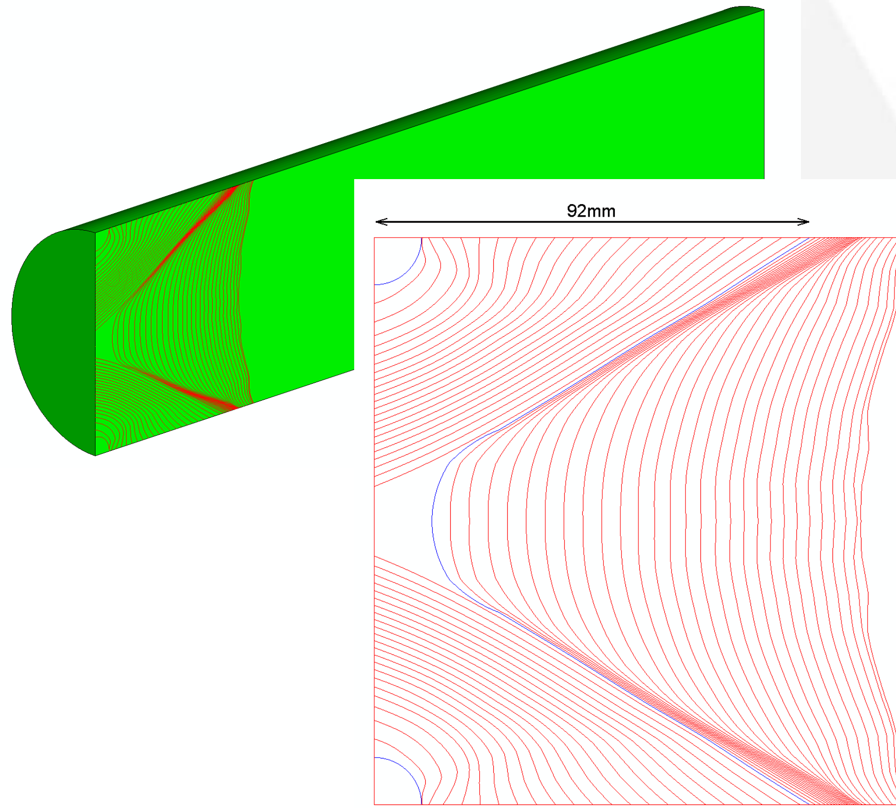
Cracked bridge roller supports

- Analysis for "roll-only" load case – no effect of contact against end guide plates – so the crack grows in-plane
- Initial 10mm corner cracks join to form a single through crack when axial crack length is 92mm
- Failure when the through crack length is 107mm



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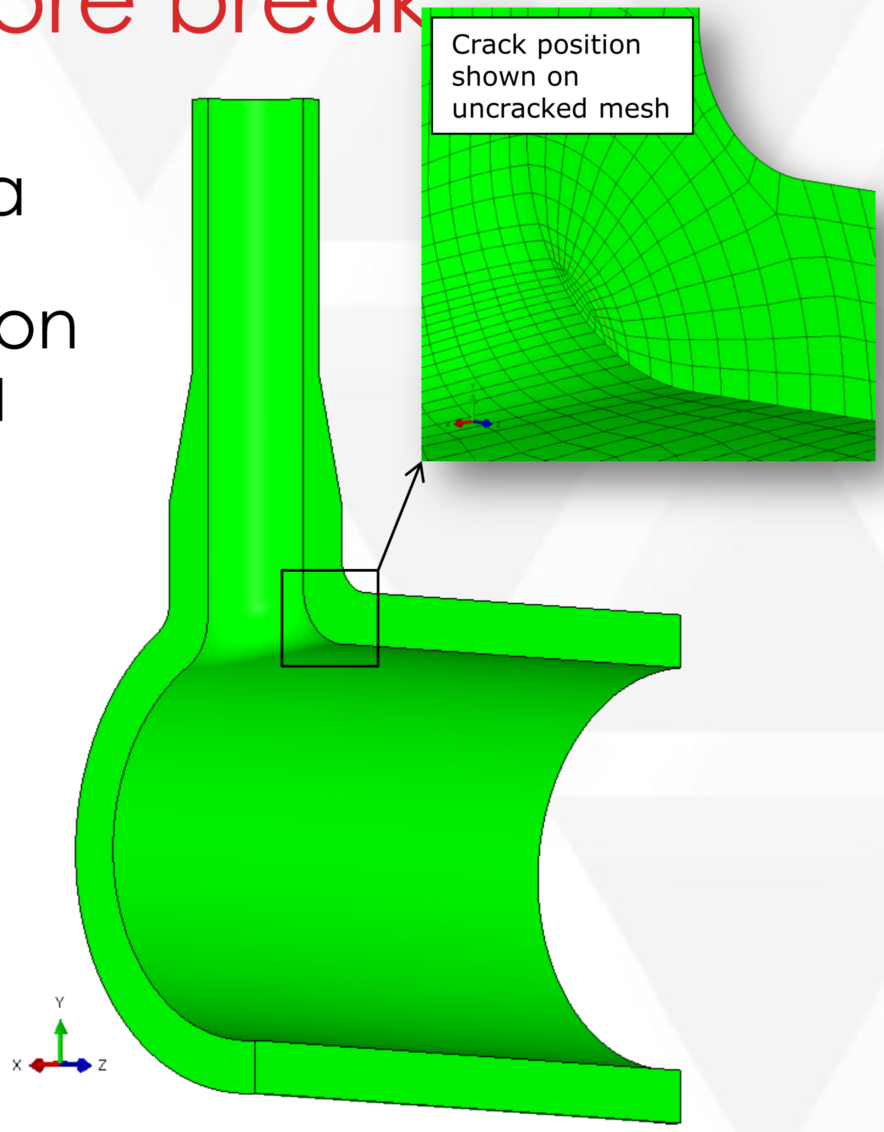
Example: Leak before break

- This example considers a crack in a pressurised header nozzle connection
  - Response to a pressurised thermal shock
  - Crack growth
- The quarter symmetry model has the following main dimensions
  - Header
    - OD 30", wall $3^1/_8$"
  - Nozzle
    - OD $10^5/_8$", wall $1^5/_{16}$"



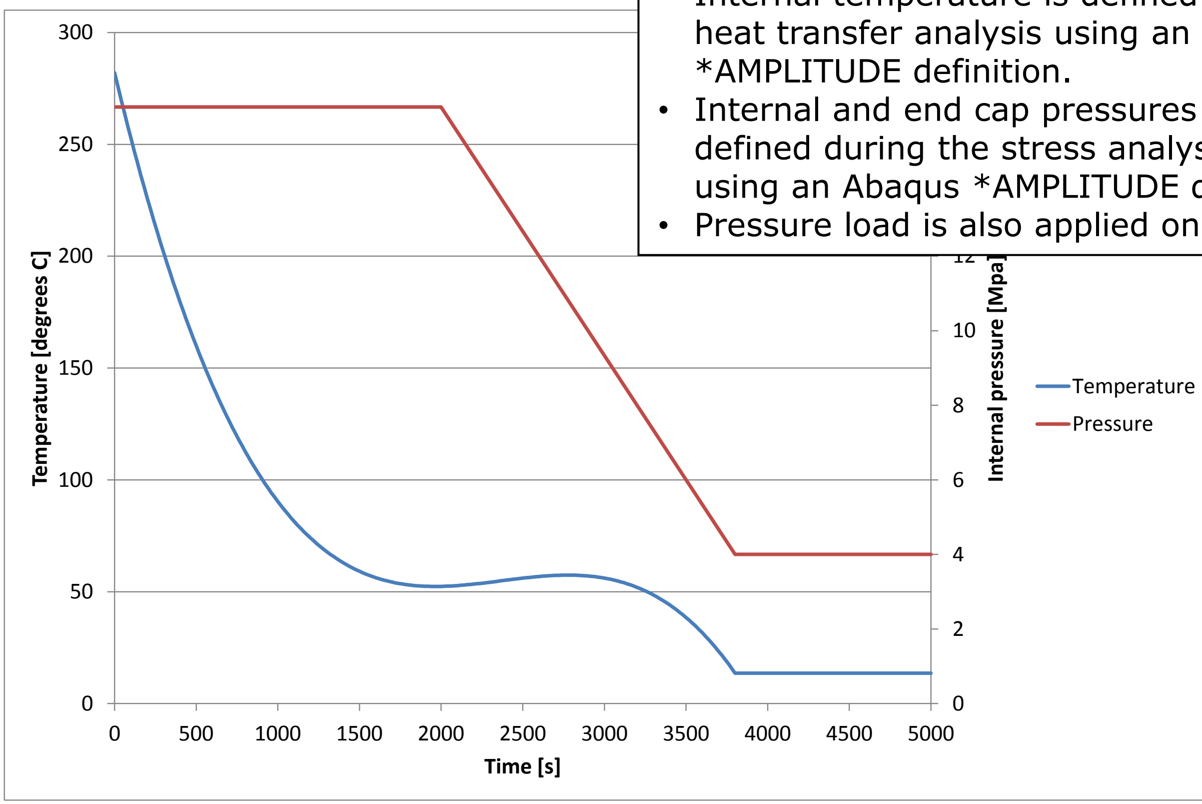
Example: Leak before break

- Temperature dependent steel data
- The transient analysis is carried out as a sequential thermal-stress analysis:
  - Heat transfer run to develop temperature distribution as a function of time
  - Stress analysis using the heat transfer results as one of the inputs, plus pressure loading

```
*Material, name=Steel
*Conductivity
 0.0518, 20.
 0.0503,100.
 0.0476,200.
 0.0445,300.
 0.0414,400.
*Density
 7.85e-06,
*Elastic
209000., 0.3, 20.
205000., 0.3,100.
199000., 0.3,200.
191000., 0.3,300.
181000., 0.3,400.
*Expansion, zero=20.
 1.15e-05, 20.
 1.17e-05, 50.
  1.2e-05,100.
 1.23e-05,150.
 1.27e-05,200.
  1.3e-05,250.
 1.33e-05,300.
 1.35e-05,350.
 1.38e-05,400.
*Specific Heat
460., 20.
480., 50.
500.,100.
520.,150.
530.,200.
540.,250.
560.,300.
570.,350.
590.,400.
```

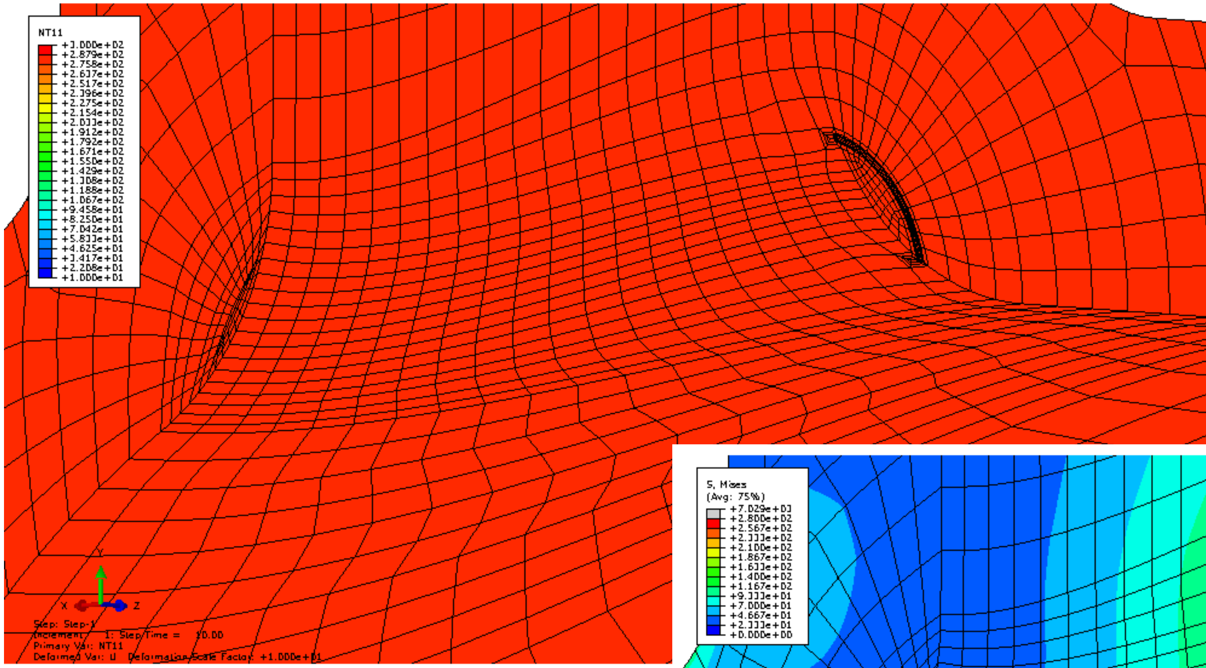
Transient definition

- Transient definition for pressurised thermal shock



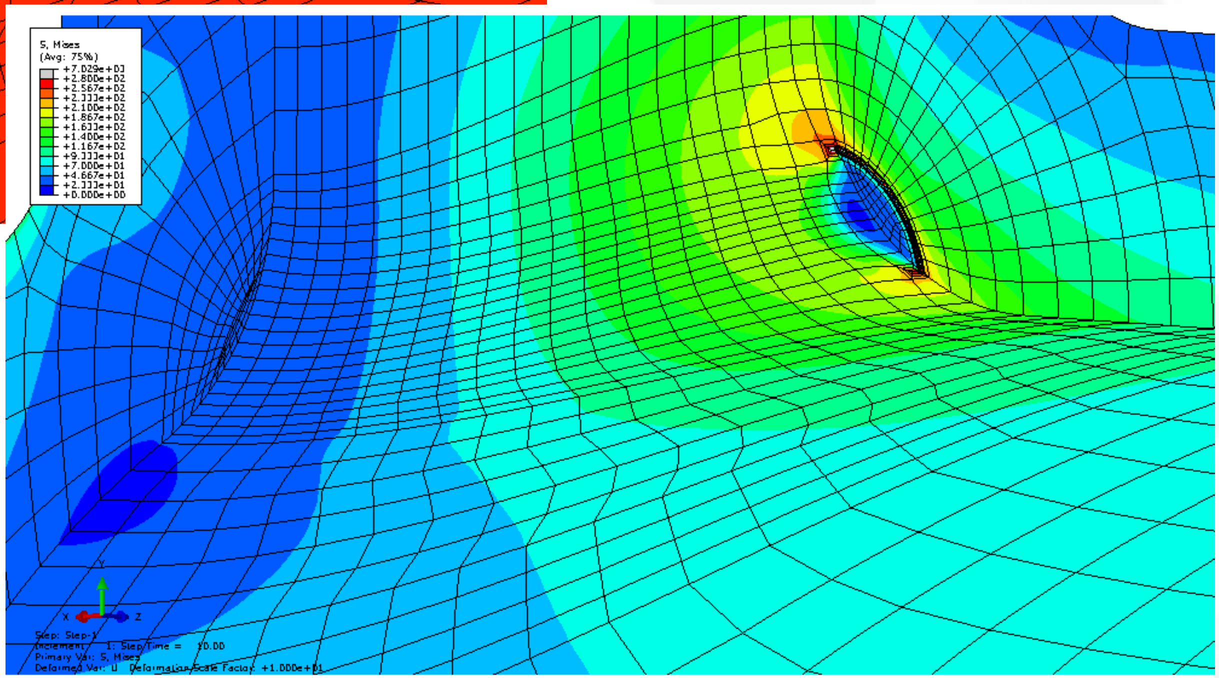
- Internal temperature is defined in the heat transfer analysis using an Abaqus *AMPLITUDE definition.
- Internal and end cap pressures are defined during the stress analysis using an Abaqus *AMPLITUDE definition.
- Pressure load is also applied on the crack face.

Cracked model transient analysis



Temperature

Von Mises stress



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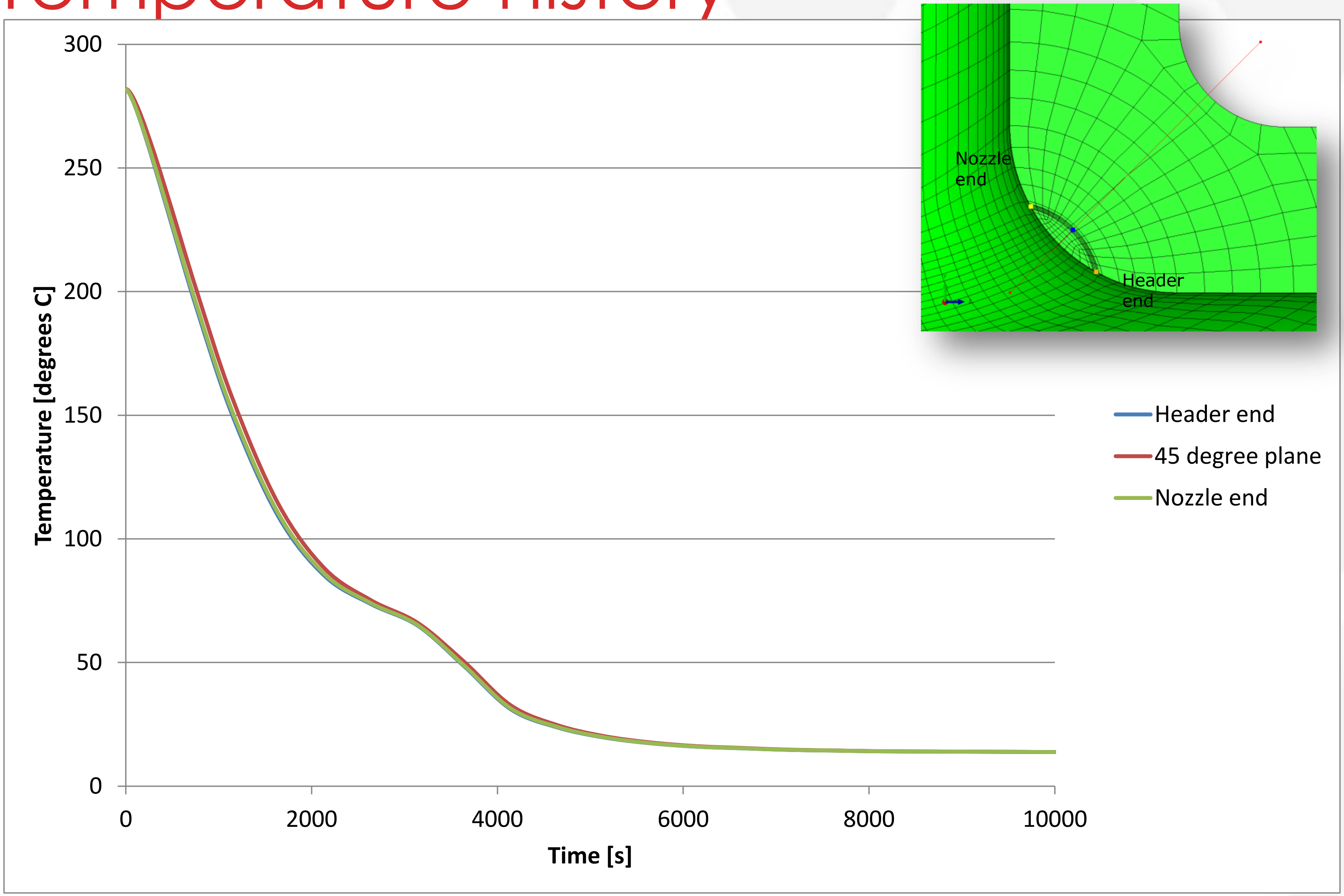
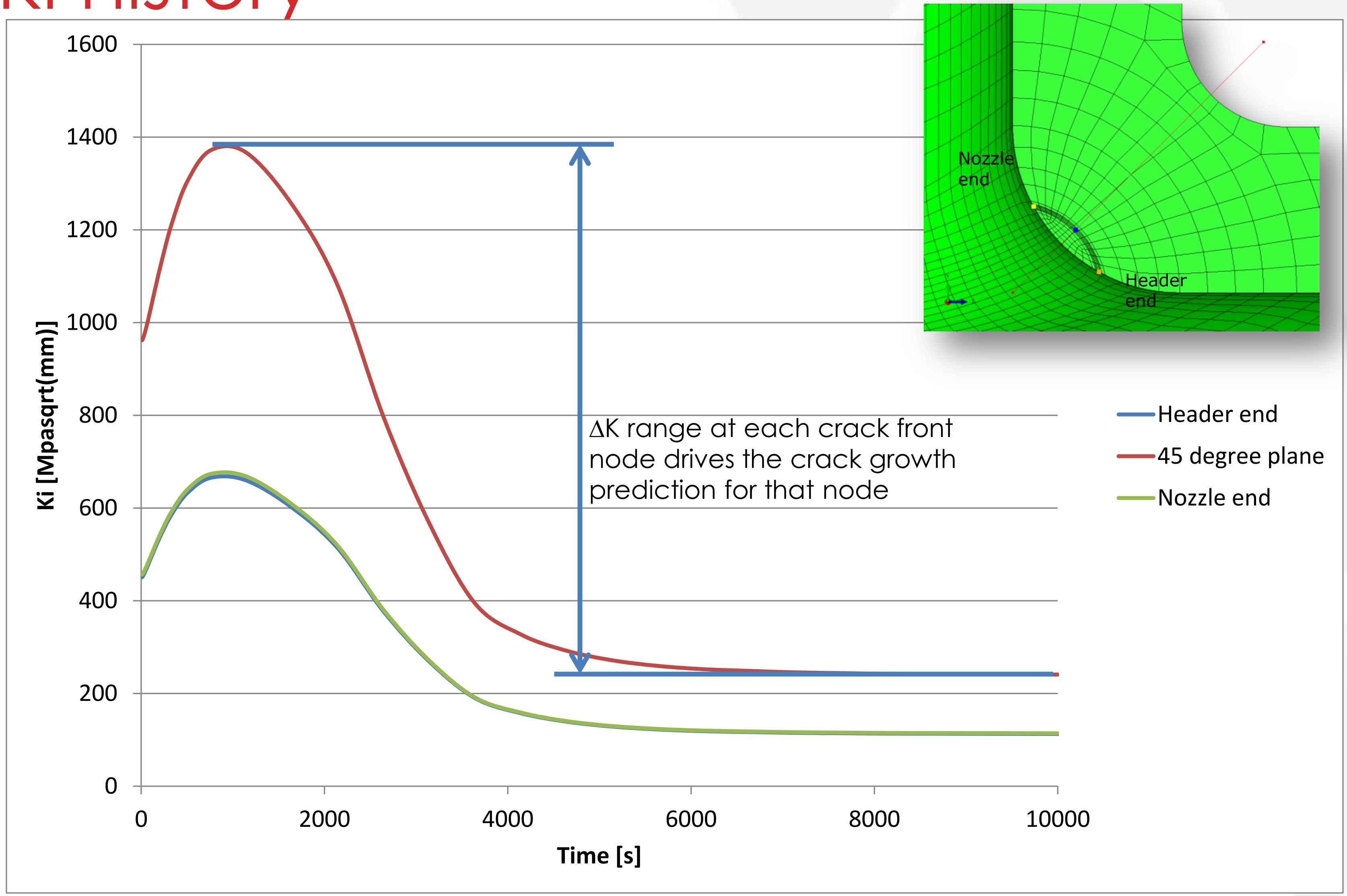
Temperature history

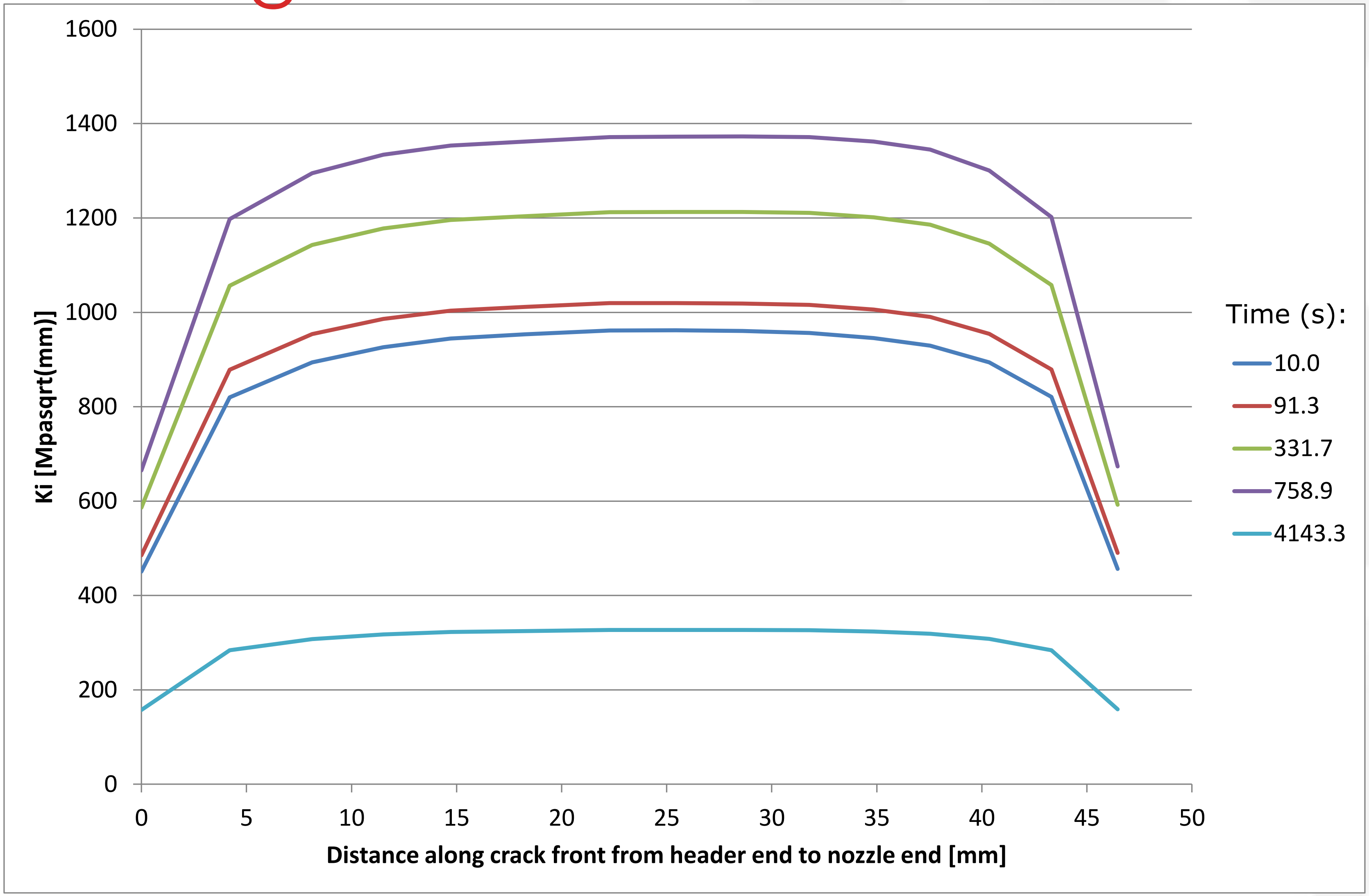


Ki history



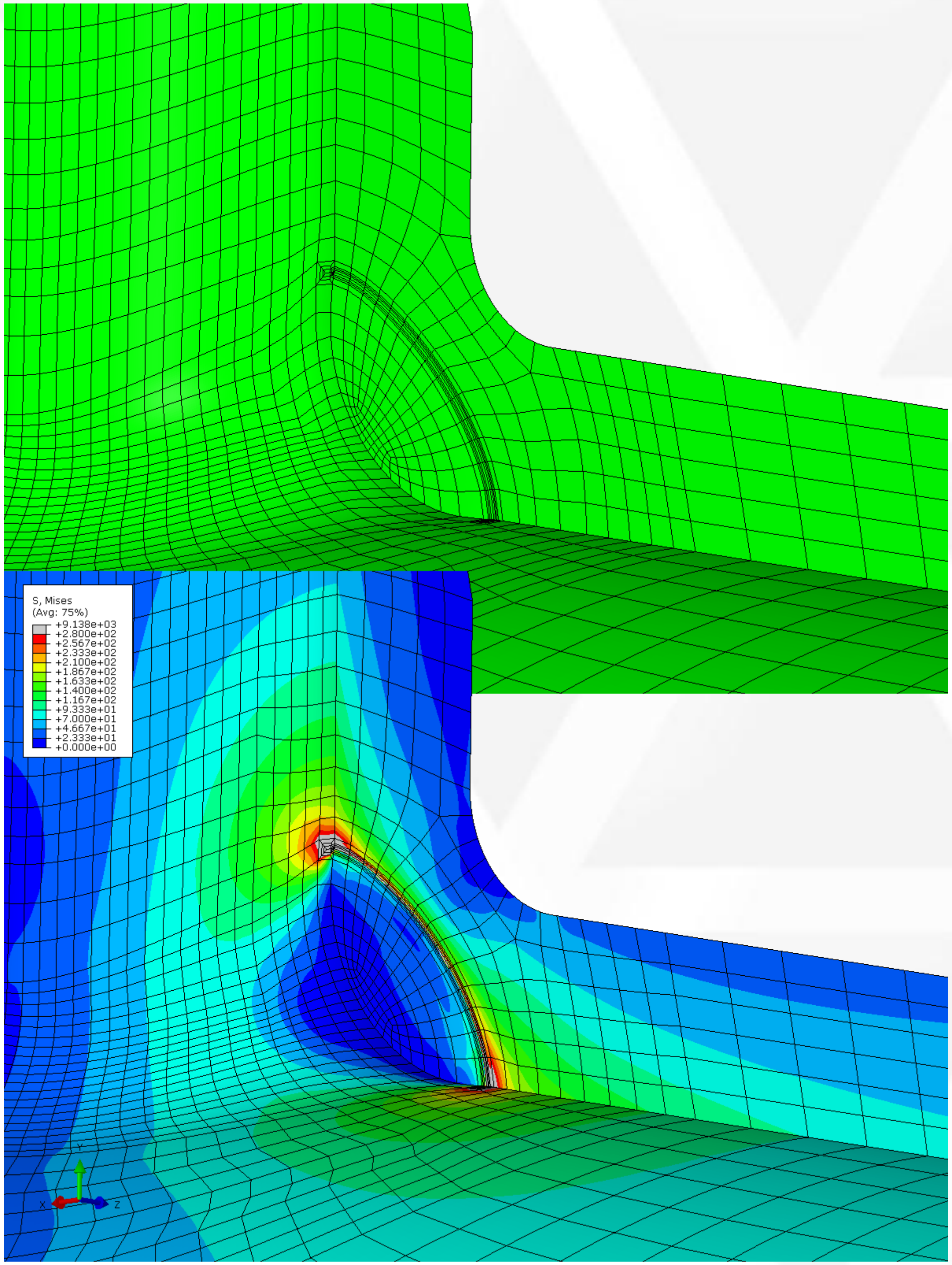
1600
1400
1200
1000
800
600
400
200
0
Ki [Mpasqrt(mm)]
0
2000
4000
6000
8000
10000
Time [s]
ΔK range at each crack front node drives the crack growth prediction for that node
Nozzle end
Header end
Header end
45 degree plane
Nozzle end

Ki along the crack front



Crack growth

- Range of ΔK through the transient is extracted for each crack front node
- Integration scheme advances each node over the next N load cycles



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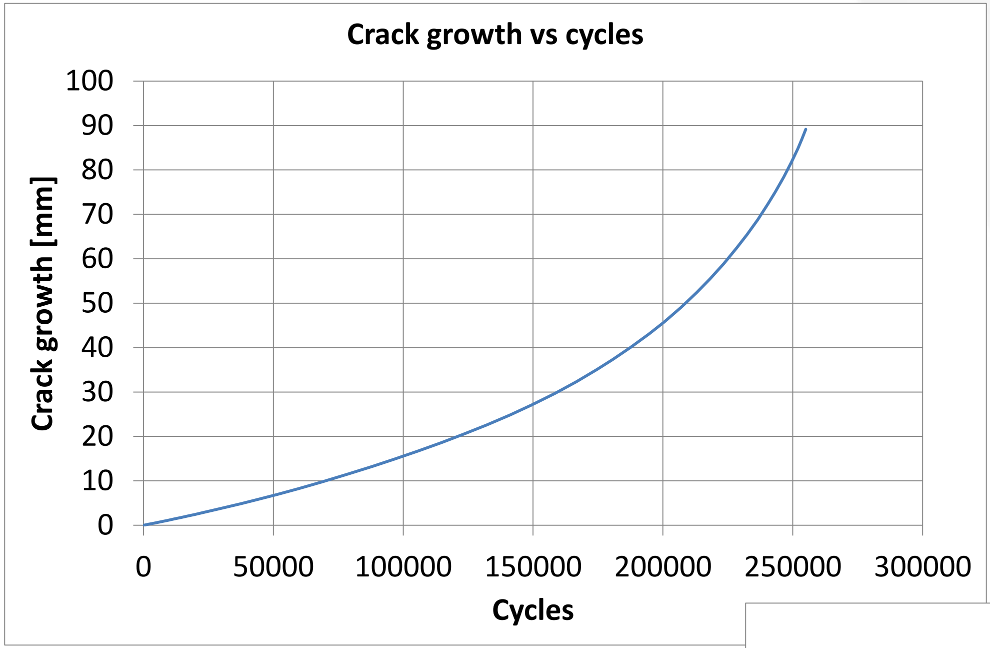
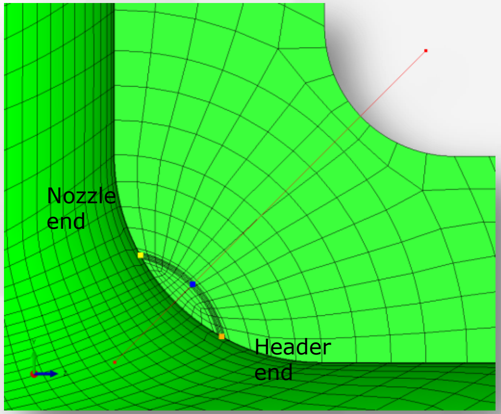
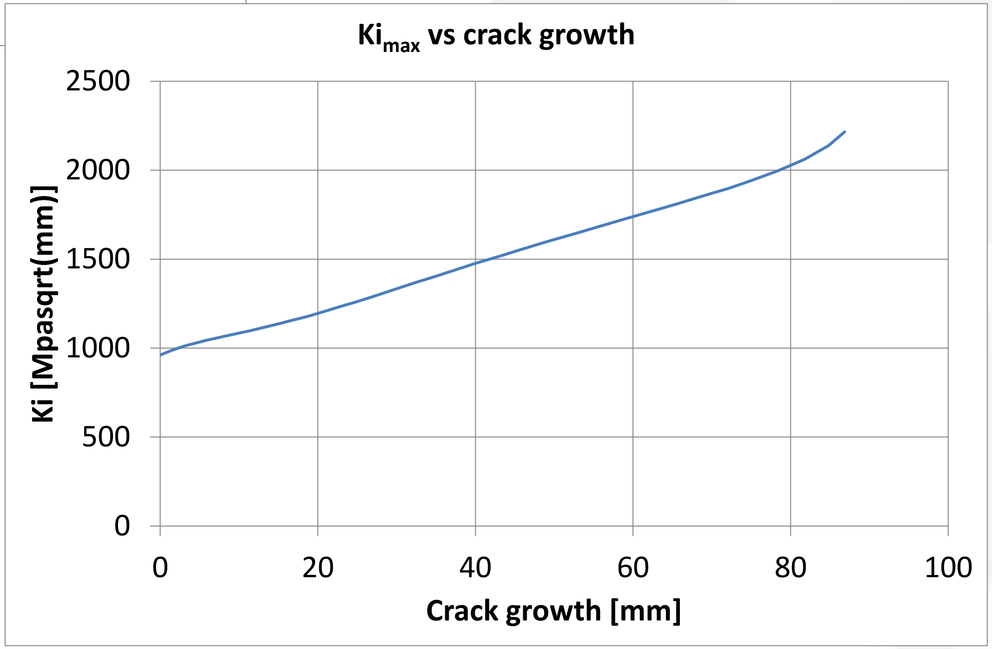


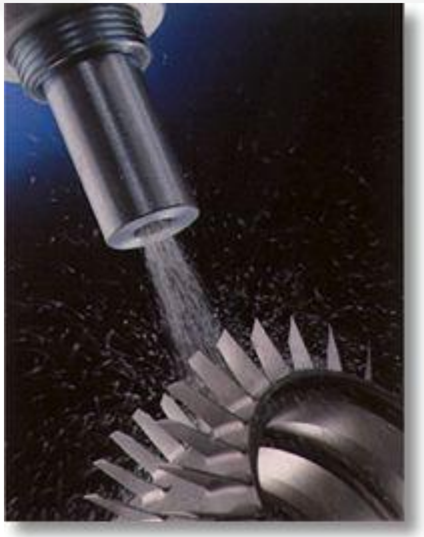


Results along 45 degree plane



Example: Shot peening

- Shot peening produces a compressive residual stress layer at the surface of metallic components and a sub-surface tensile stress
  - Surface is impacted with shot (round metallic, glass or ceramic particles) with sufficient force to generate plastic deformation
  - the compressive stress provides resistance to fatigue crack development
  - shot peening can increase fatigue life by up to1000%



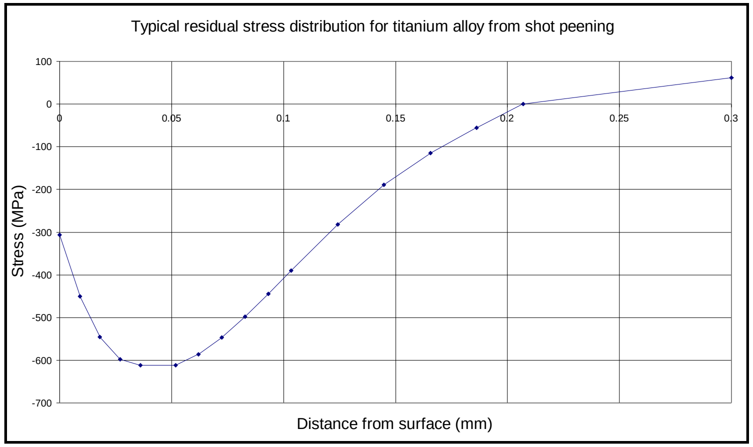
Example: Shot peening

- Often used in aircraft structures and engine disk and blade components
- Inclusion of the effect of the shot peening process can have a considerable effect on a crack growth simulation
- This is demonstrated by a simple example

Blade assembly

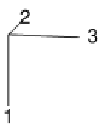
Typical treated components

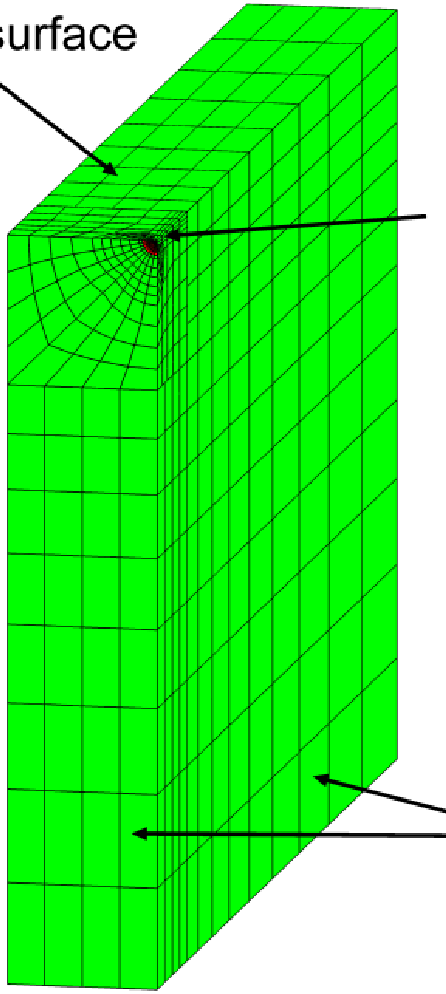
Effect of residual stress on growth



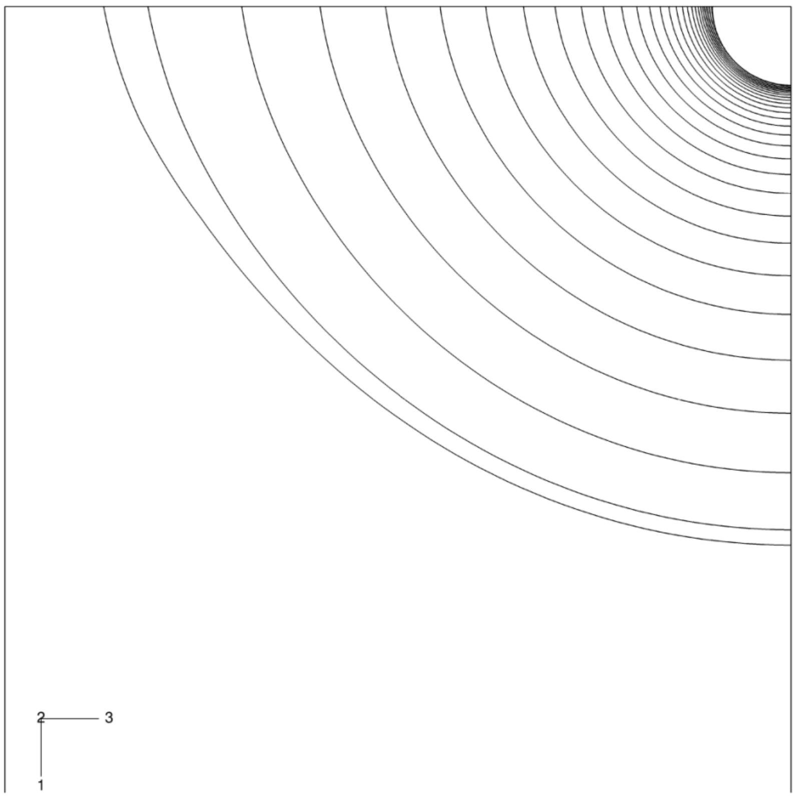
Residual stress distribution.

Elastic shakedown after a small number of load cycles.



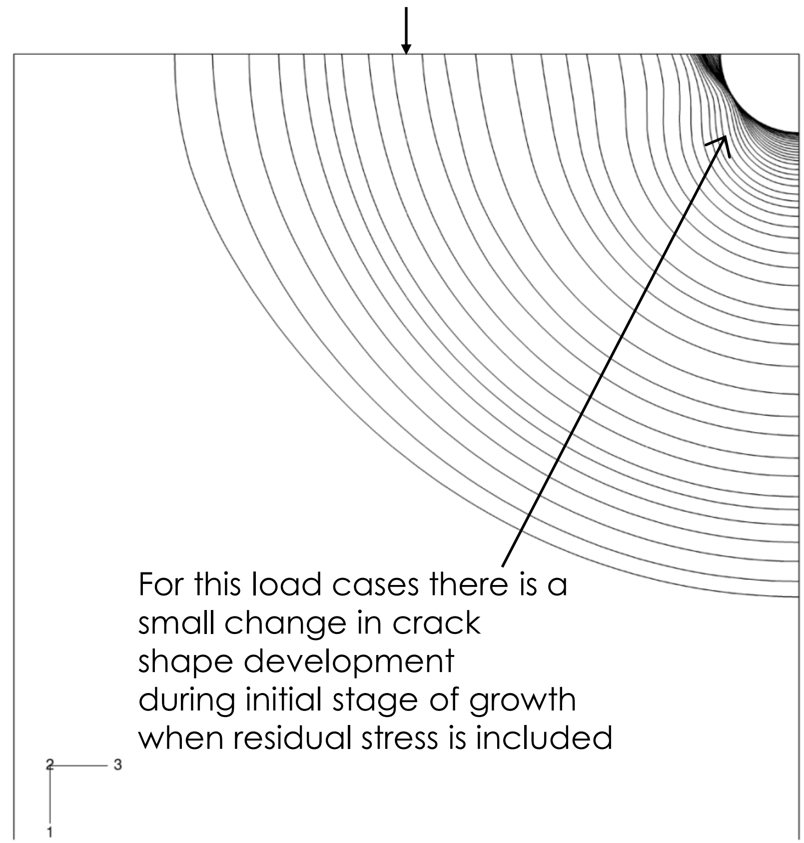


Effect of residual stress on growth



No surface treatment.
External load at R=0.75

Treated surface



With residual stress induced from shot peening.
External load at R=0.75

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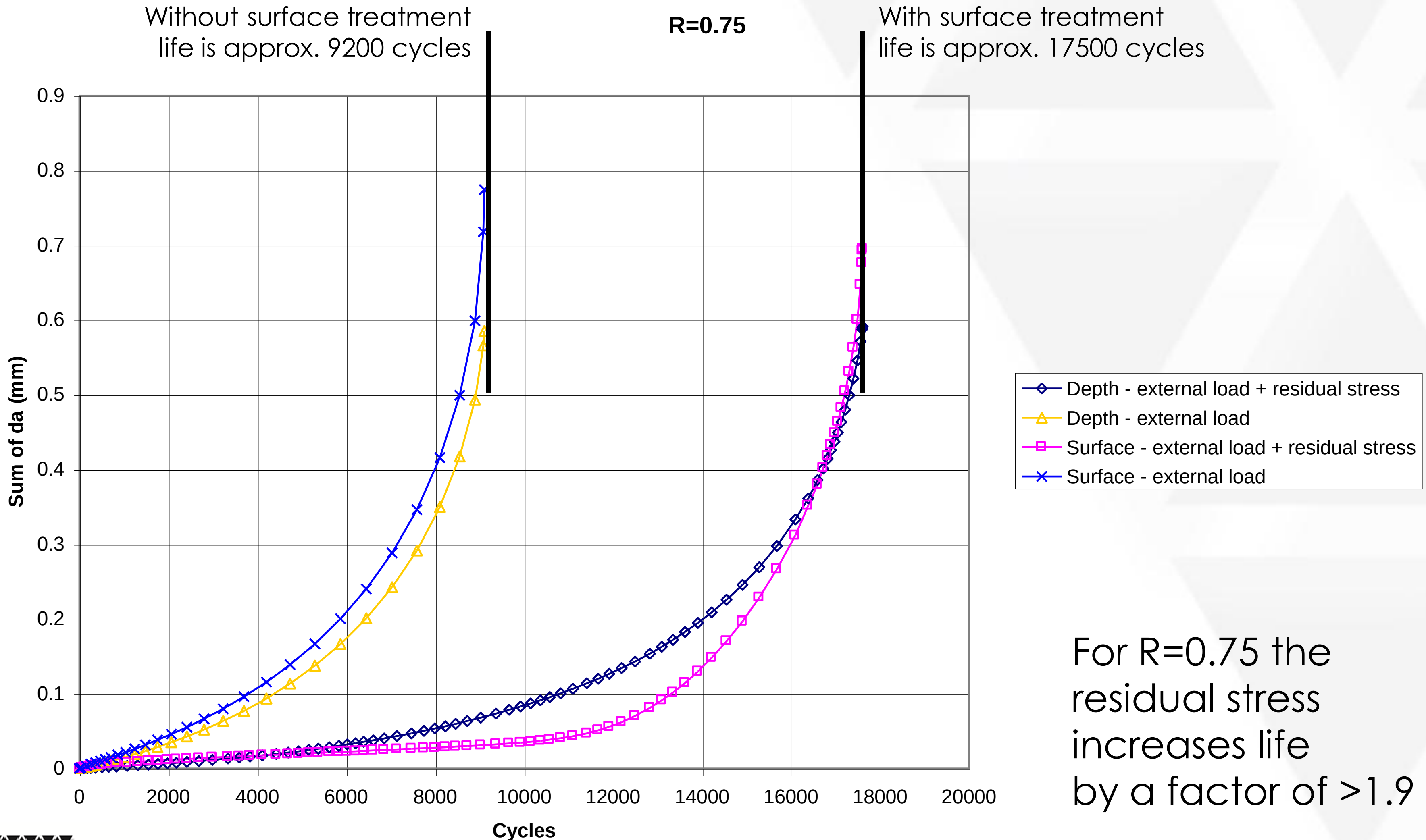
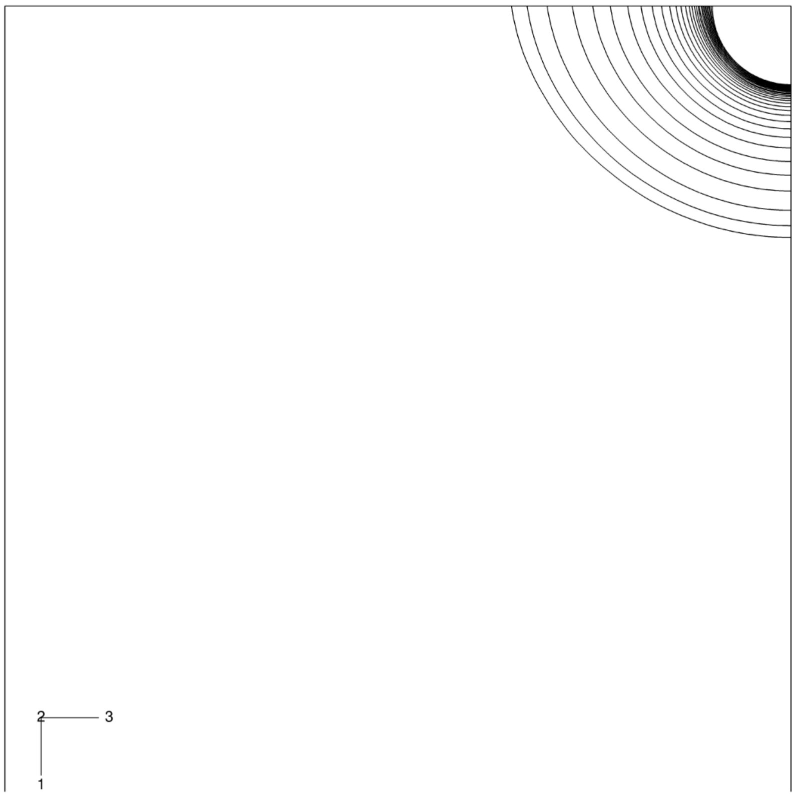
Effect of residual stress on growth

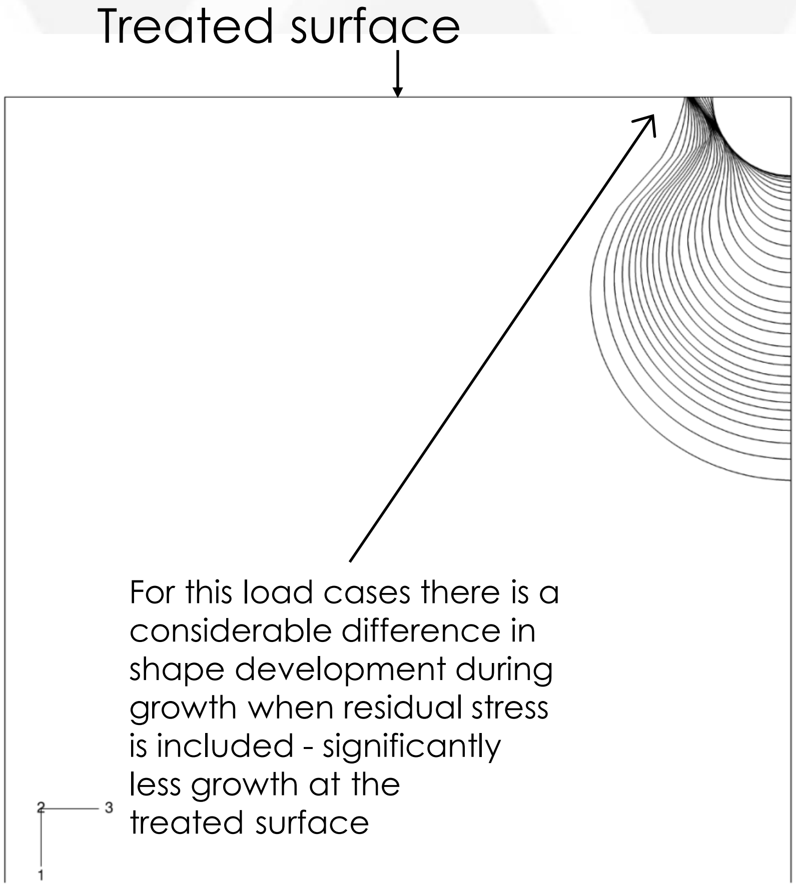


For R=0.75 the residual stress increases life by a factor of >1.9

Effect of residual stress on growth



No surface treatment.
External load at R=0.0



With residual stress induced from shot peening.
External load at R=0.0

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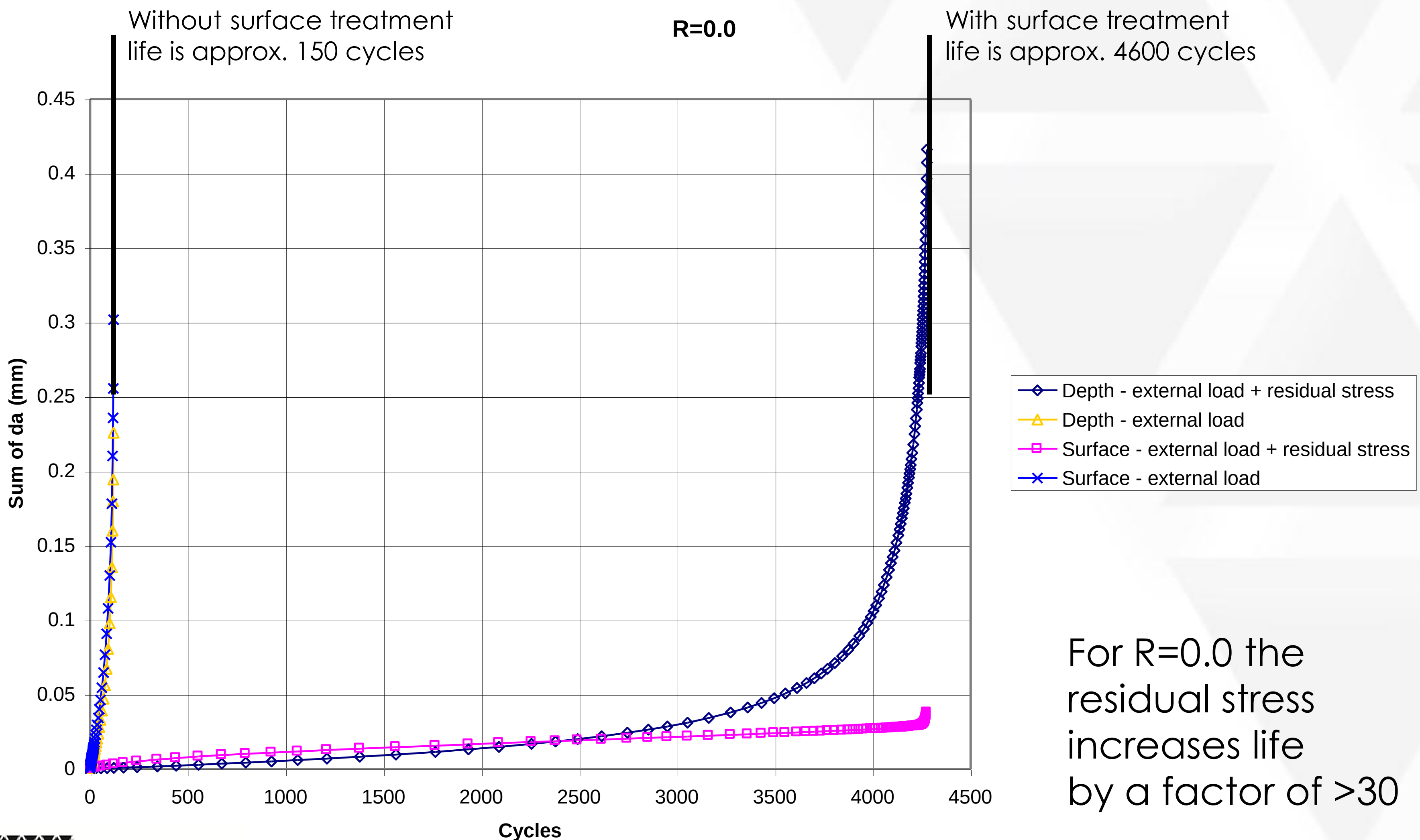
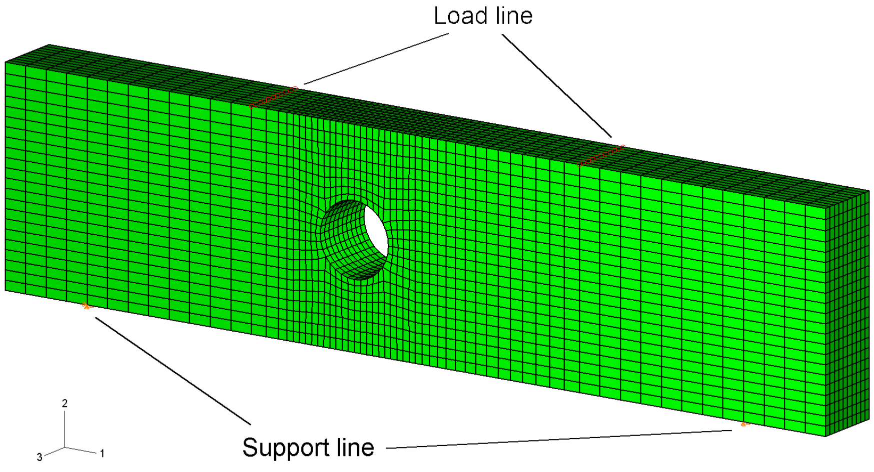
Effect of residual stress on growth

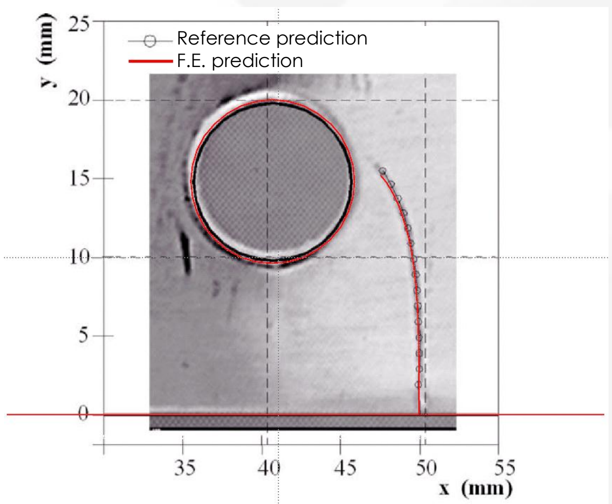


For R=0.0 the residual stress increases life by a factor of >30

Example: Parametric studies

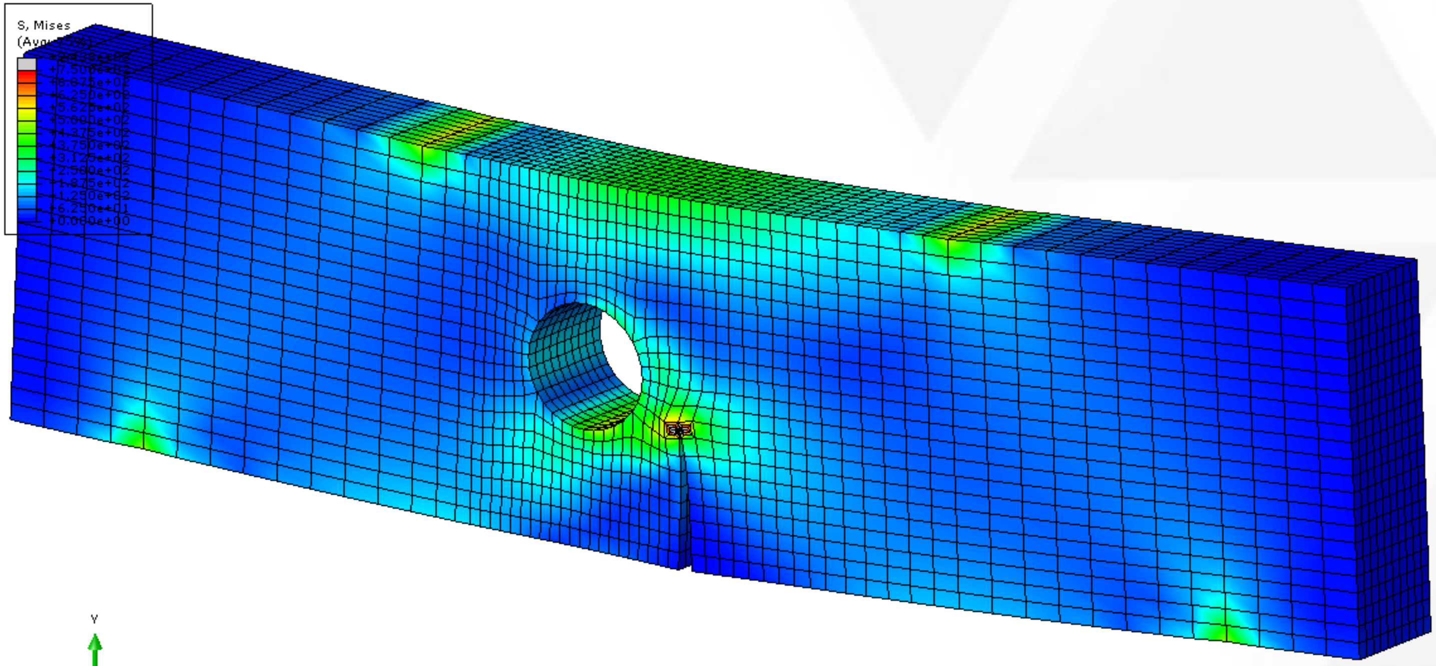
- SEN specimen with a hole in 4-point bending
- Determine effect of hole on crack path

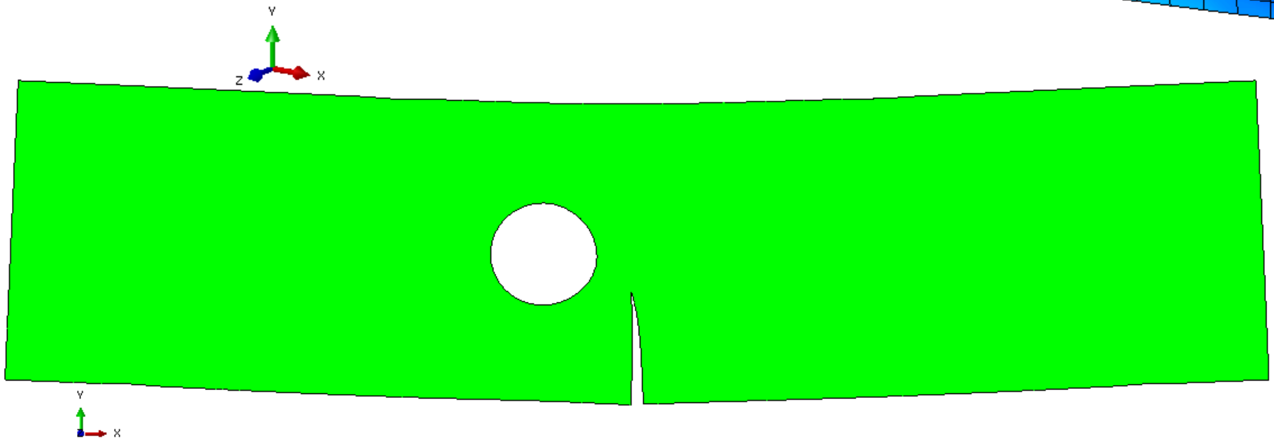


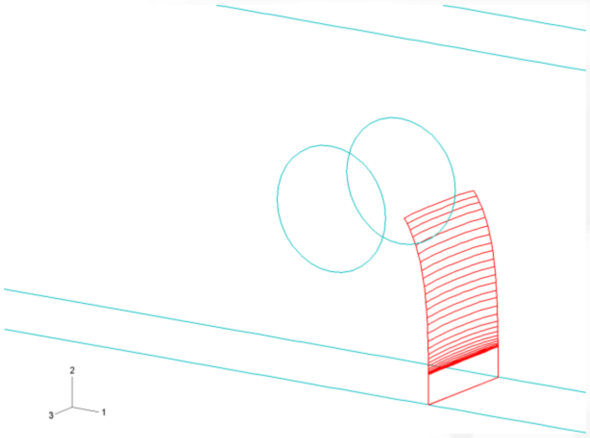


Reference data:
"Fatigue life and crack path predictions in generic 2D structural components"
A.C.O. Miranda, M.A. Meggiolaro, J.T.P. Castro, L.F. Martha, T.N. Bittencourt, Eng. Frac. Mechanics 70 (2003) 1259-1279.

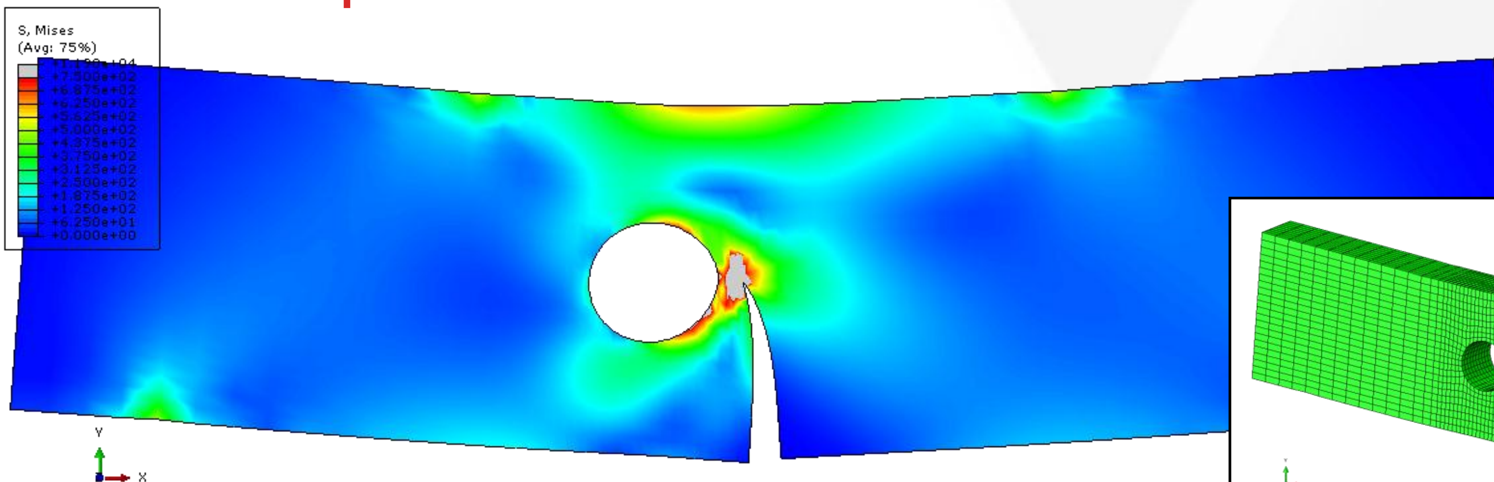
Example: Parametric studies



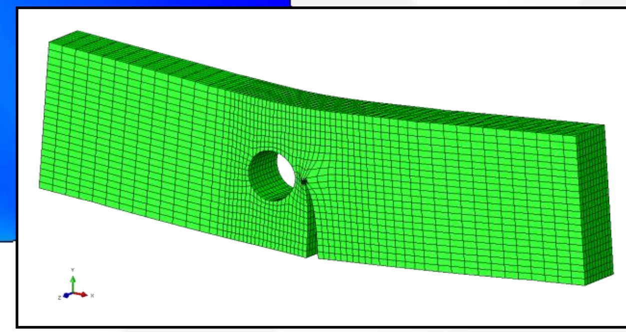


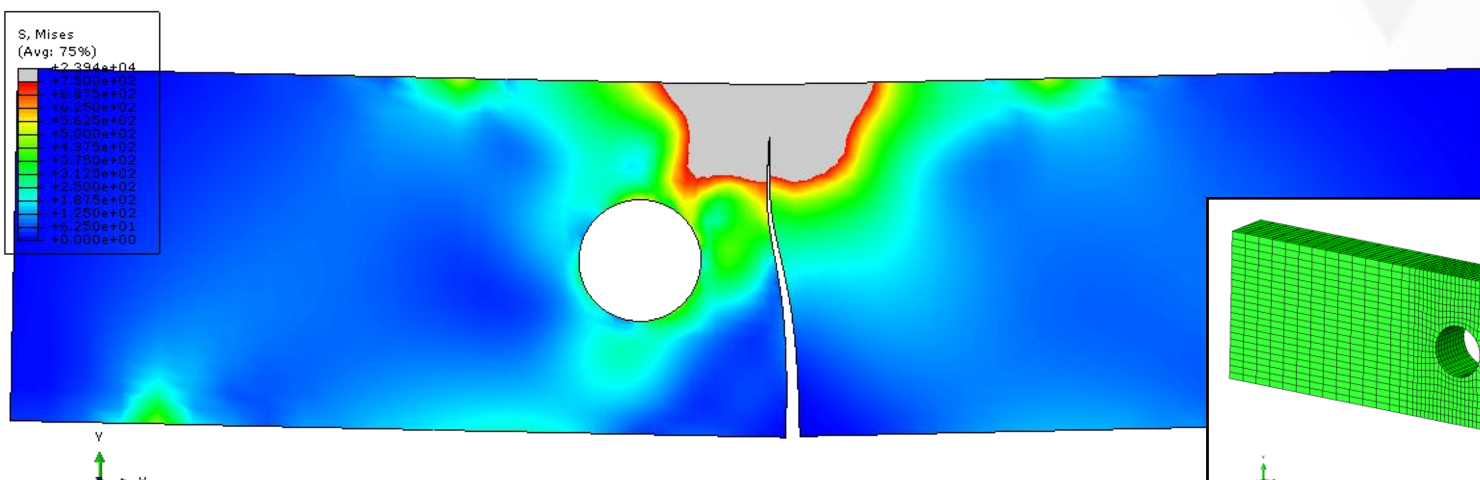


Example: Parametric studies

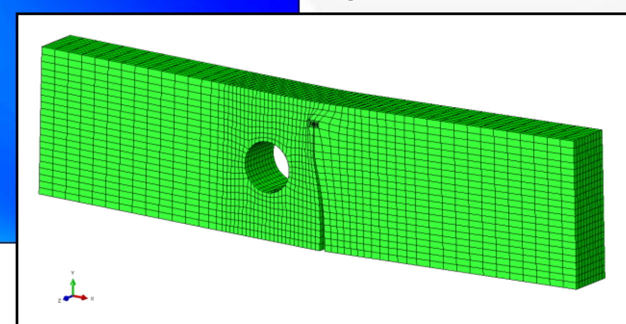


First analysis





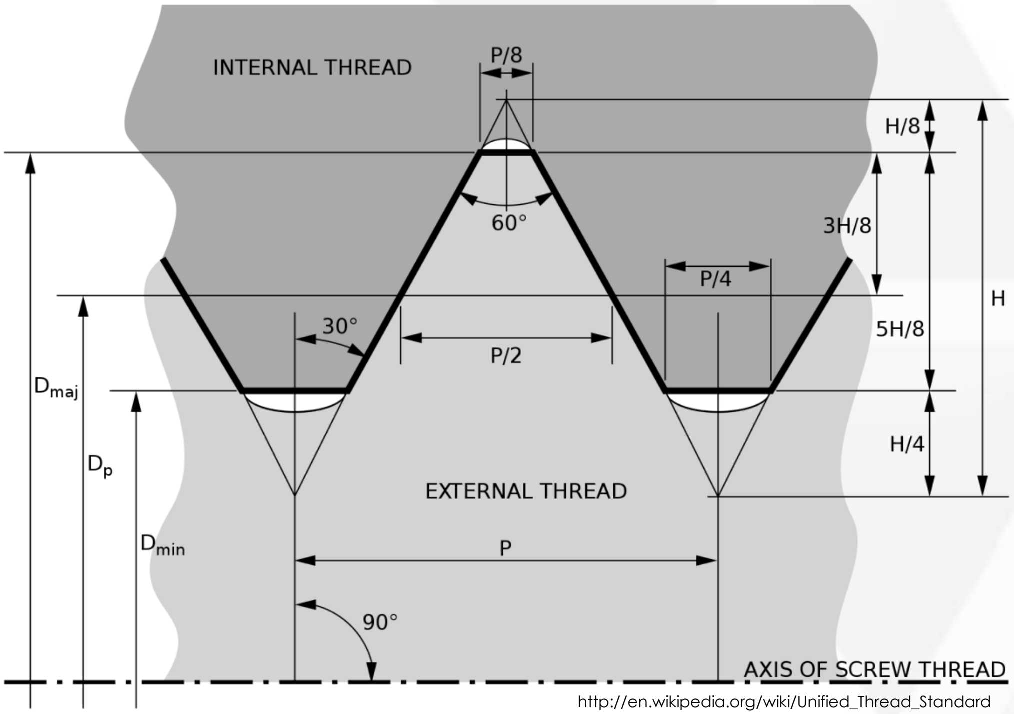
Second analysis: initial crack moved a small amount to the right



Animations on this slide are not included in the pdf version

Example: Complex contact

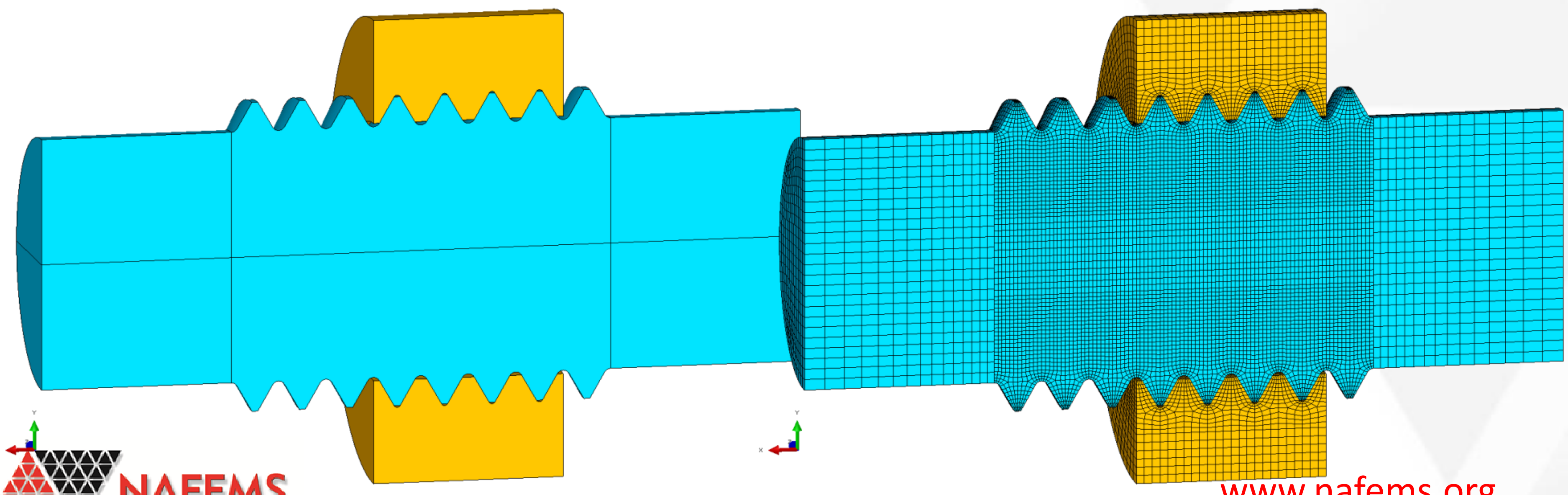
- Geometry is a coarse (UNC) 0.5 inch major diameter thread
- In terms of the definitions below:
  - Major diameter
    - D_{maj}=0.5"
  - Pitch
    - P=1/13“
    - i.e. 13 threads per inch



http://en.wikipedia.org/wiki/Unified_Thread_Standard

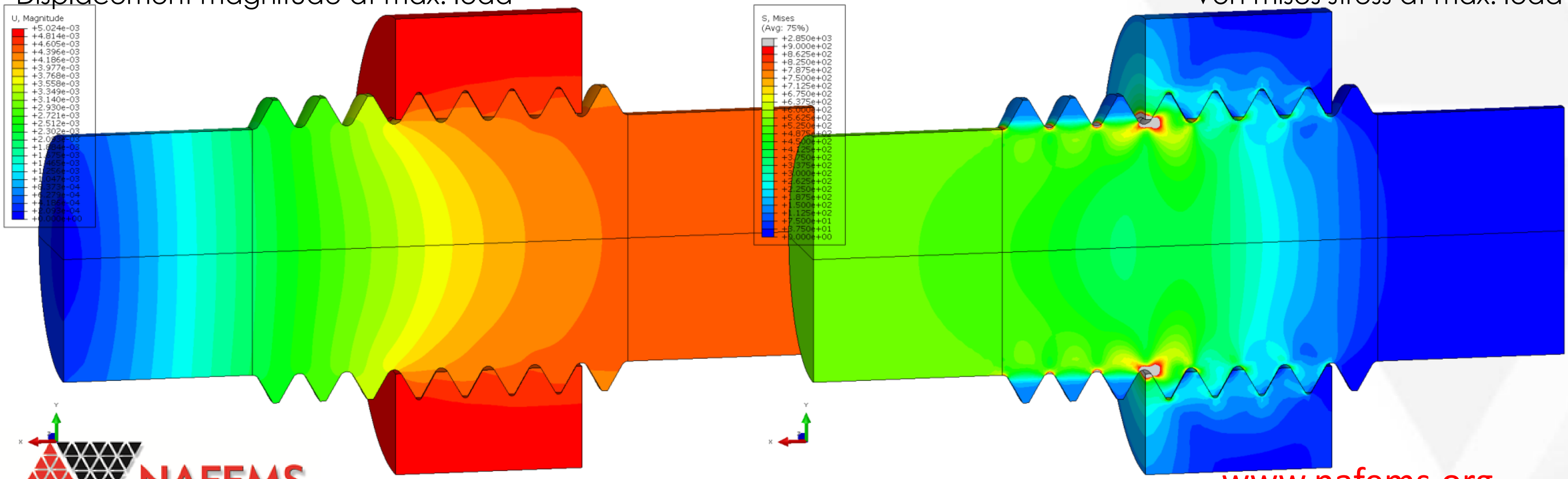
Example: Complex contact

- Simplified model
  - no circumferential effect of pitch
  - crack extending around the full circumference

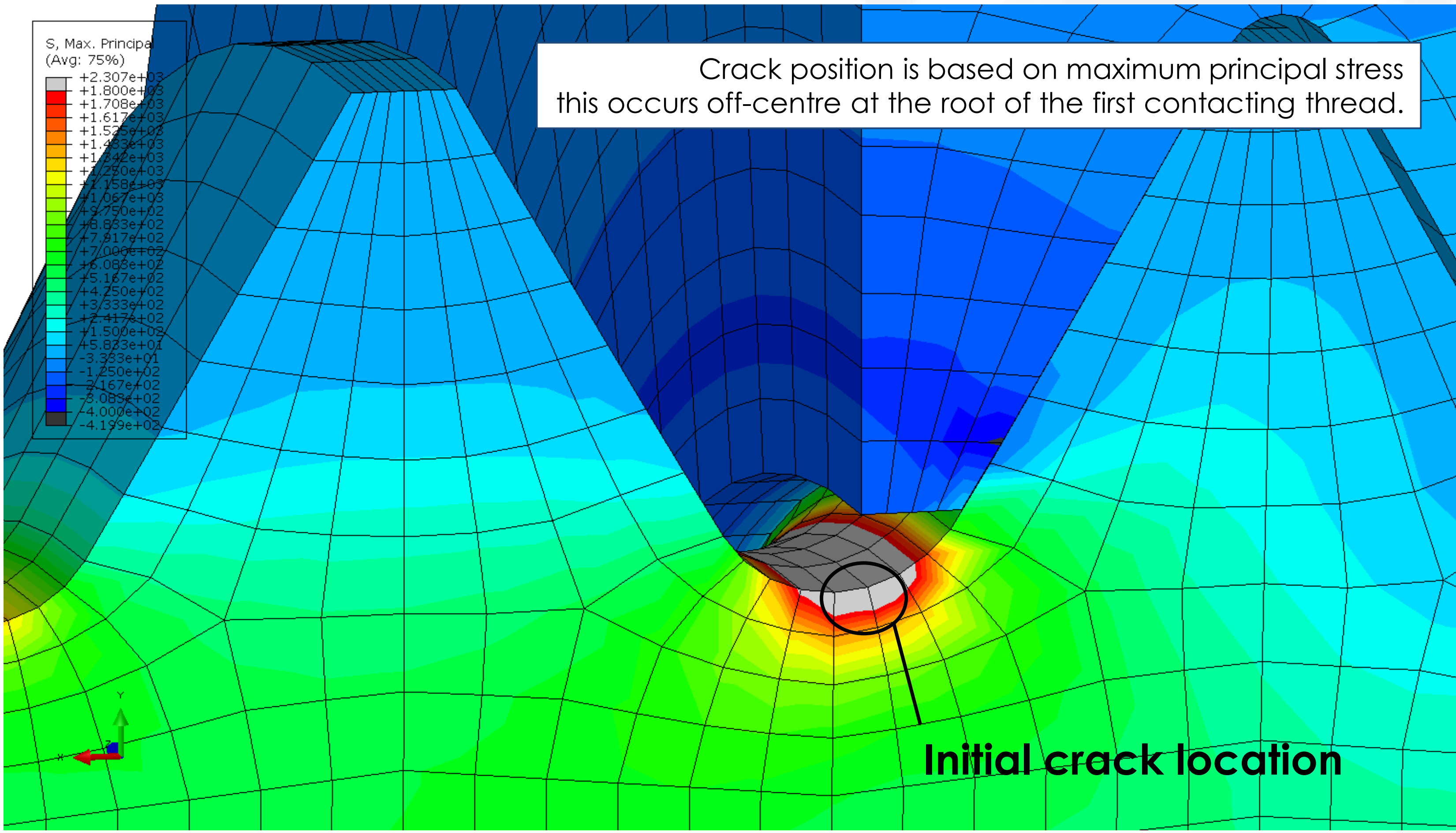


Example: Complex contact

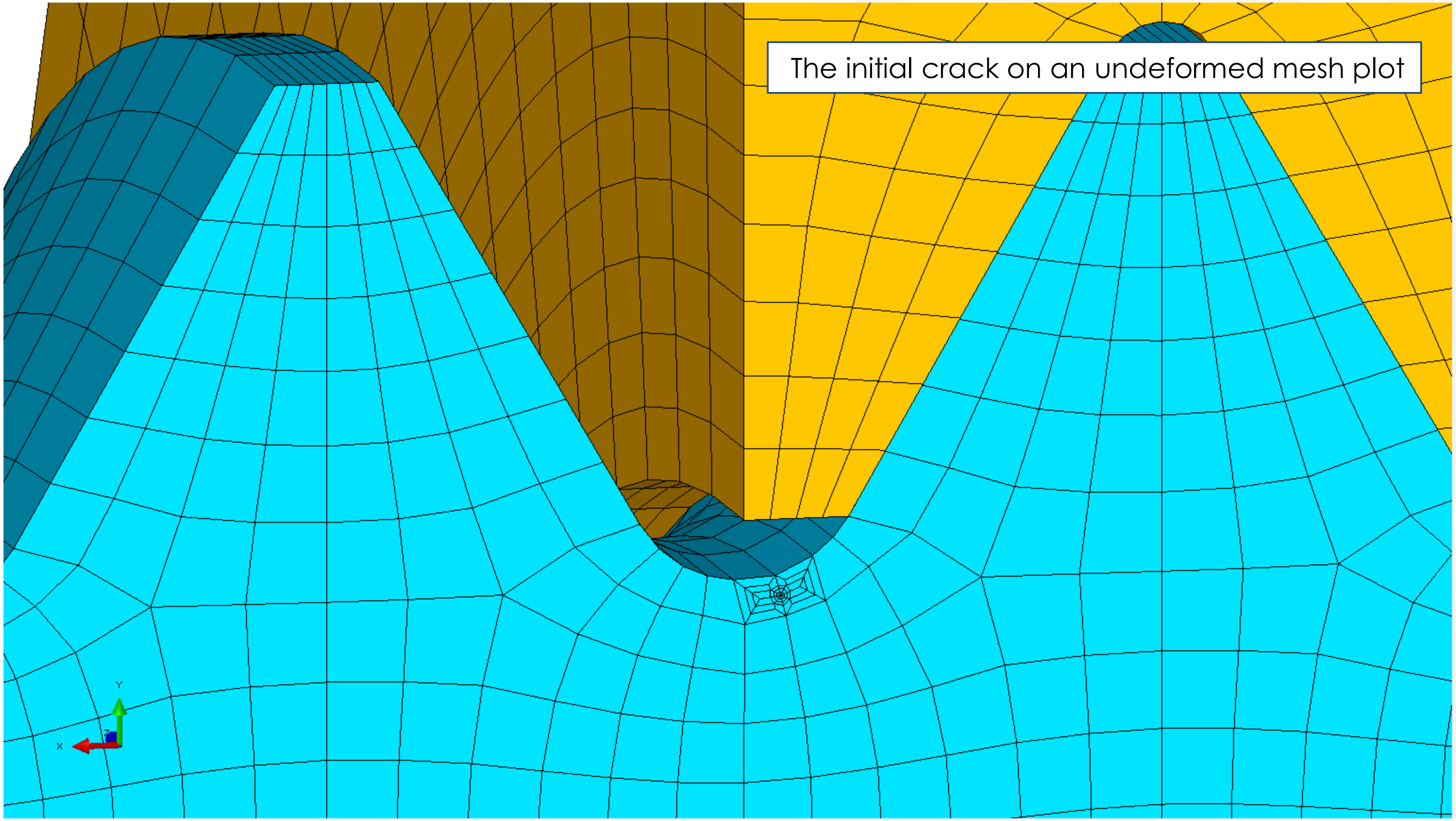
- Displacement constraints applied to load the component
- Constant amplitude fatigue cycle
  - zero-to-maximum load



Crack position

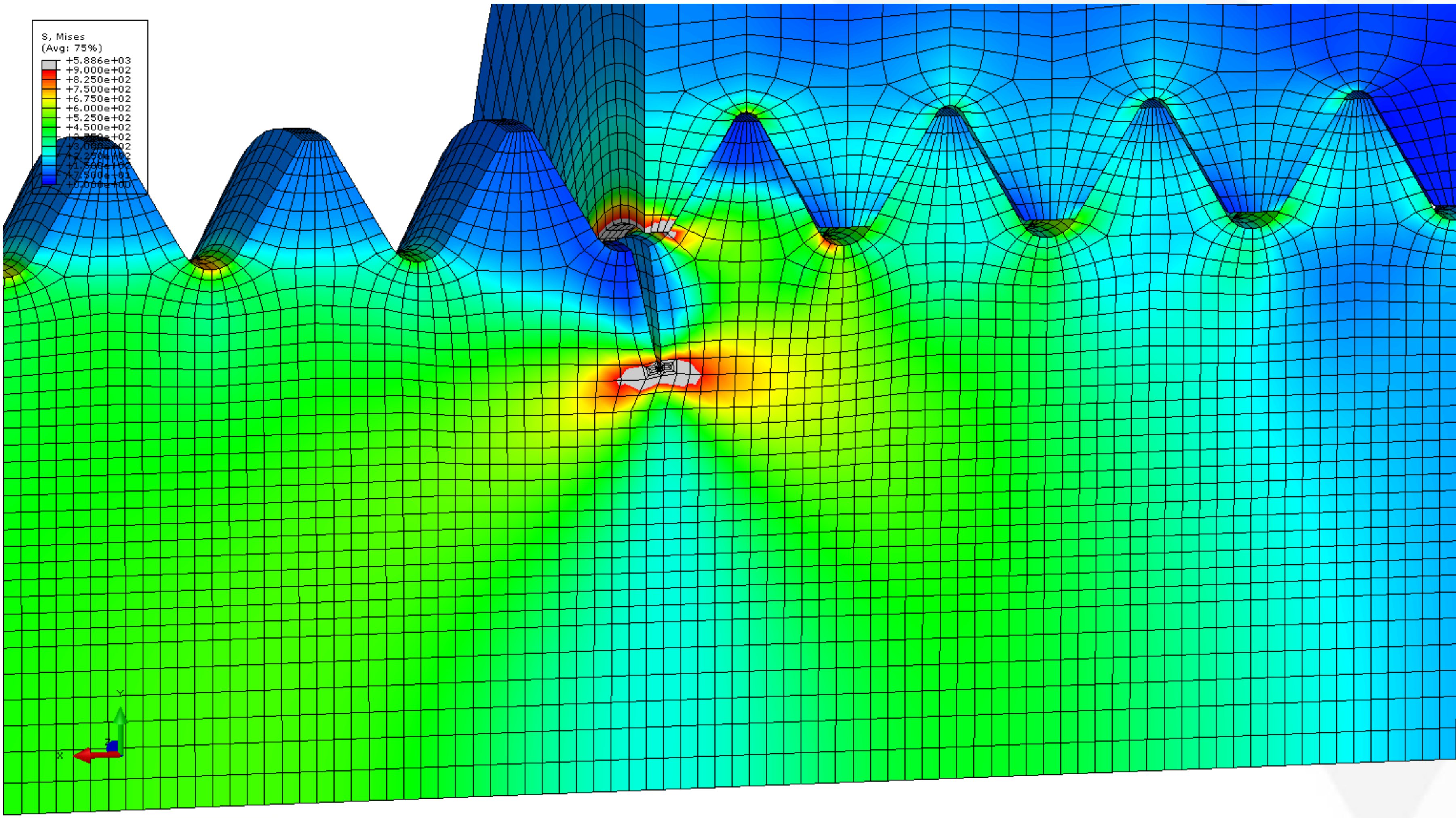


Initial crack



Load cycle for one crack position

Von mises stress, deformation x8 (through a load cycle)



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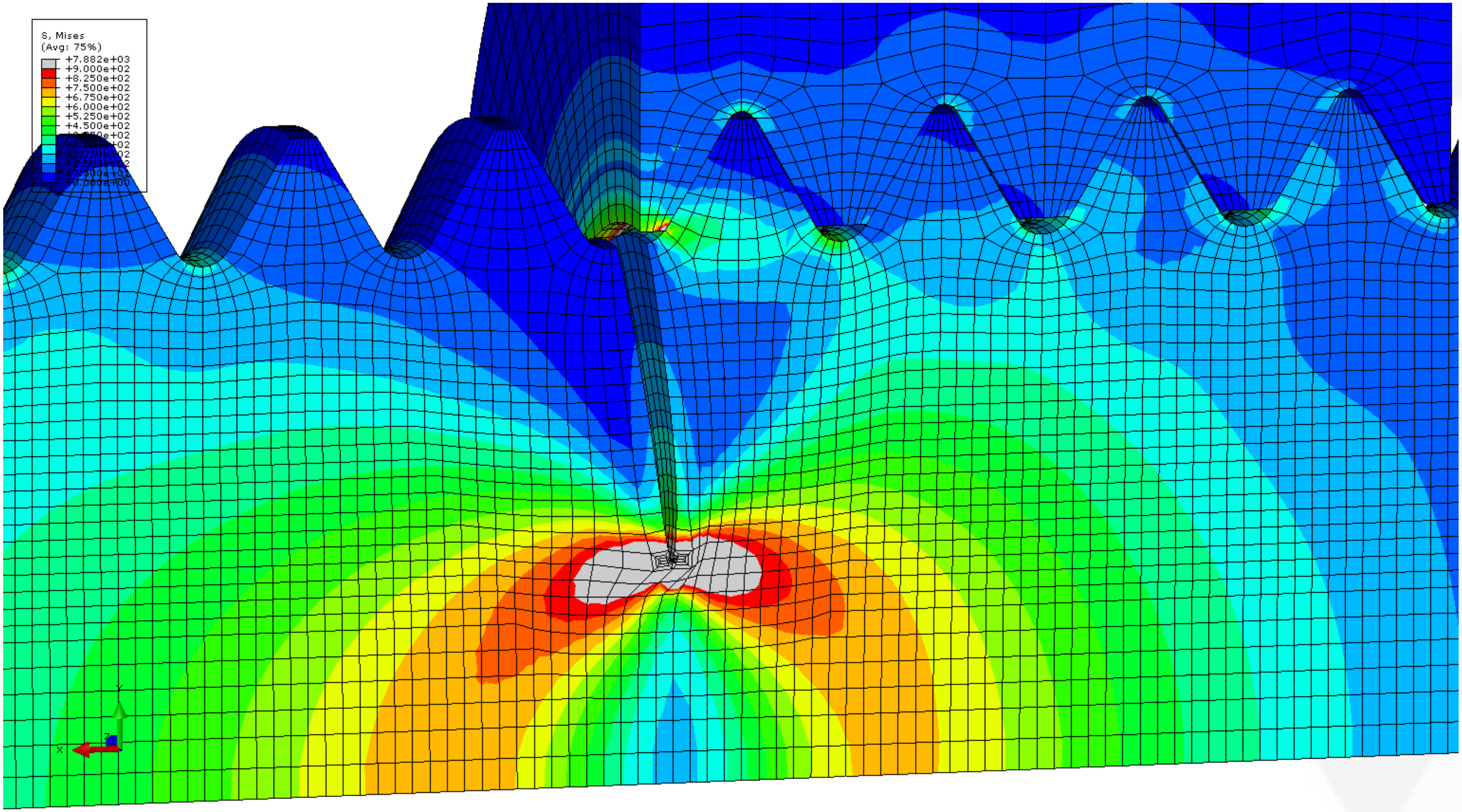
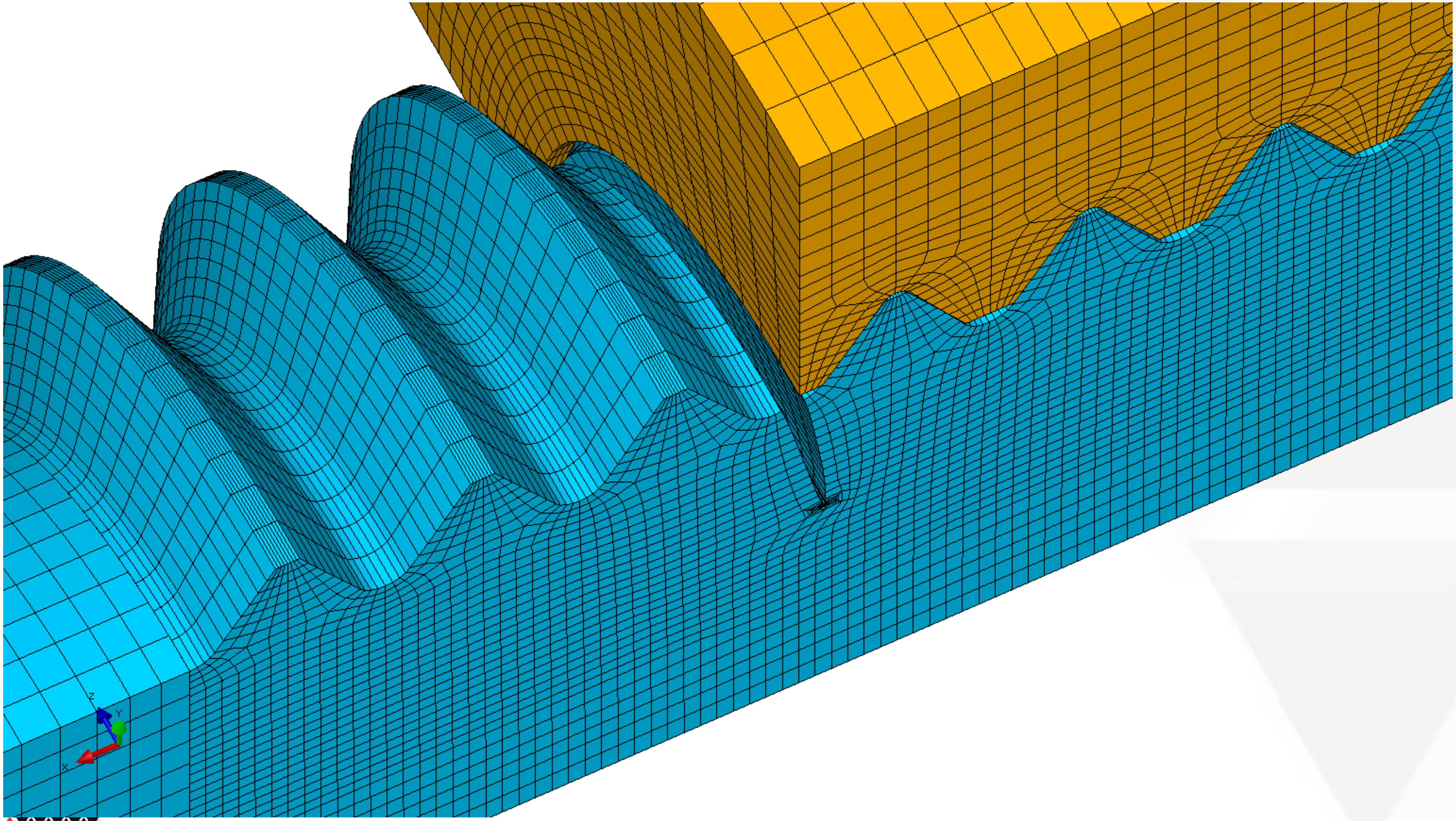
Crack growth

Von mises stress as the crack advances, deformation x8 (at max. load)



Crack growth

deformation x8 (at max. load)



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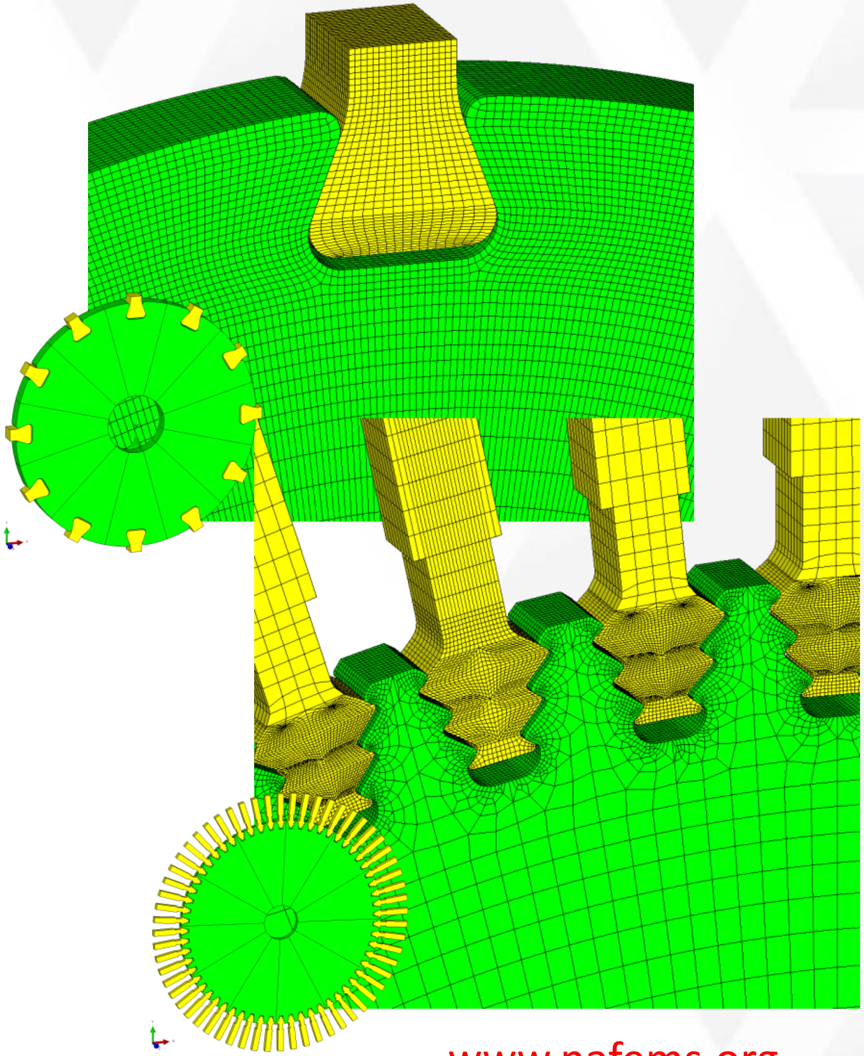
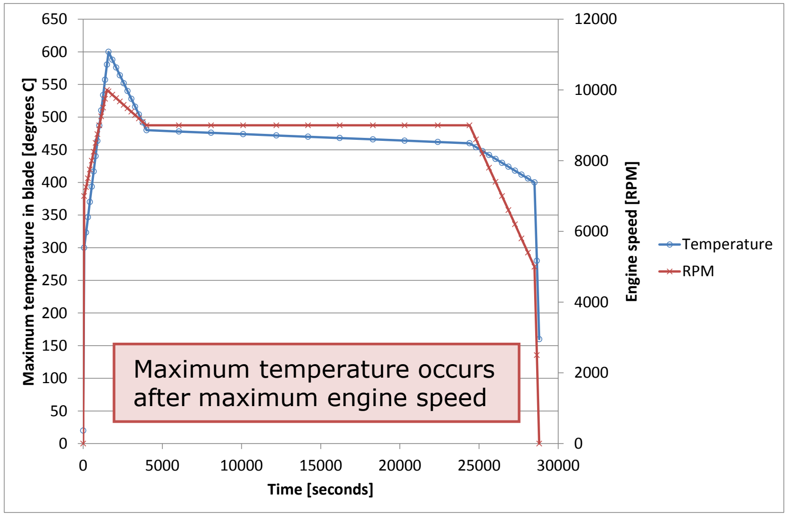
Example: Aero engine thermo-mechanical fatigue

- In addition to geometry issues, the loading at a blade/disk interface is complex:
  - Rotation forces
  - Blade aerofoil loads
  - Friction
  - Temperature distribution
  - Variation of loads and temperatures through a flight cycle
- In addition, for modelling purposes, displacement boundary conditions can be applied to represent adjacent structure

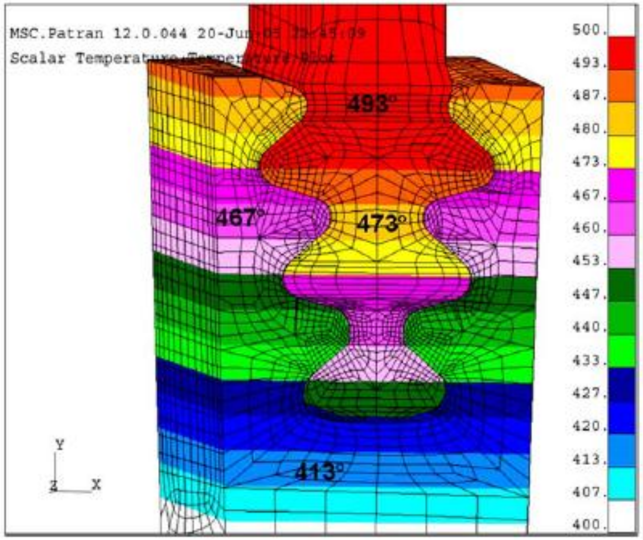


Model data

- Time and spatial temperature distribution
- Time varying loads



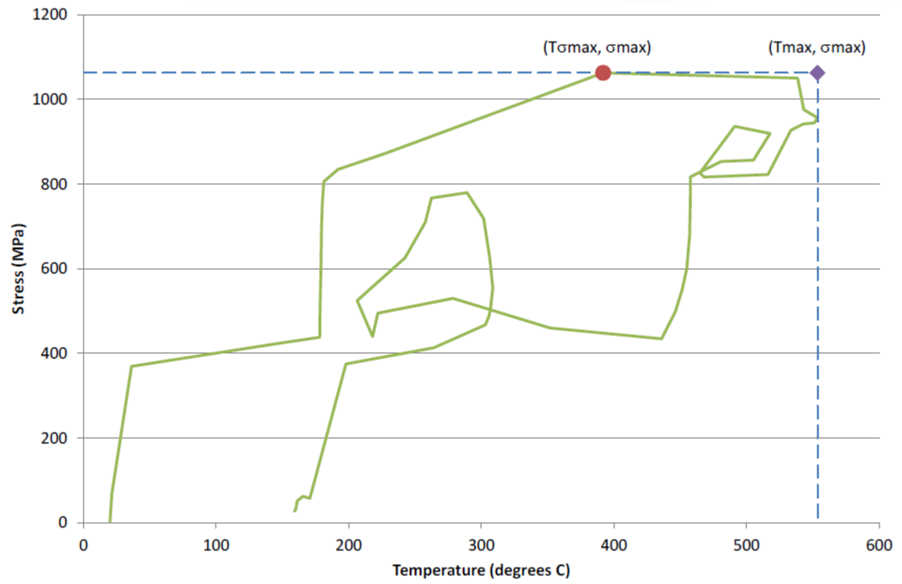
All spatial temperatures follow a time history (applied using Abaqus UTEMP subroutine)
Rotational speed also varies with time (applied using a *AMPLITUDE definition)



Spatial temperature distribution:
Failure analysis of turbine disc of an aero engine
Witek
Engineering Failure Analysis, 13 (2006) 9-17

Model data

- Temperature dependent material data and crack growth laws
  - Walker law, da/dn
  - COMET* equation for time dependent crack growth, da/dt
- Fatigue calculations use the “mean rate” method:

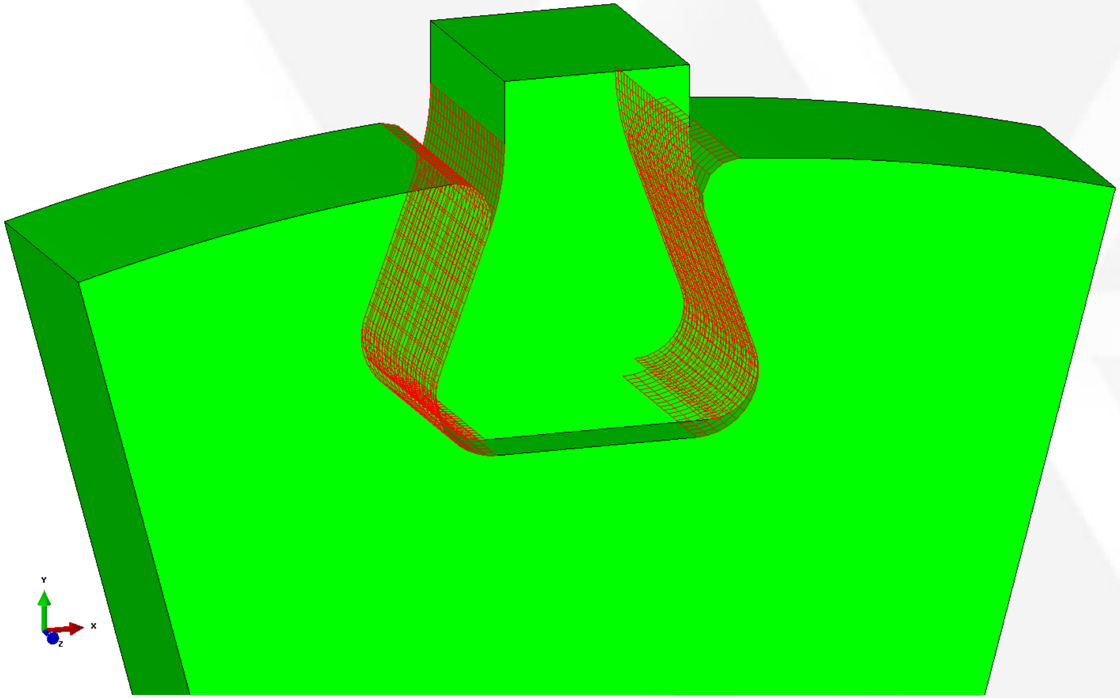


$$\left.\frac{da}{dn}\right|_{\substack{mean\,rate\\method}} = \frac{1}{2}\left[C_{T\sigma\max}\left(\Delta K_{eff}\right)^{n_{T\sigma\max}} + C_{T\max}\left(\Delta K_{eff}\right)^{n_{T\max}}\right]$$

* COMET crack growth law reference:
A Time Dependent Crack Growth Law for High Temperature Conditions
R. Chandwani, C. Timbrell (Zentech Int.Ltd.); D.W. MacLachlan, S.J. Williams (Rolls-Royce plc)
NAFEMS European Conference: Multiphysics Simulation 2012
16-17 October 2012, Frankfurt, Germany

Model data

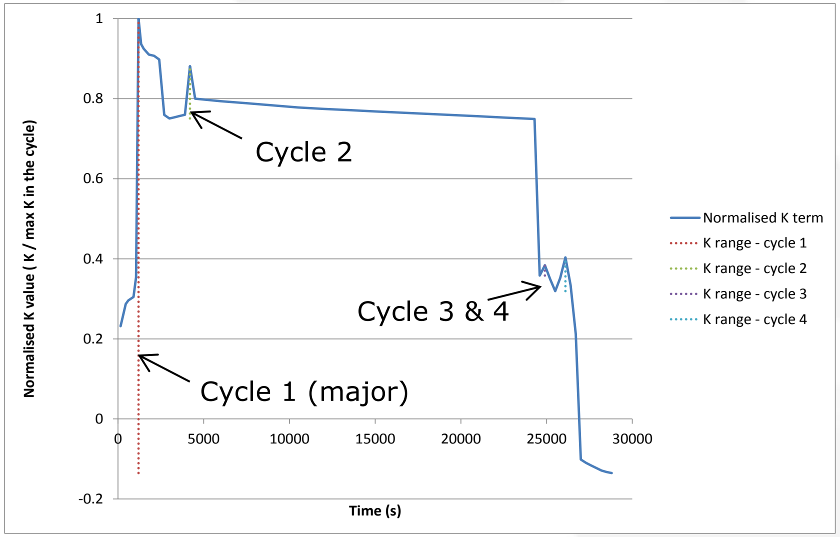
- Two contact pairs are defined between the blade and disk



- Effects not included in this simplified model but which can be included if required are:
  - No blade aerofoil loading is defined
  - No non-zero applied boundary displacements have been defined in this model

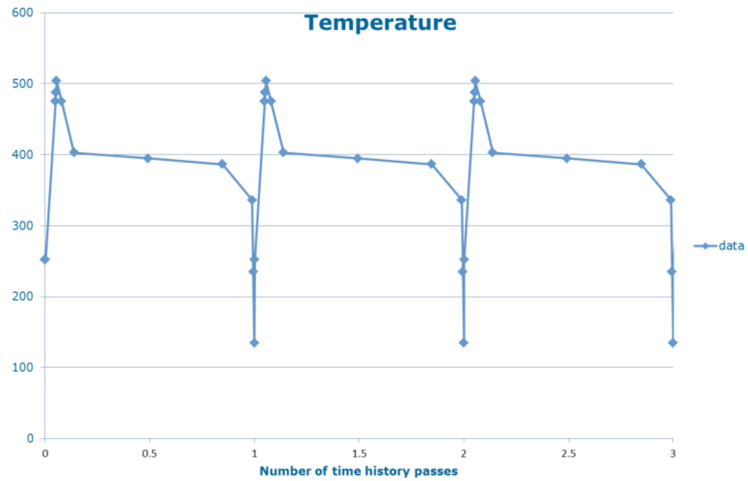
Load cycle analysis

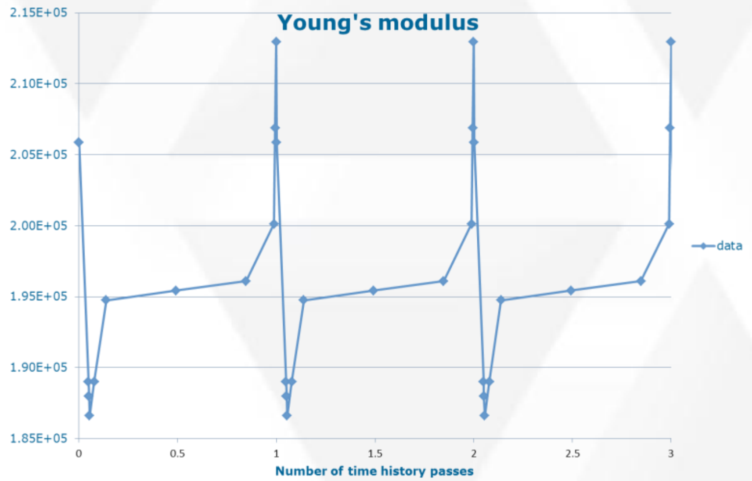
- A "full cycle" capability performs combined fatigue and time dependent crack growth
  - Load and temperature variations modelled in a multi-increment finite element analysis
  - Results extracted from each increment
  - Gives time history and rainflow counted fatigue cycles

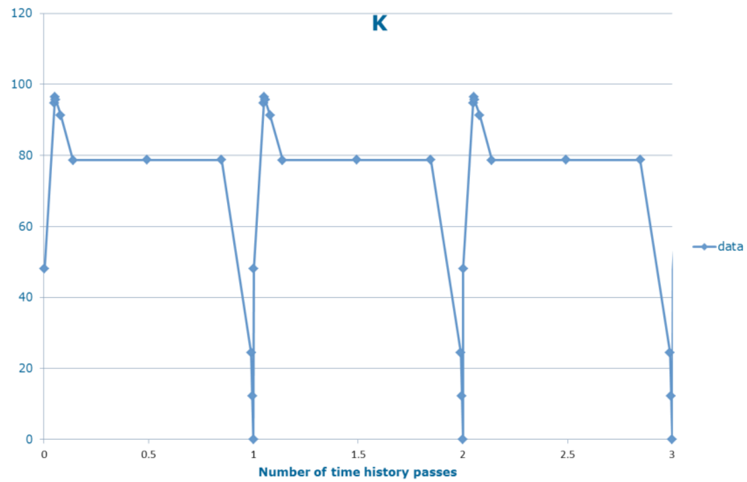


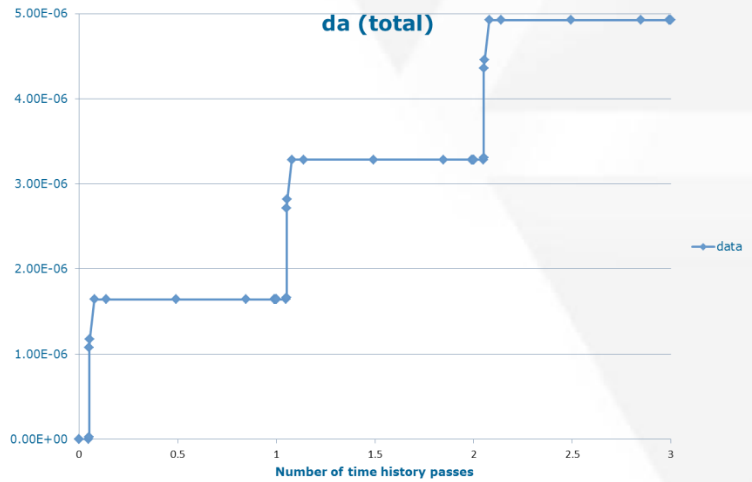
Example:
Extracted K vs time and the counted cycle positions
(four fatigue cycles within the overall load sequence)

Detailed output

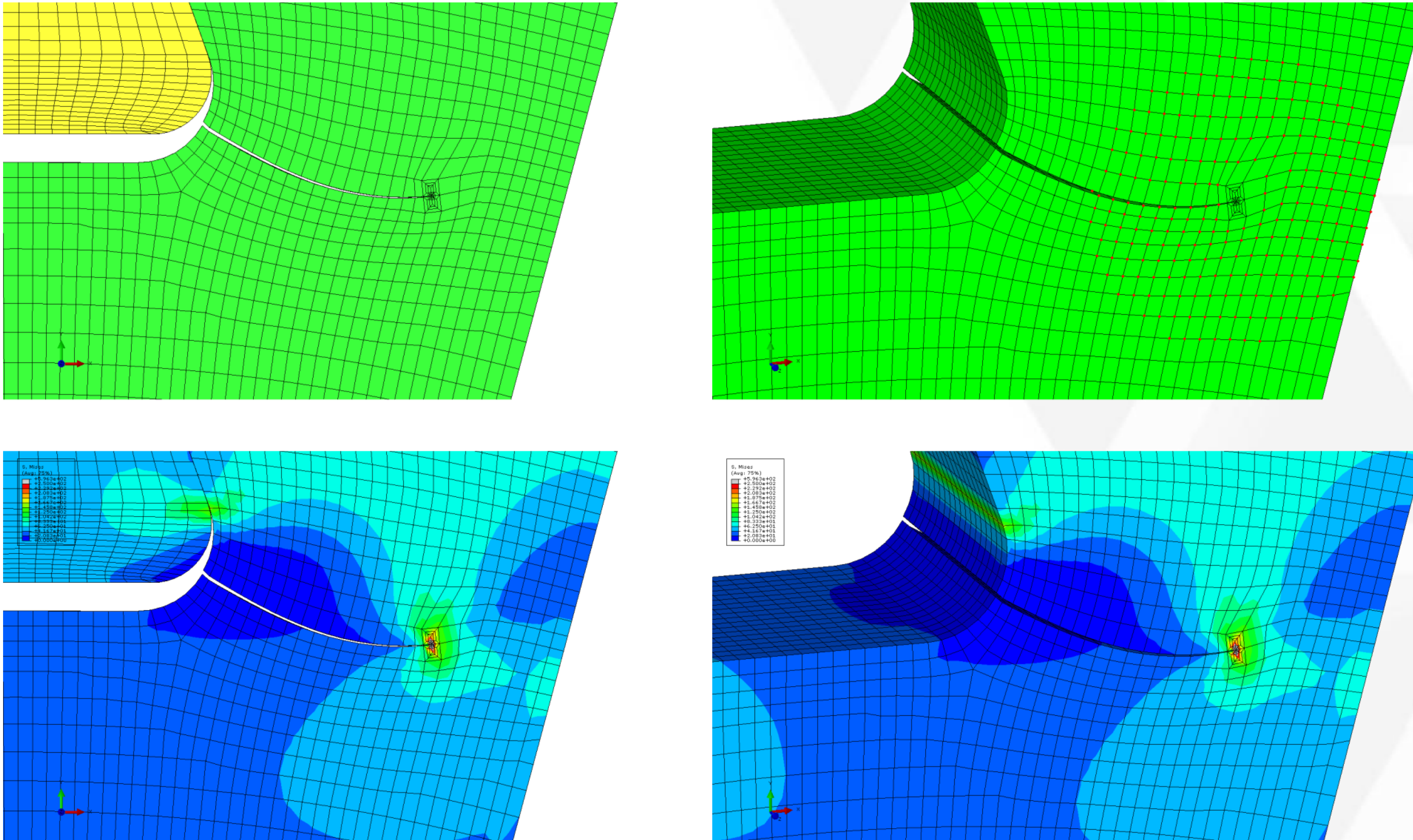








Through crack example



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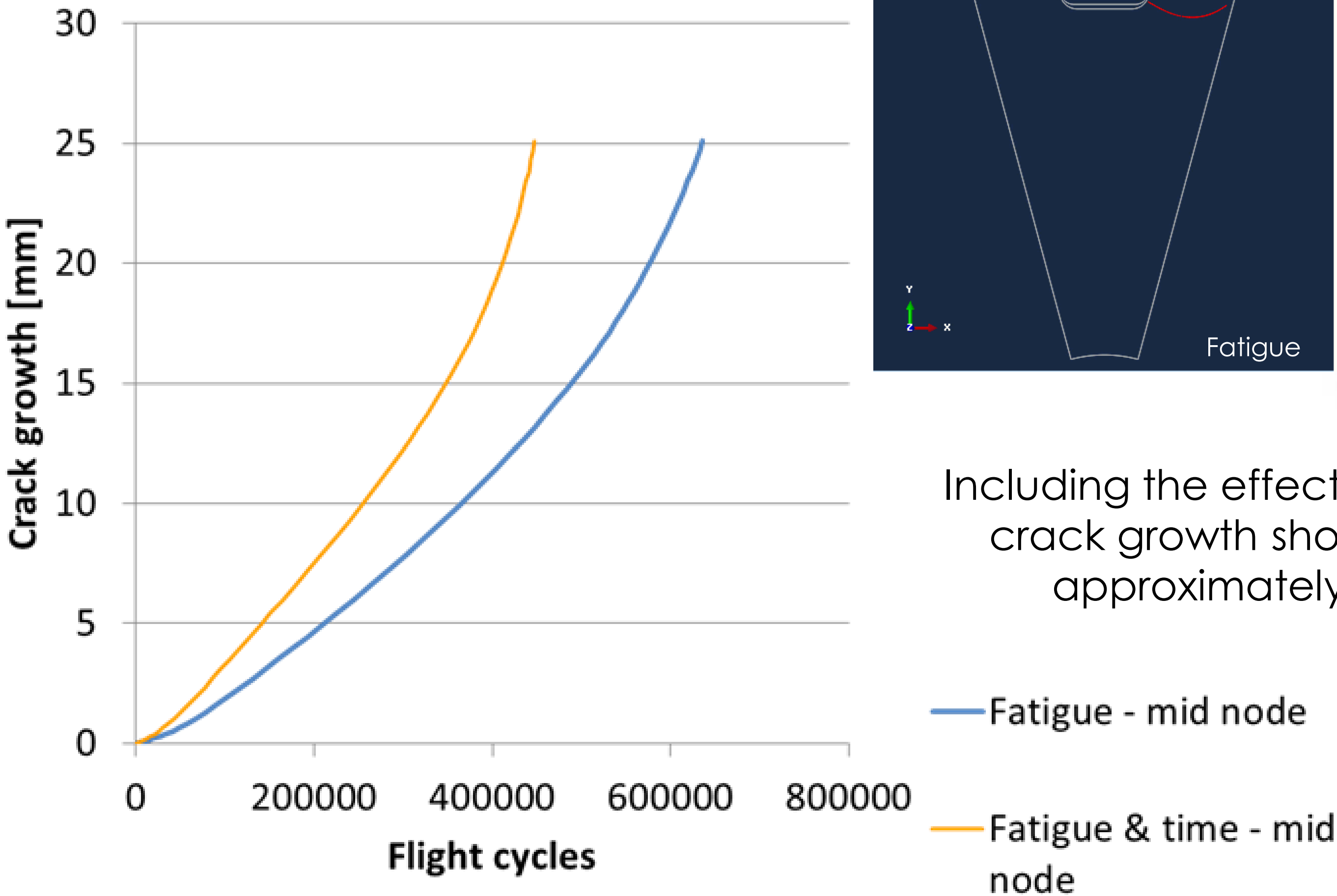
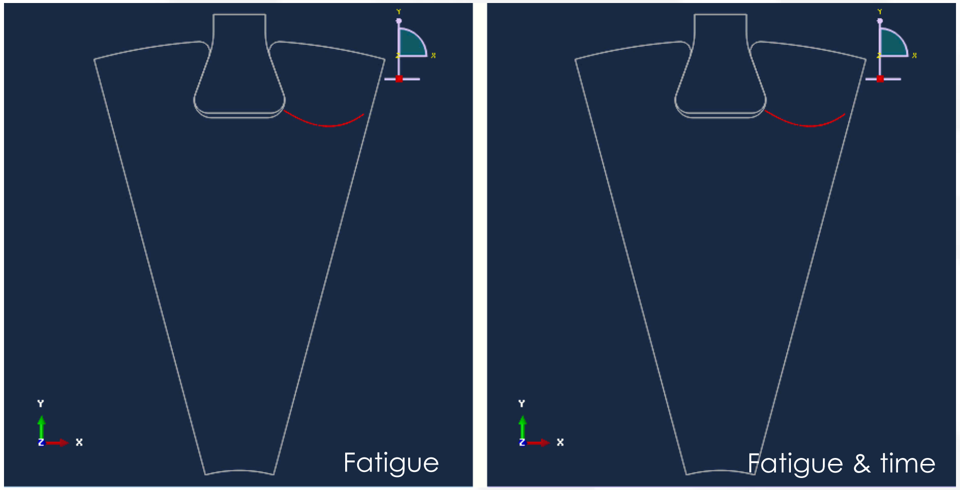
Through crack example





Including the effect of time dependent crack growth shows a reduction of approximately 25% in the life

Mid node = crack position half way through the disk thickness

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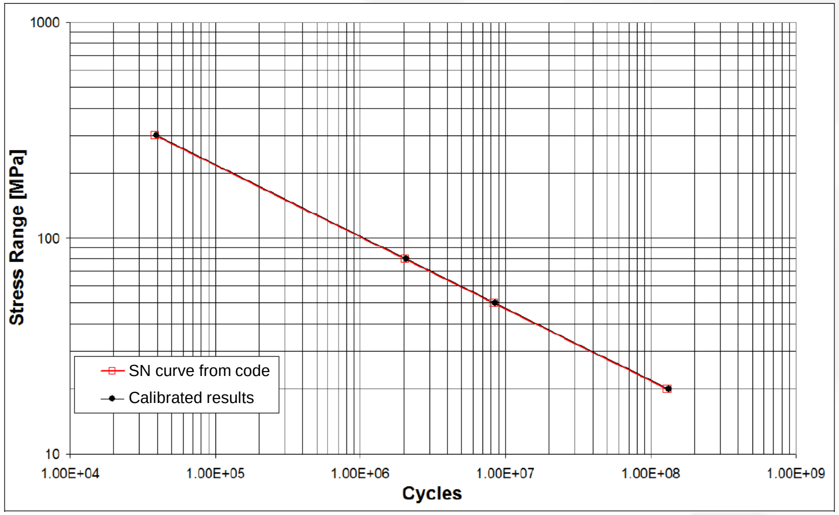
Example: Combining fracture mechanics with an SN approach

- Aim: Develop inspection regime
  - For an observed crack size the remaining life can be estimated from a calibrated model
- With reference to BS7910 for welded joints:
  - Calibrate a model to fit a selected quality category SN curve
    - Estimate an initial crack size to achieve the life stated by the curve for a range of load levels
    - May require modification of Paris coefficients



Summary

- The physical mechanism for fatigue is divided into two stages
  - Life to crack initiation
  - Life to propagate crack to failure
- Analysis method are also split into two stages
  - "Traditional" fatigue
  - Fracture mechanics based assessment
- A complete fatigue prediction could therefore use a combination of both methods:
  - Total Life = Life to crack initiation +
Life to propagate crack to failure