The University of Nottingham
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Plasticity 2020 – Cancun

Modelling the Influence of Plastic Deformation on Local Material Stiffness to Predict the Crack Growth Behaviour of a Nickel Based Superalloy

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University of Nottingham

Background

At present 3 Gtonnes of CO_2 are produced every year by air travel. This is completely unsustainable and is driving the need for greater efficiency in aeroengines.

Similar motivations are present in the power generation sector.

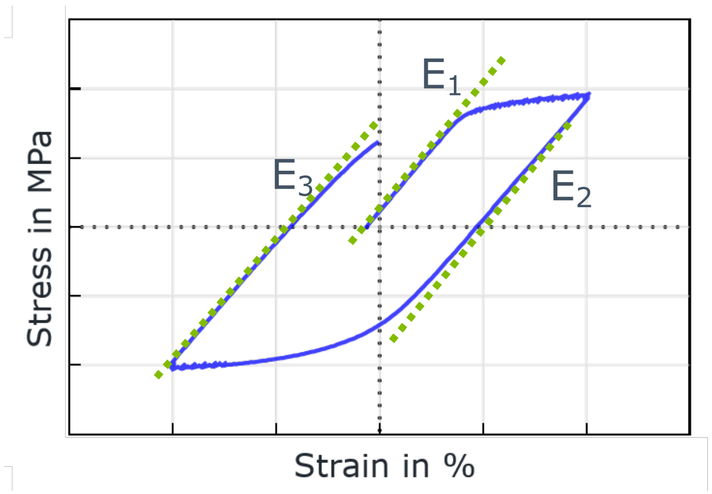
Future engineering systems are expected to utilise higher temperatures and lower component weights in order to meet targets.

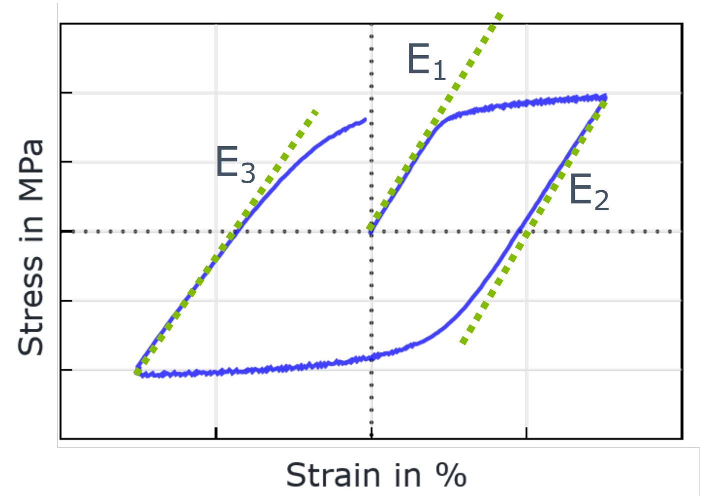
Much work is being carried out at UoN to increase service life of present and future critical components and reduce CO_2 emissions, by enabling more accurate predictions of design life and in-service behaviour.

Better understanding of the properties of the materials that drive the behaviour of them in service, along with modelling capabilities to represent this will lead to technological leaps.

Introduction

During LCF experimental testing of a Nickel-based superalloy, it was noticed that there was a cyclic decrease in Young's Modulus.





- $\varepsilon_{a,t}$ = 1 %, R = -1 & 700°C
- Decreasing Young's moduli: $E_1 > E_2 > E_3$
- $E_3 = 0.9E_1$
- After stabilisation, $E_{stab} = 0.87E_1$

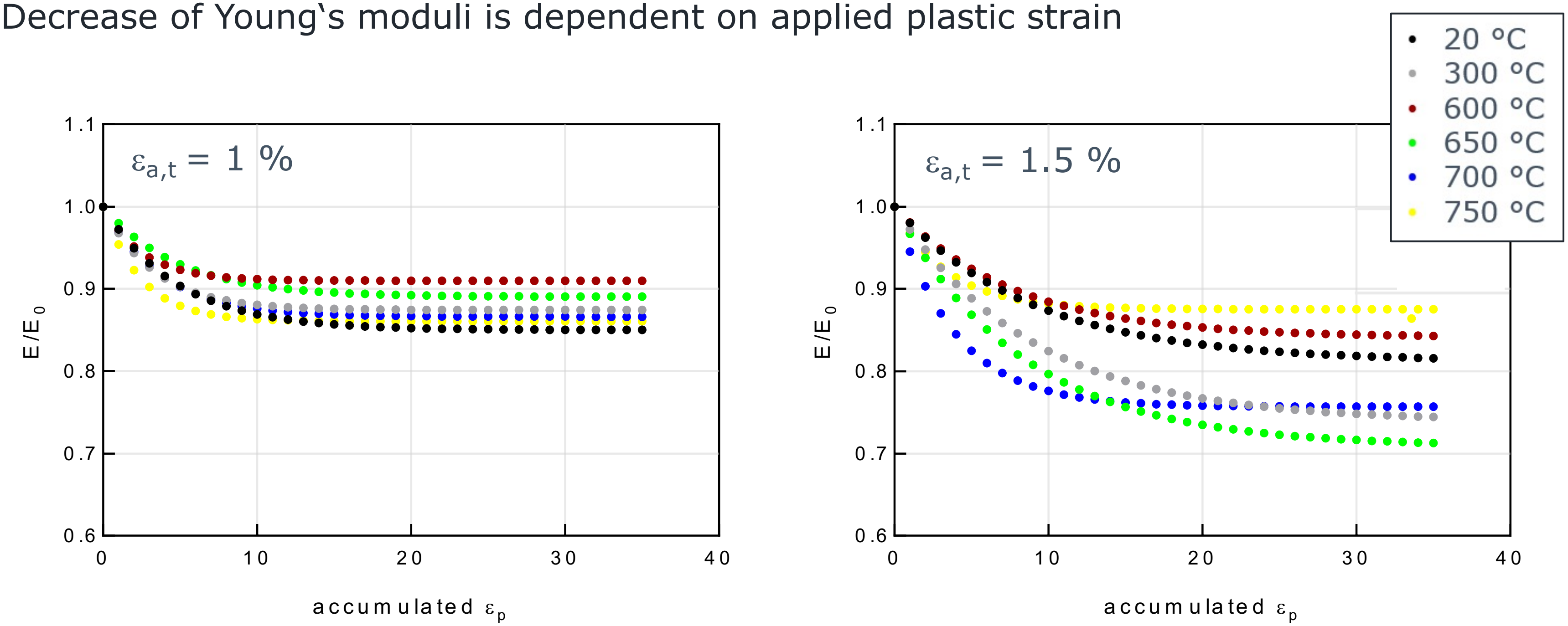
- $\varepsilon_{a,t}$ = 1.5 %, R = -1 & 700°C
- Decreasing Young's moduli: $E_1 > E_2 > E_3$
- $E_3 = 0.85E_1$
- After stabilisation, $E_{stab} = 0.75E_1$

Observation

For tests with no induced plasticity ($\varepsilon_{a,p} \approx 0$), no measurable change in Young's modulus was observed.

Therefore, plasticity induced changes in elastic properties are present

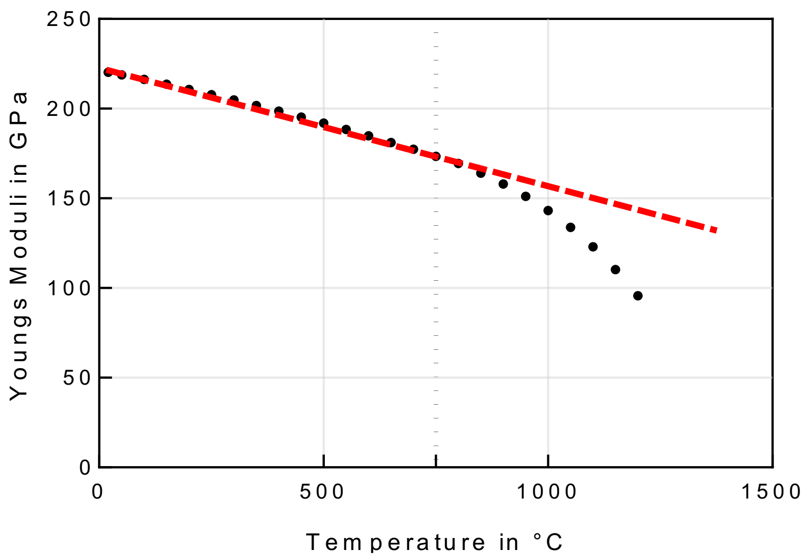
Decrease of Young's moduli is dependent on applied plastic strain



Characterisation

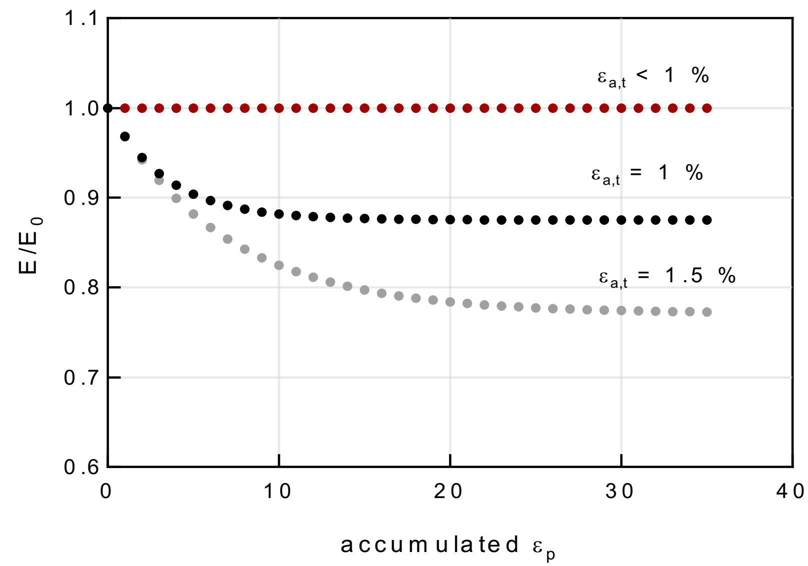
- Step 1: Calculation of the initial Young's modulus E_0 As a function of temperature (from tensile testing).
  - Up to 750 °C a linear behaviour can be assumed:

$$E_0 = \mathrm{a} \cdot \mathrm{T} + \mathrm{b}$$



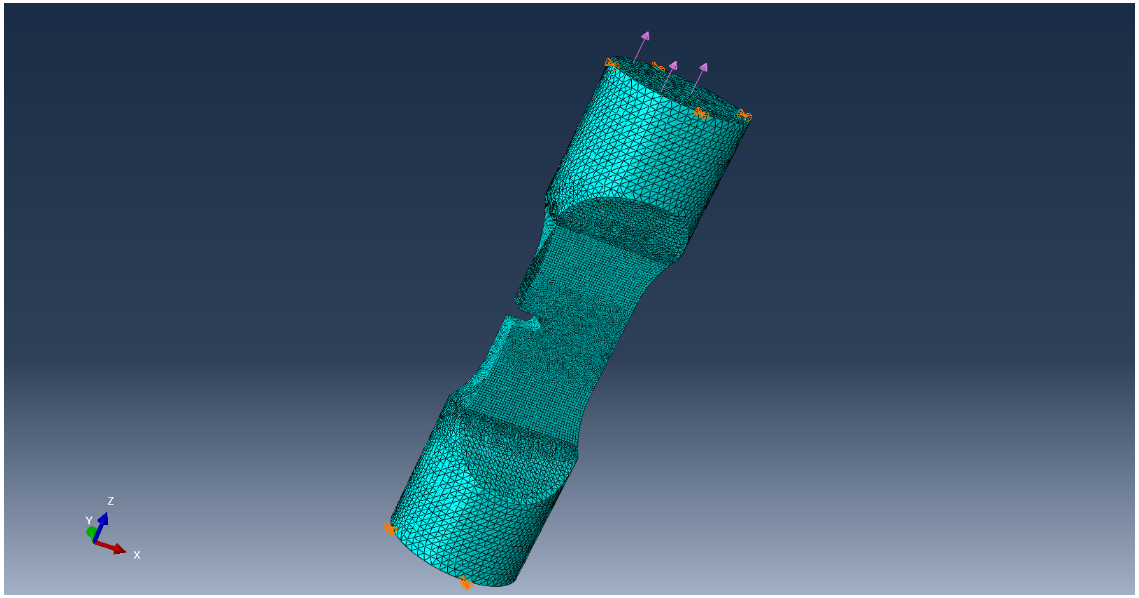
- Step 2: Determination of a function to represent the decrease in Young's modulus as a function of accumulated plastic strain:

$$E = 1 - (\mathrm{c} \cdot (1 - \exp(-d \cdot \varepsilon_p)) \cdot E_0$$



Aim

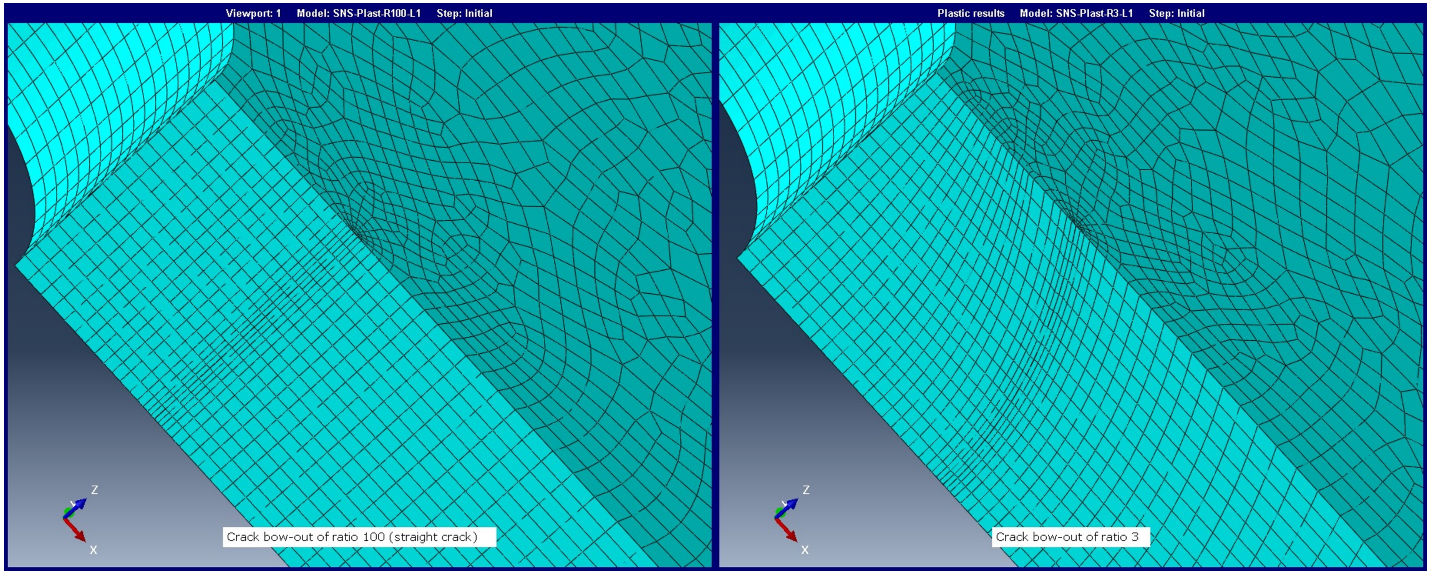
Model the effect of the experimentally observed plasticity-induced changes in elastic properties on crack growth behaviour (through the lens of SIF).



SEN specimen considered for the study

Methodology

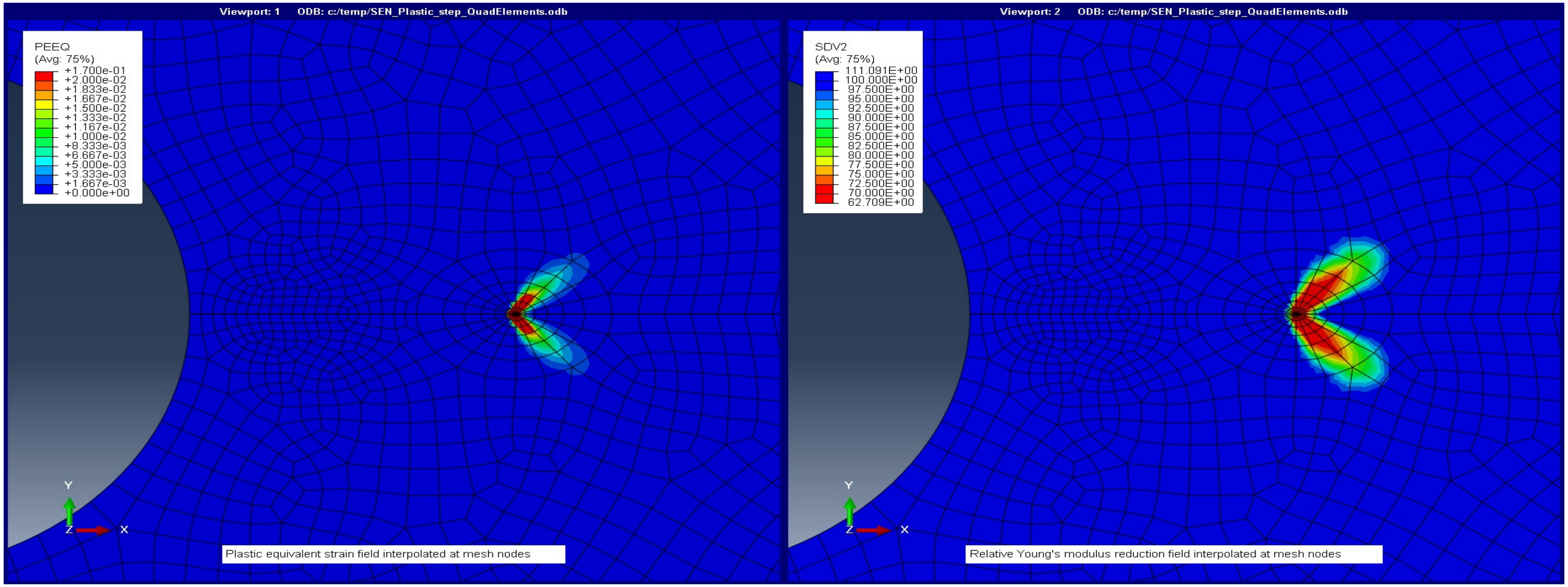
- Abaqus FEM simulation
- Two-step sequential simulation:
  1. Plastic model to extract plastic strain
  2. Elastic model (with modified Young's modulus field as a function of local plastic strain) to extract SIF using contour integral method
- Cracks of different (tunnelling) geometries have been modelled



Procedure

1st Step: Plastic analysis

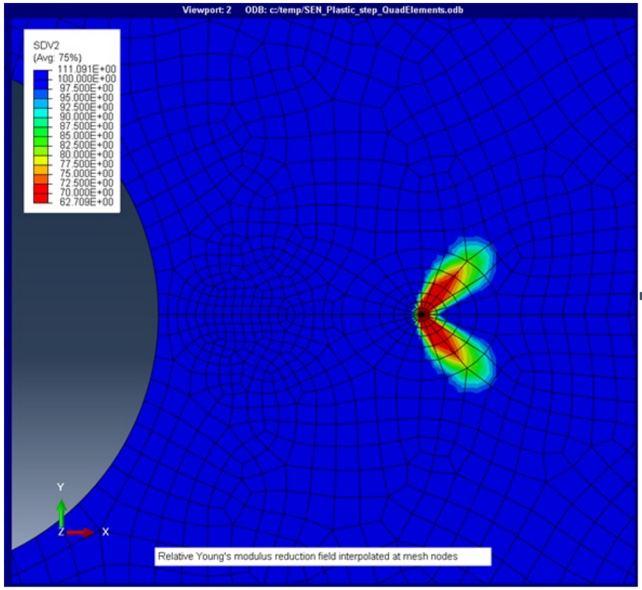
- Plastic model at the neighbourhood of the crack
- Subroutine USDFLD used to evaluate the Young's Modulus as a function of PEEQ

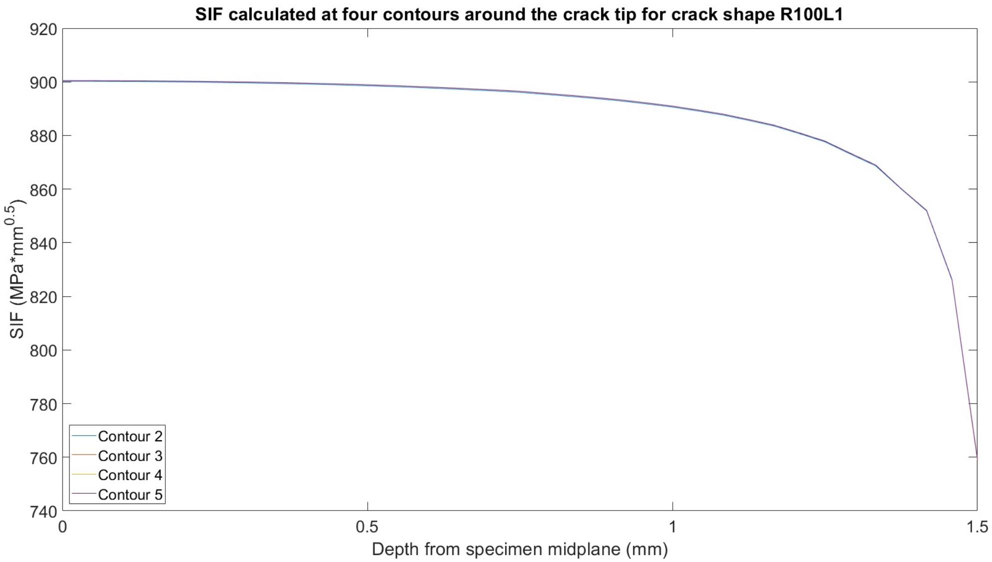


Procedure

2nd Step: Elastic analysis

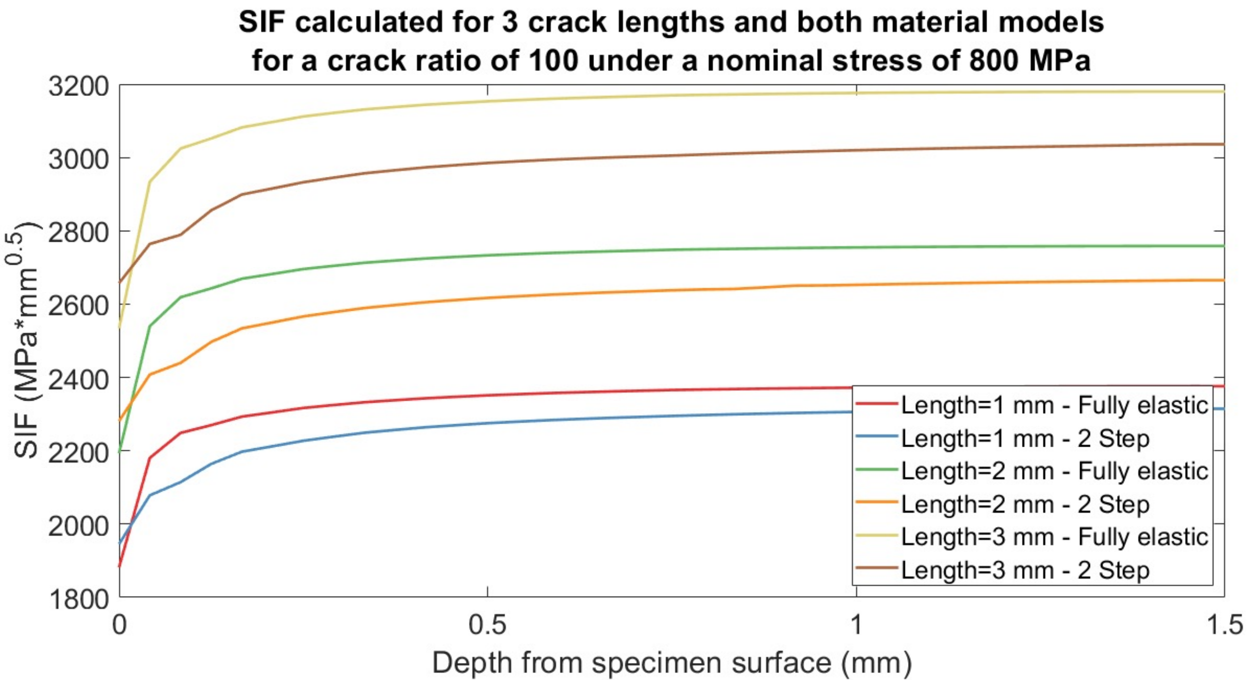
- Elastic model with varying E at crack neighbourhood
- E reduction field obtained from plastic step
- SIF calculated through contour integrals

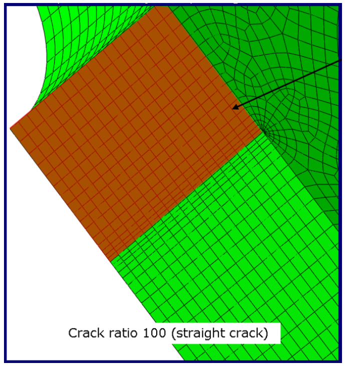




Results

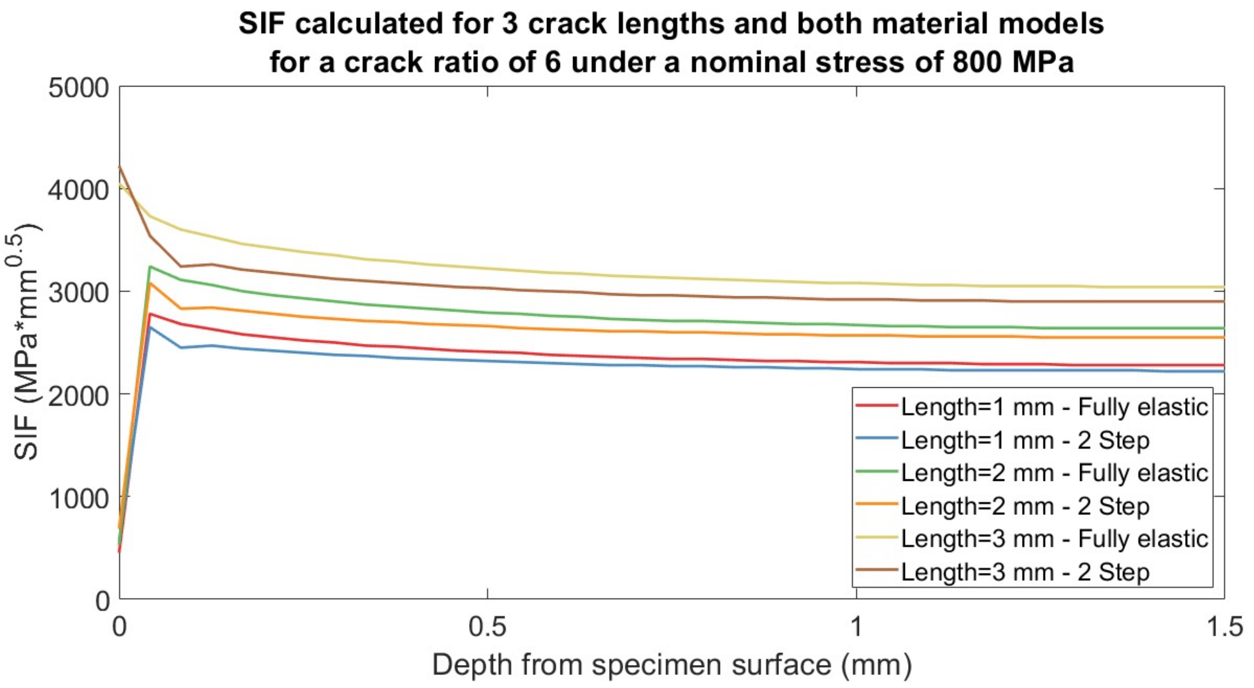
800 MPa for 1 mm pre-crack, straight crack

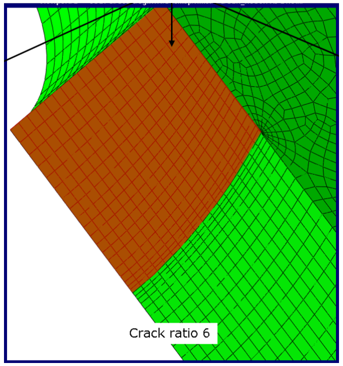




Results

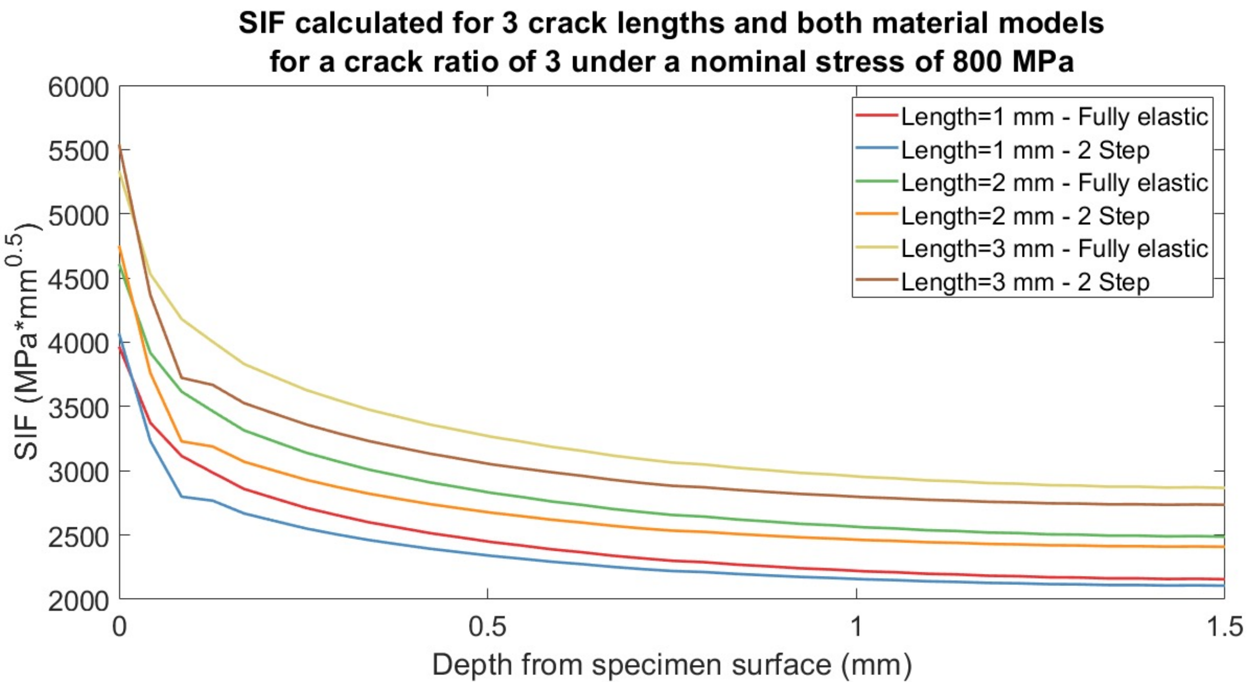
800 MPa for 1 mm pre-crack, low tunnelled crack

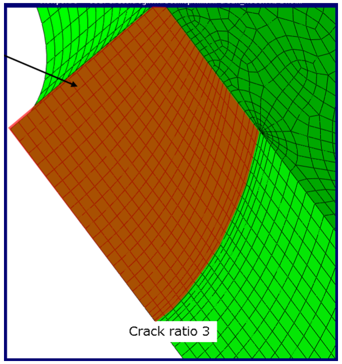




Results

800 MPa for 1 mm pre-crack, high tunnelled crack





Conclusions

- During LCF experimental testing of a Nickel-based superalloy, it was noticed that there was a cyclic decrease in Young's Modulus.
- For tests with no induced plasticity, this change in Young's modulus was not observed. Therefore, plasticity induced changes in elastic properties are present and are a function of applied plastic strain.
- This has been applied to SEN FE simulations via a plastic strain dependant Young's modulus field in the specimen geometry.
- Even for relatively small decreases in Young's modulus, effects are consistently observed on the stress intensity factor at the crack tip.
- Relative impact of the decrease seems to be tied to the shape of the crack
  - The flatter the crack the higher the observed difference (load shedding)

Further developments

- Microstructural determination of the cause of this apparent decrease in Young's modulus (thought to be the pinning and subsequent bowing of dislocations during plasticity).
- Comparison of FE calculated SIFs for SEN geometries to be compared with experimental results.

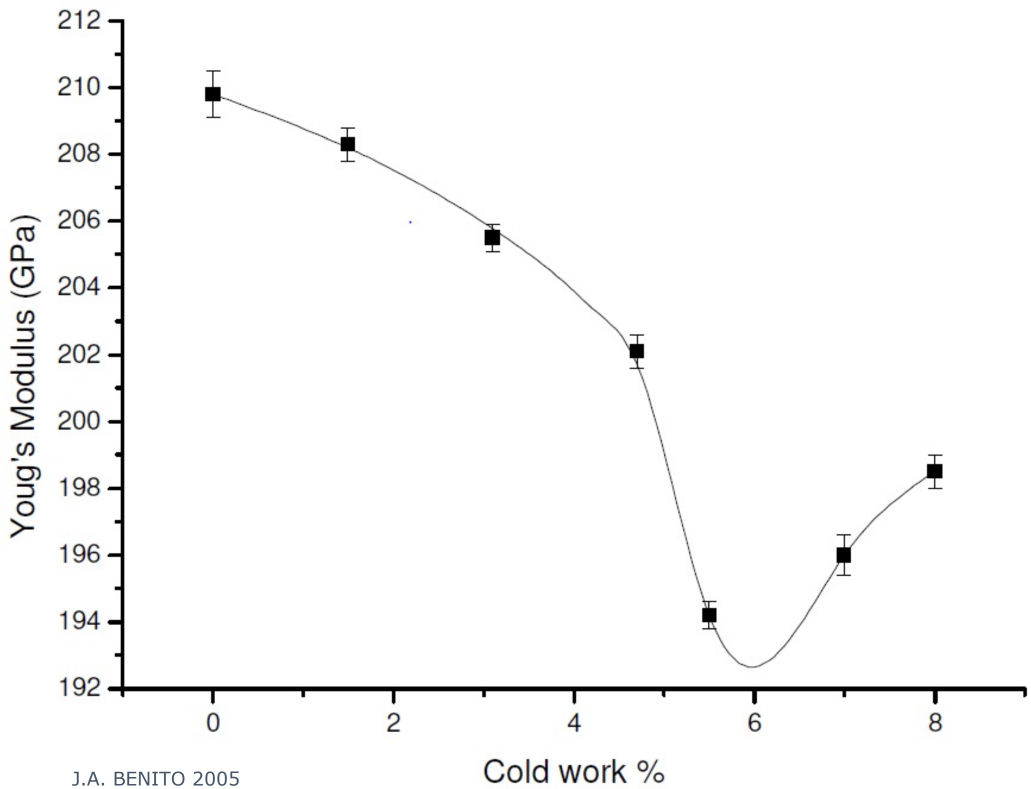
Thank You for Your Attention.
Any Questions?

Literature Review – Changes in Young's Moduli

- Changes in Young's Moduli in dependence of plastic strains up to 15 % are known for:
  - Pure iron, low carbon steels, stainless steel, aluminium, brass, copper, stainless steel
  - At room temeprature and very high plastic strains in tension tests (no cyclic testing)
  - Effects are mostly attributed to dislocation distribution (no effect of texture, resiudal stresses)

DevTMF

Where does the decrease come from? – Literature Review



J.A. BENITO 2005

$$\frac{\Delta E}{E} = -\rho \cdot \frac{l^2}{6 \cdot \alpha}$$

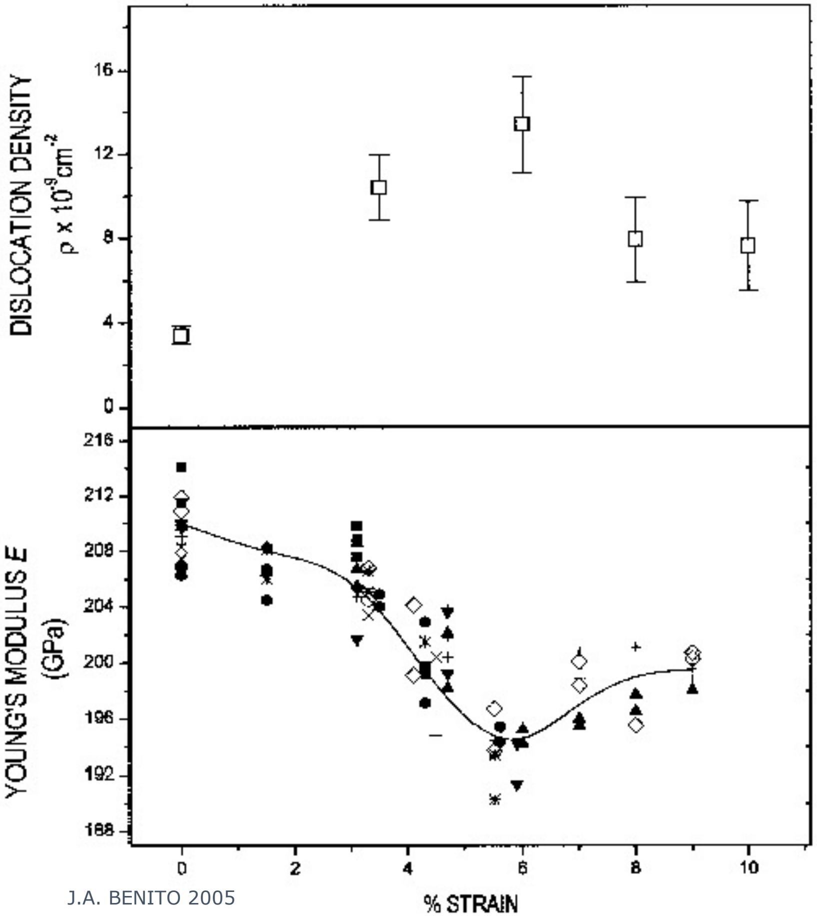
ρ: dislocation density

l : is the average length line of dislocations between pinning points

α: is a function of l

DevTMF

Pure Iron in tensile test



J.A. BENITO 2005

Their conclusion:

Increase of plastic strain leads to increase in dislocation density

Dislocation form a bow out while formation of cellular arrays, which gives additional strain → decreases Youngs Moduli

Recovery attributed to no new formation of cellular dislocation distribution

Benchmarking Abaqus results

- Comparison to 2D formulas from the literature
  - Jintegral : Bucci et al. 1972
  - SIF: Evans et al. 2014
- Comparison to 3D formulas from the literature
  - SIF : Newmann, Raju 1984

Benchmarking : Bucci et al. 1972

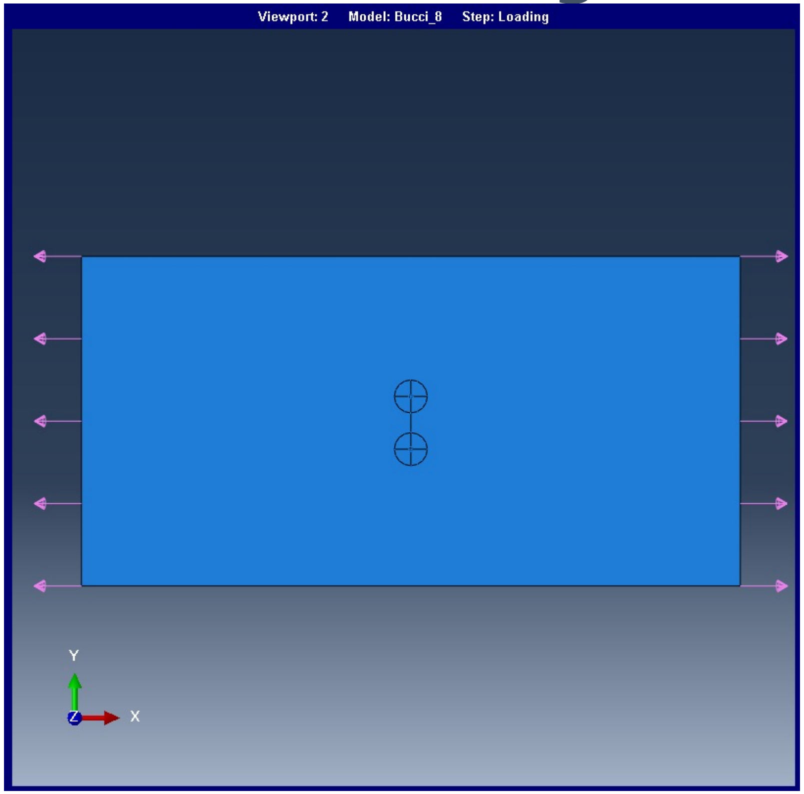


Figure 3 : Geometry considered by Bucci et al.

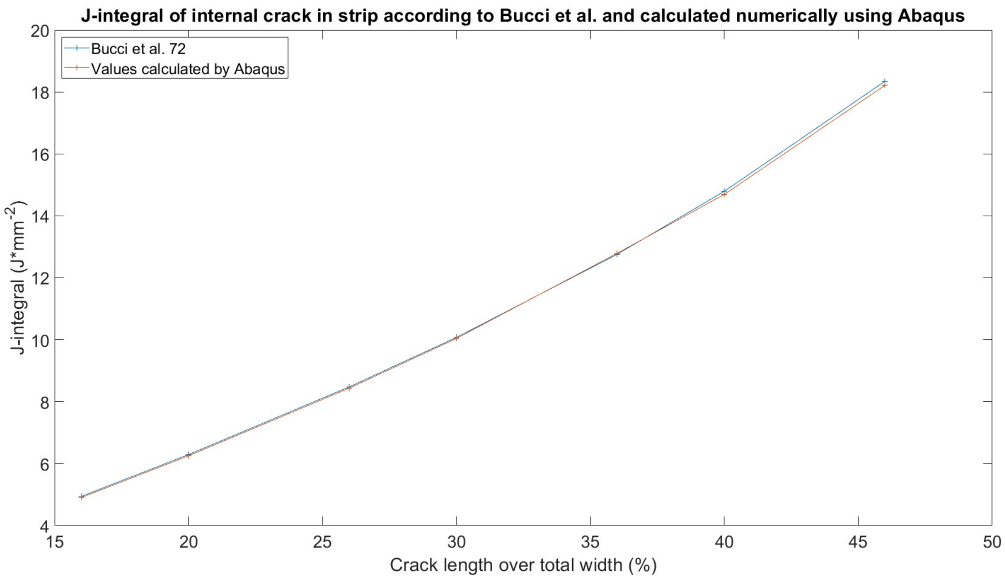


Figure 4 : Results computed with the Bucci formula and by Abaqus

Benchmarking : Evans et al. 2014

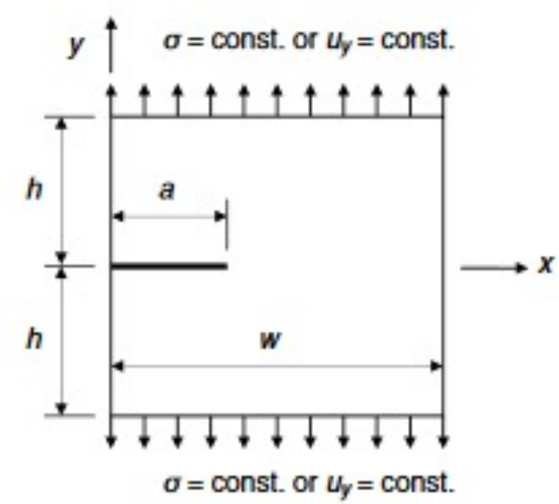


Figure 5 : Geometry considered by Evans et al.

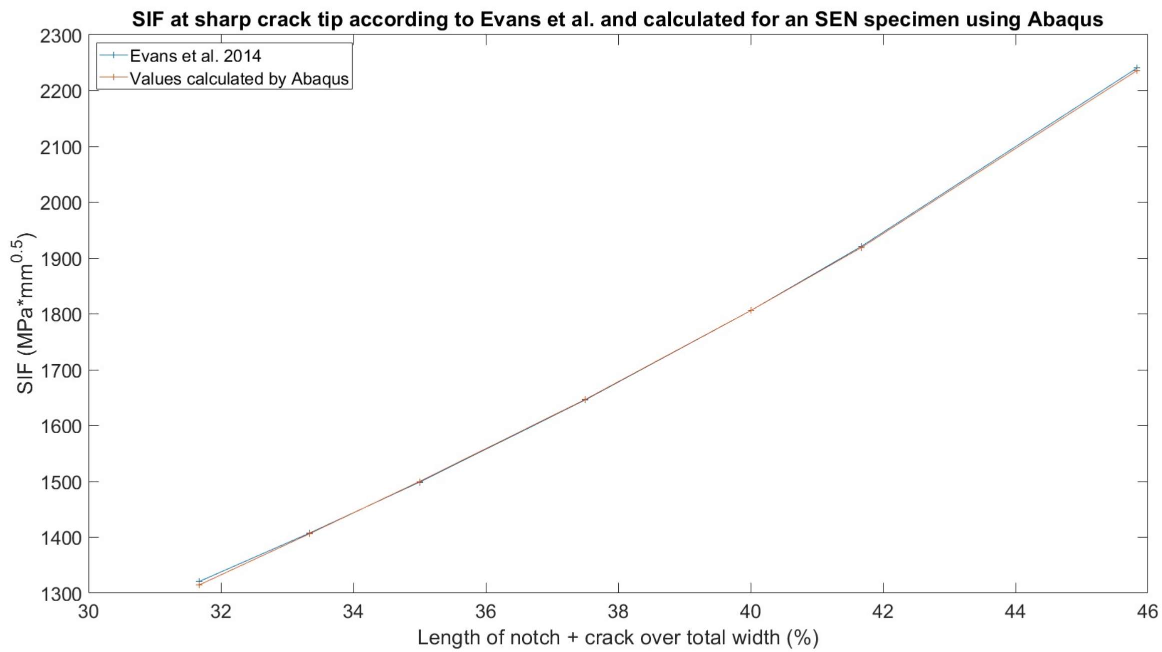
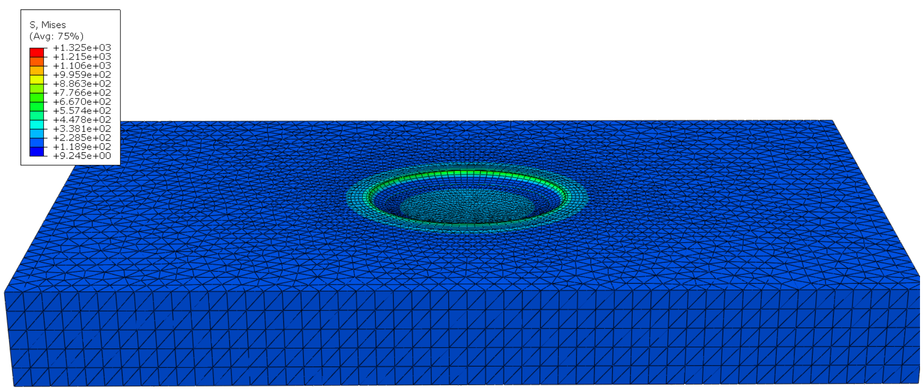
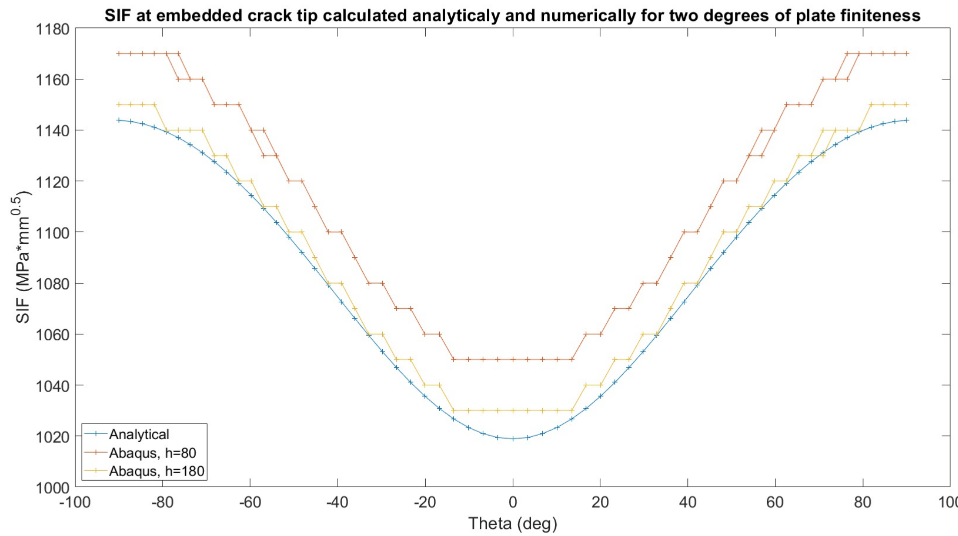


Figure 6 : Results computed with the Evans formula and by Abaqus

Benchmarking : Newman and Raju 1972





Newman and Raju

Figure 8 : Results computed with the Newman-Raju formula and by Abaqus

Simplifications

- Exploiting planes of symmetry

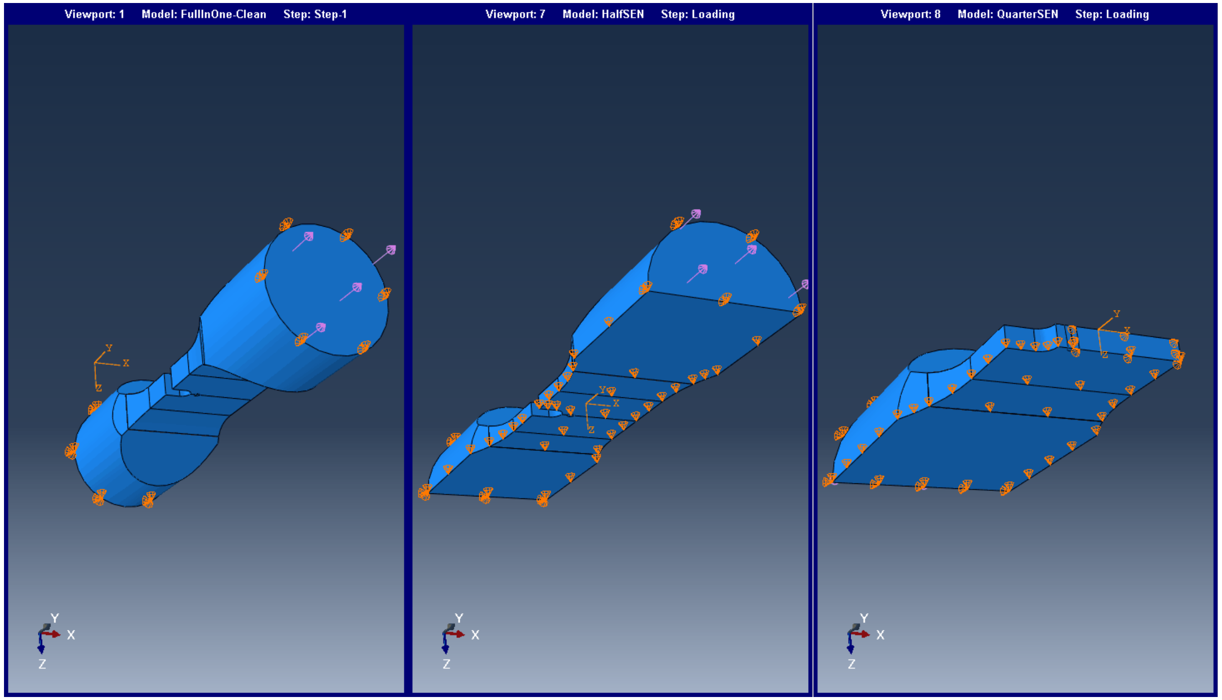


Figure 9 : Three models exploiting various symmetry planes

Simplifications : exploiting planes of symmetry

- Comparing SIF for all three models

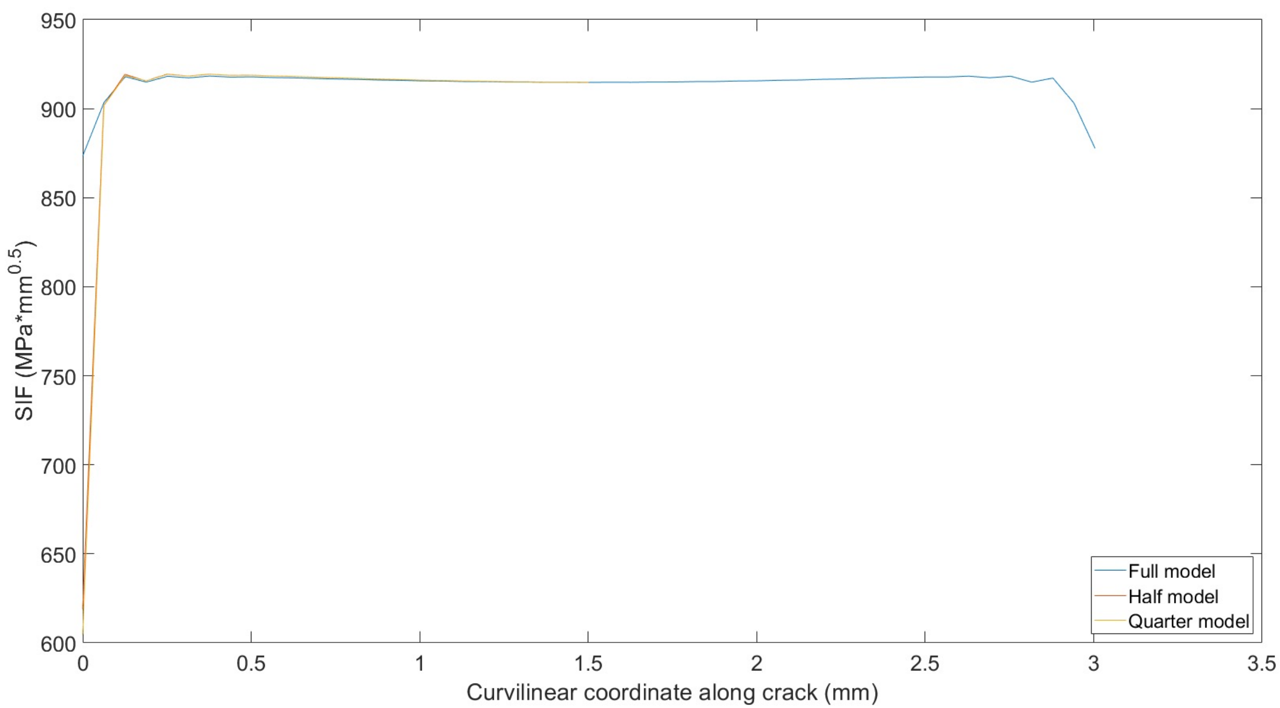


Figure 10 : SIF calculated for the three models

Simplifications : Exploiting planes of symmetry

- Comparing maximum von Mises equivalent stress

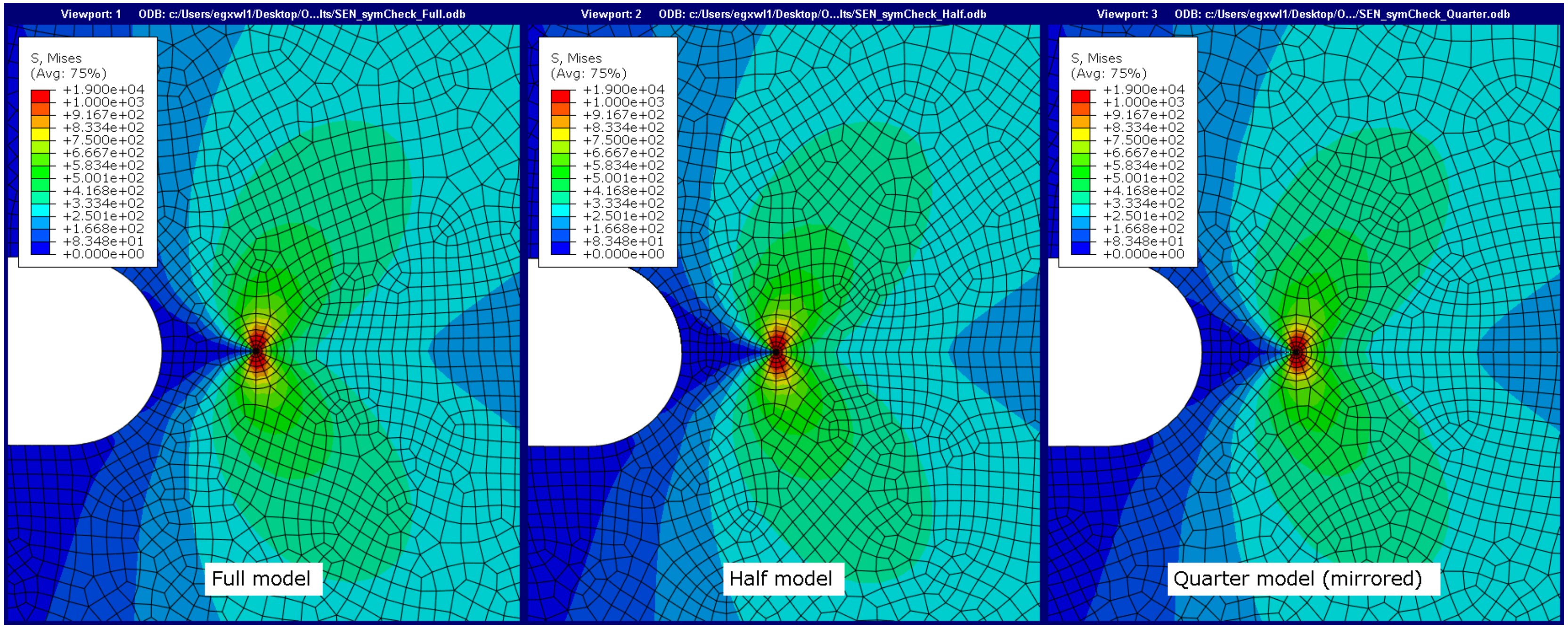


Figure 11 : Max. principal stress calculated for the three models

Simplifications

- Ignoring geometric non-linearity

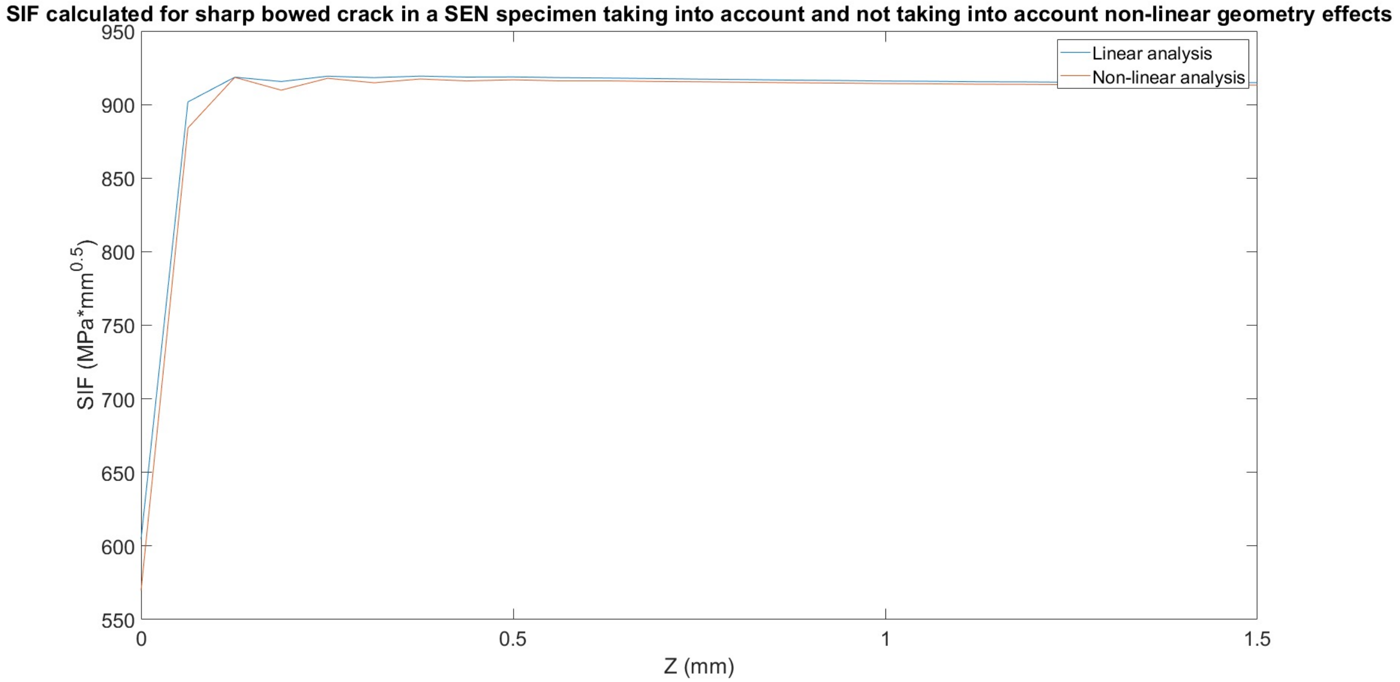


Figure 12 : SIF calculated with and without considering geometric non-linearity

Mesh convergence

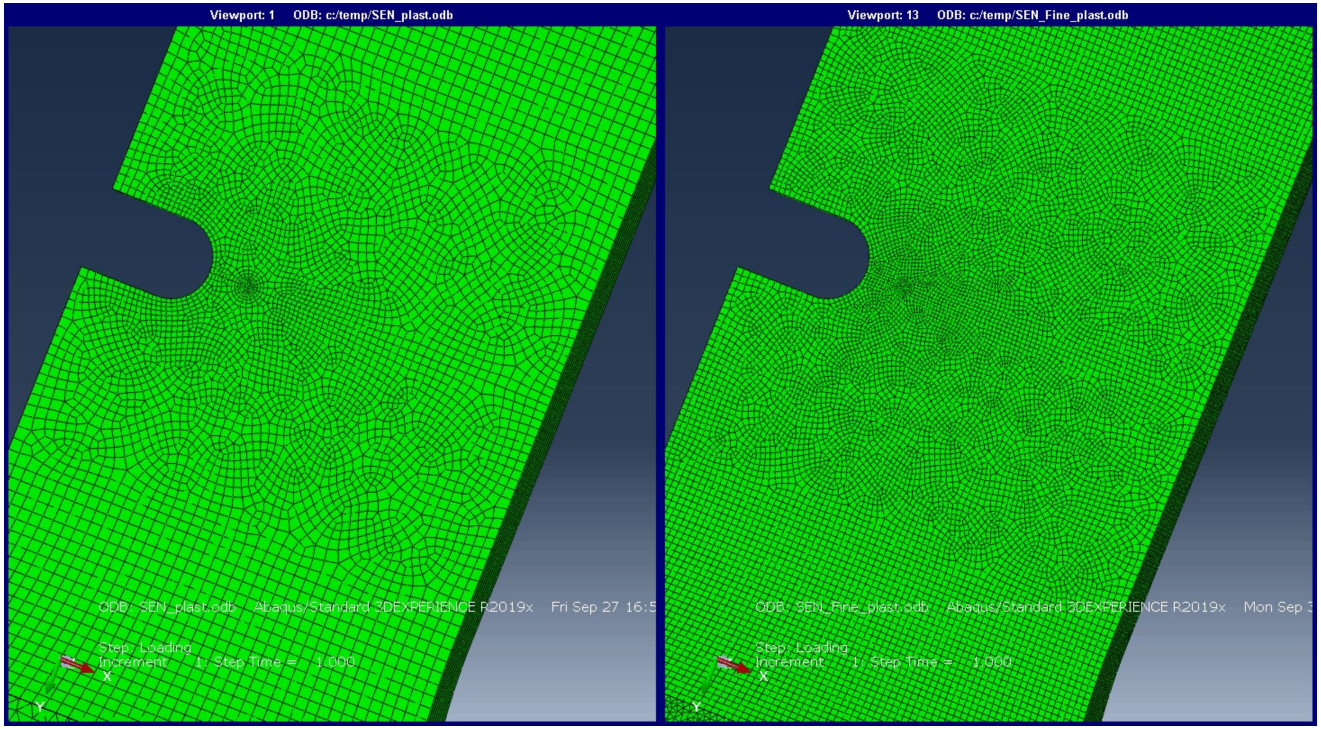


Figure 13 : A coarse and a fine mesh

Mesh convergence : convergence of the SIF

- Coarse meshes are sufficient when considering SIF

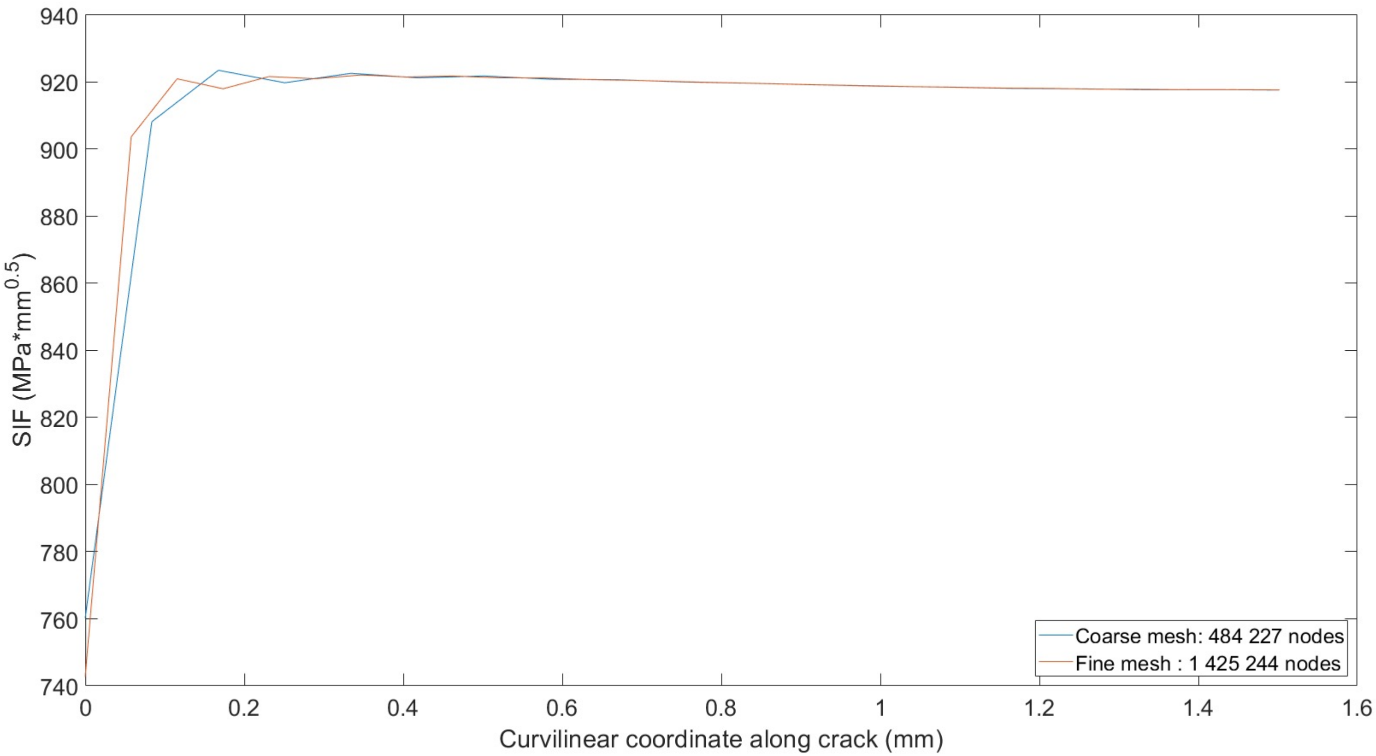
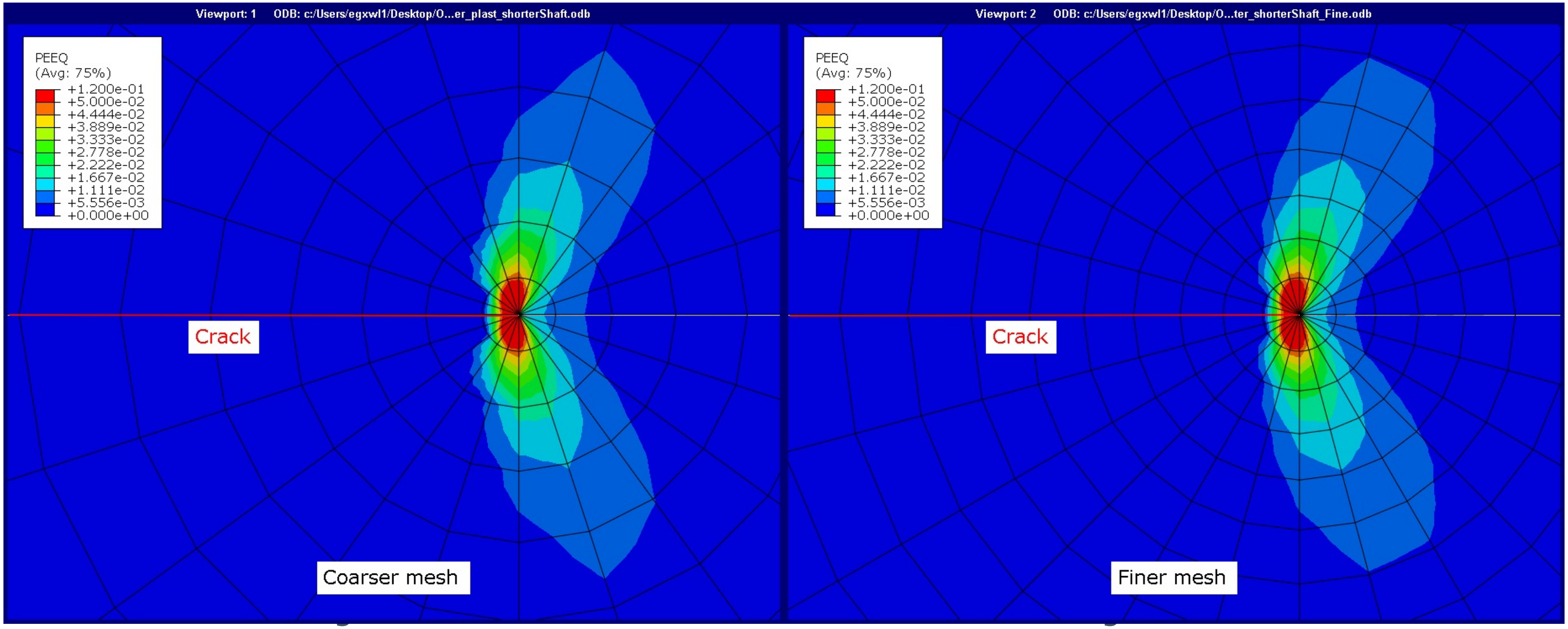


Figure 14 : SIF calculated for two degrees of mesh refinement

strain


Viewport: 1 ODB: c:/Users/egxwl1/Desktop/O...er_plast_shorterShaft.odb
PEEQ
(Avg: 75%)
+1.200e-01
+5.000e-02
+4.444e-02
+3.889e-02
+3.333e-02
+2.778e-02
+2.222e-02
+1.667e-02
+1.111e-02
+5.556e-03
+0.000e+00
Crack
Coarser mesh
Viewport: 2 ODB: c:/Users/egxwl1/Desktop/O...ter_shorterShaft_Fine.odb
PEEQ
(Avg: 75%)
+1.200e-01
+5.000e-02
+4.444e-02
+3.889e-02
+3.333e-02
+2.778e-02
+2.222e-02
+1.667e-02
+1.111e-02
+5.556e-03
+0.000e+00
Crack
Finer mesh

Mesh convergence : comparing average normalised plastic strain error indicators

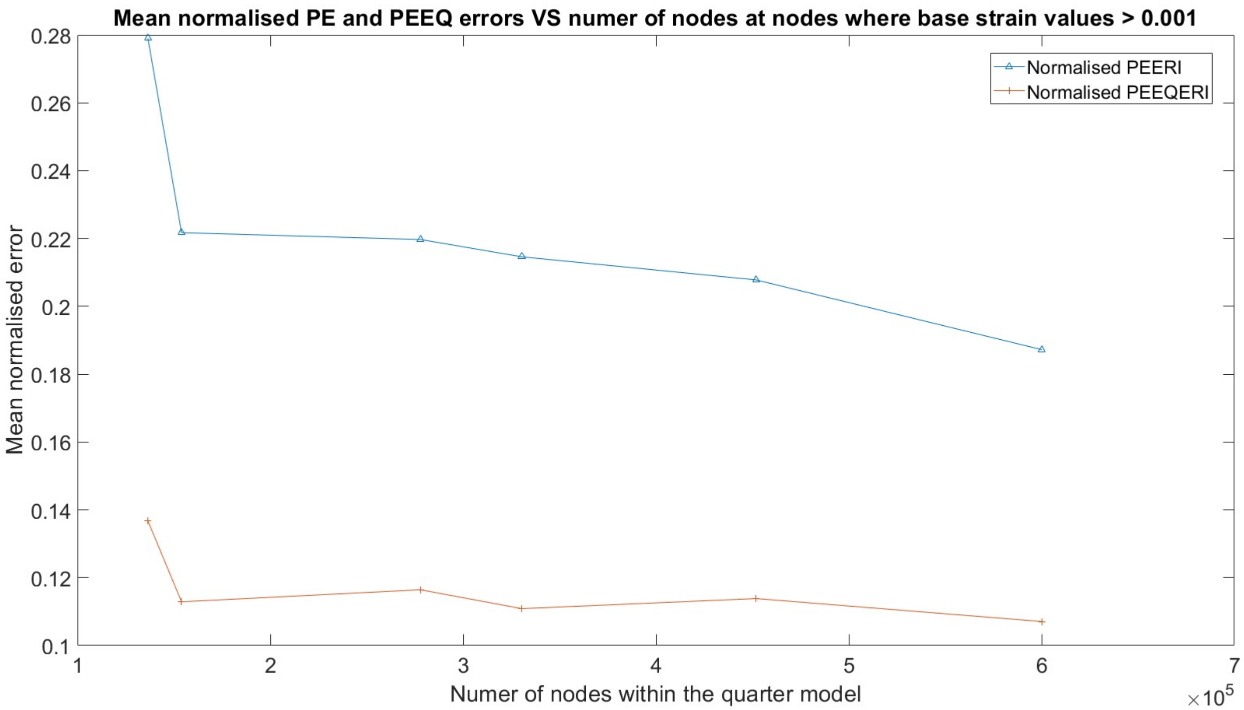
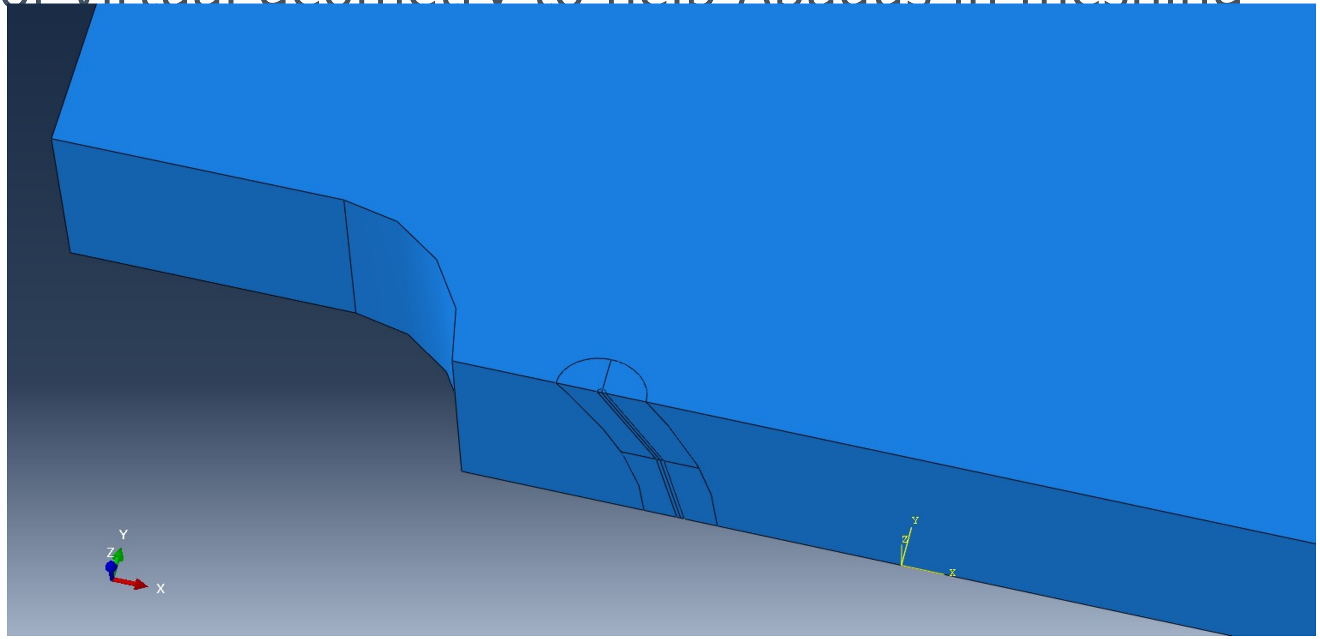


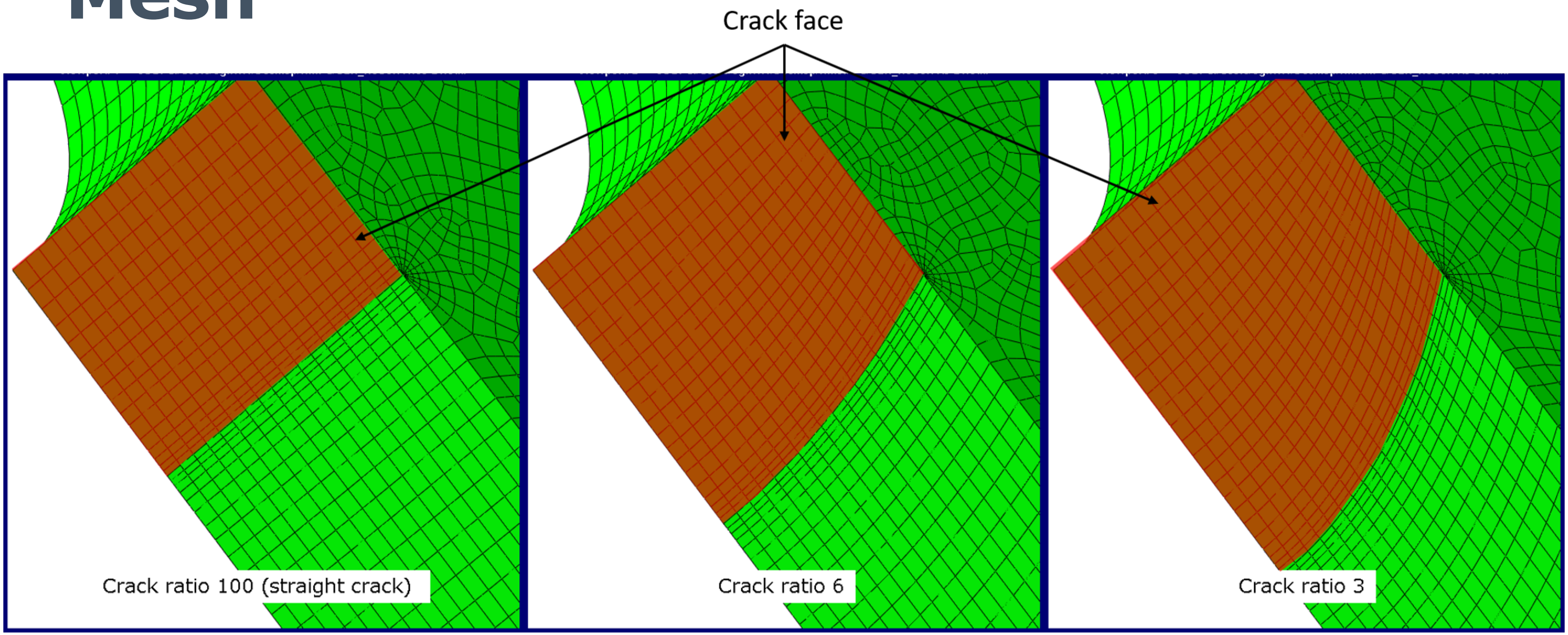
Figure 16 : Mean normalised plastic strain errors according to Abaqus

Geometry

- Classic SEN specimen
- Quarter model
- Use of virtual geometry to help Abaqus in meshing



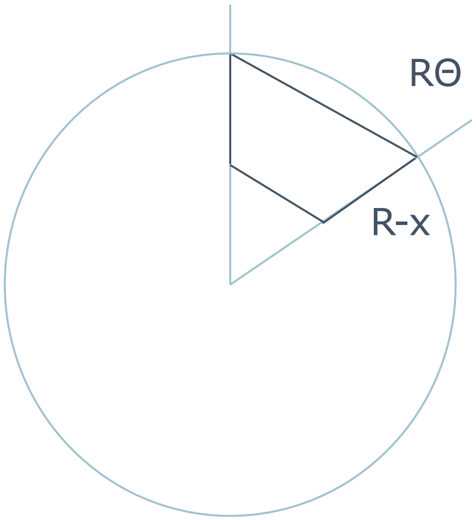
Mesh


Crack face
Crack ratio 100 (straight crack)
Crack ratio 6
Crack ratio 3

Inherent meshing difficulties

- Contour integrals necessitate concentric element rings
- Many elements in a ring lead to heavily biased elements

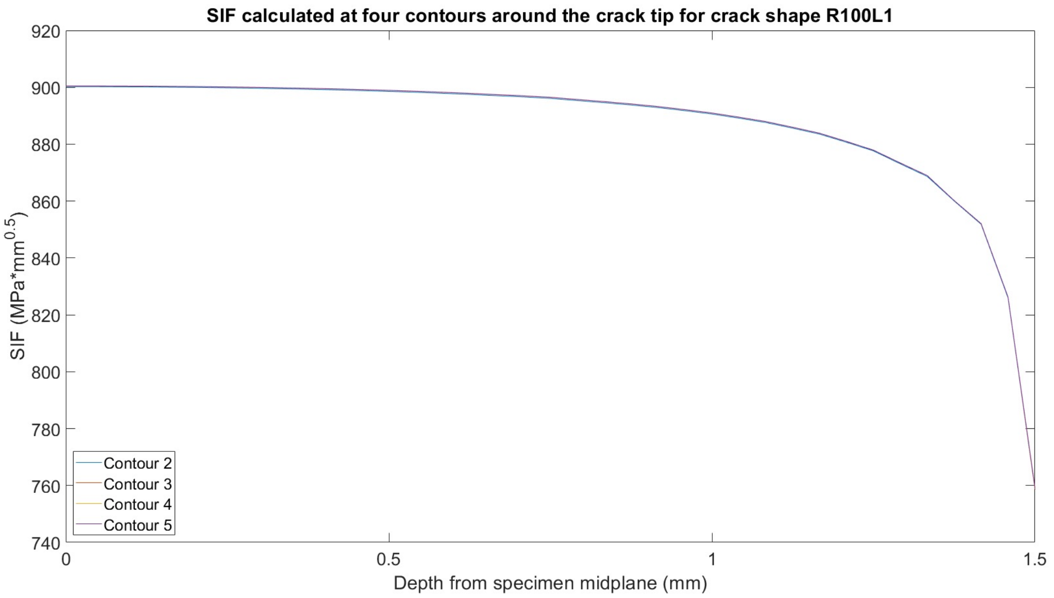
→ Trade-off



Ratio = (R-x)/RΘ
→ 1/Θ at the crack

Inherent meshing difficulties

- 5 contours seems to be enough to enable SIF result convergence



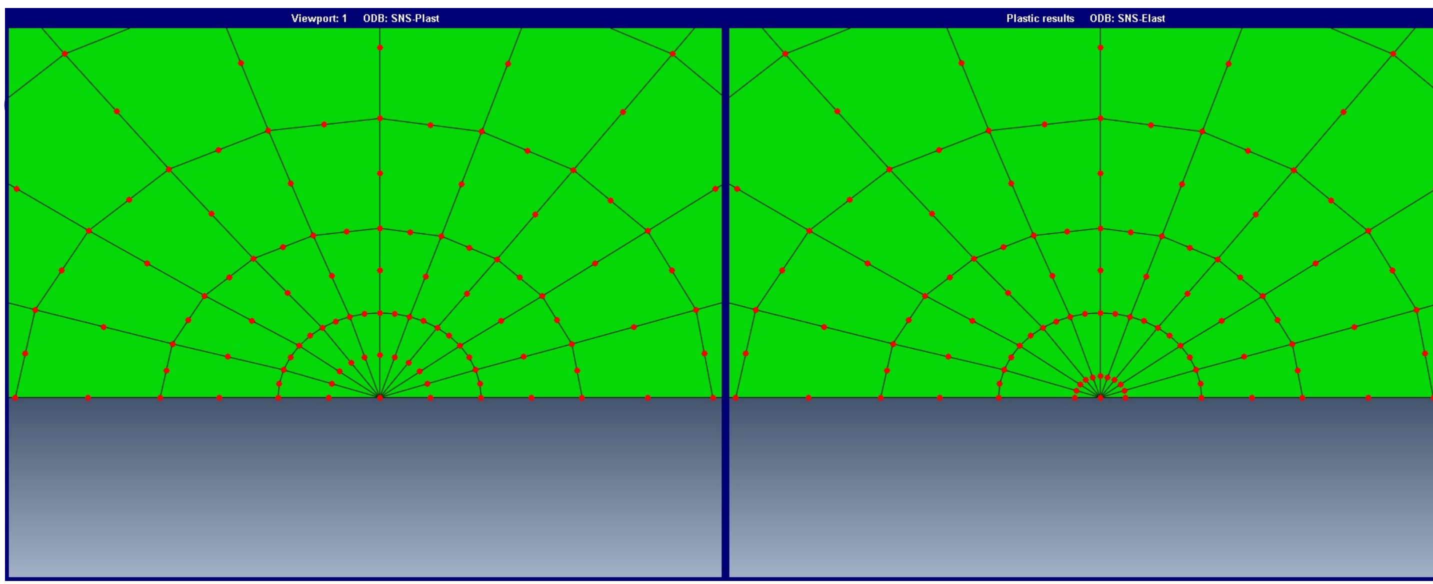
Inherent meshing difficulties

- Cylindrical load introduction sections are geometrically complex
- Tetragonal elements can’t be used around the crack tip

→ Two seperate meshes and a tie constraint

Inherent meshing difficulties

- Crack singularity must be taken into account:
  - Inverse singularity for plastic model, duplicate midside nodes
  - ed



Elastic analysis

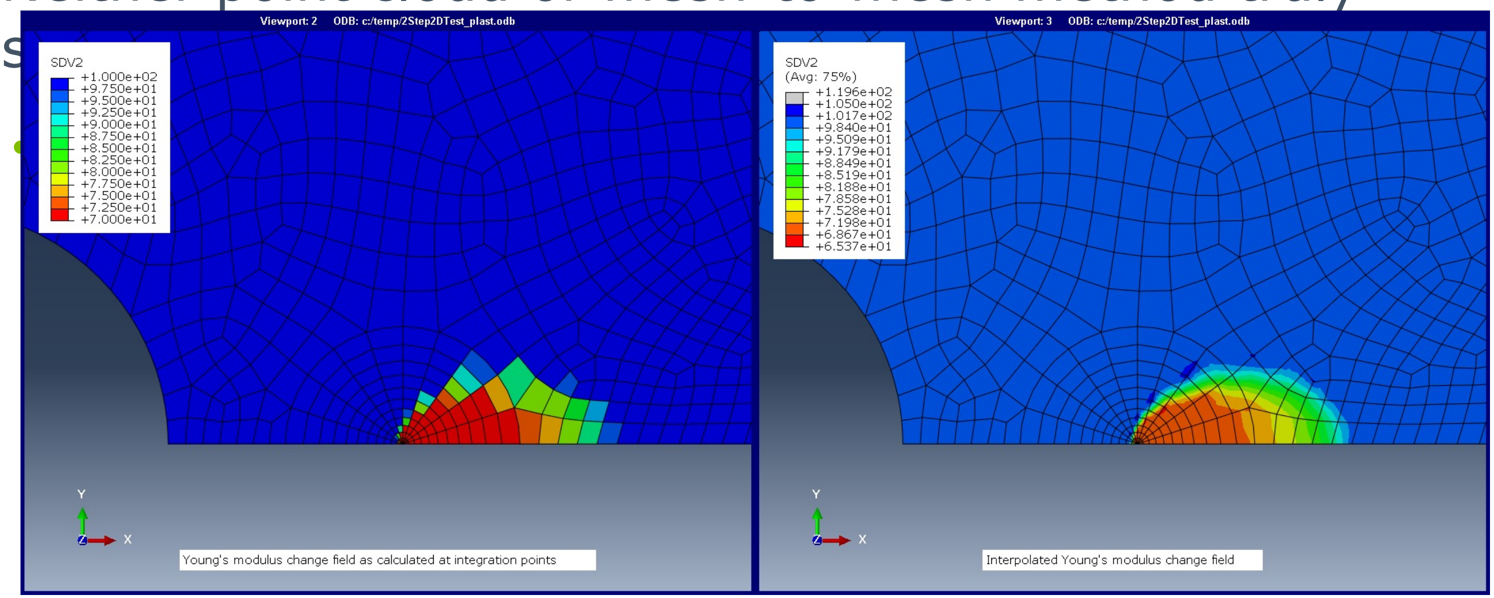
- Issues in field importation
  - Abaqus can only import fields at nodes, resulting in two consecutive interpolations when mapping integration point fields

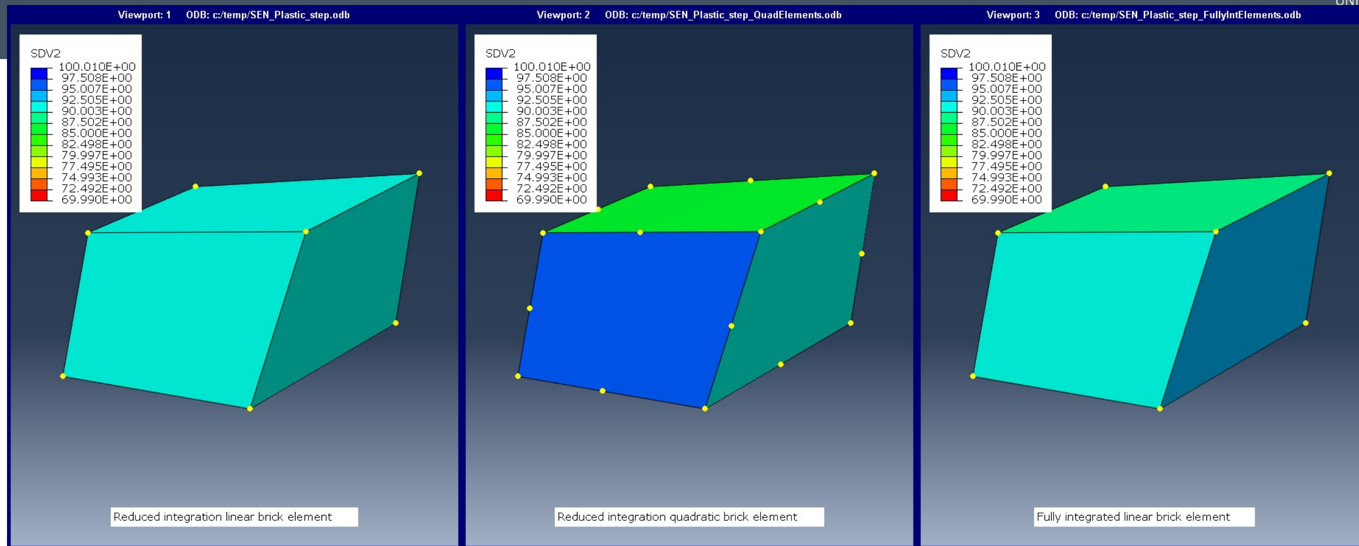
```
f = elastModel.MappedField(name='SDV Field',
    description='', regionType=MESH, partLevelData=False, localCsys=None,
    mappingAlgorithm=VOLUMETRIC, defaultUnMappedValue=100.0)


f.OdbMeshRegionData(odbFileName=odbName,
    variableLabel='SDV2', stepIndex=1, frameIndex=1,
    quantityToPlot=FIELD_OUTPUT, averageElementOutput=False,
    useRegionBoundaries=True, regionBoundaries=ODB_REGIONS,
    includeFeatureBoundaries=True, averageOnlyDisplayed=False,
    computeOrder=EXTRAPOLATE_COMPUTE_AVERAGE, averagingThreshold=100.0,
    numericForm=REAL, complexAngle=0.0, featureAngle=20.0, dataType=SCALAR,
    displayDataType=SCALAR, outputPosition=INTEGRATION_POINT,
    displayOutputPosition=NODAL, refinementType=NO_REFINEMENT,
    refinementLabel='', refinementIndex=-1, sectionPoint=())



elastModel.Field(name='SDV Field Predefined',
    createStepName='Initial', region=elastModel.rootAssembly.instances['crackedBlock-1'].sets['Block - Plastic Zone'],
    distributionType=FIELD, crossSectionDistribution=CONSTANT_THROUGH_THICKNESS,
    field='SDV Field', fieldVariableNum=1, magnitudes=(1.0, ))
```

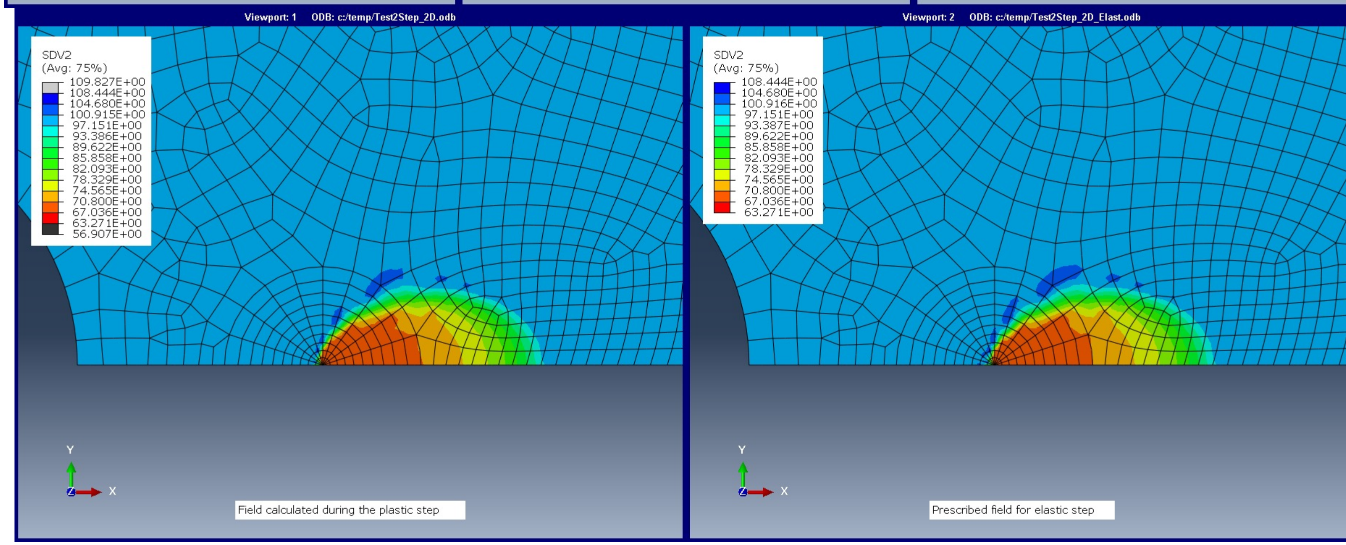
```
*Elastic, dependencies=1
223120.,    0.3, , 82.332
271000.,    0.3, ,   100.
*User Defined Field
**
** PREDEFINED FIELDS
**
** Name: SDV Field Predefined   Type: Field Using Field: SDV Field
*Initial Conditions, type=FIELD, variable=1
crackedBlock-1.1, 99.3858
crackedBlock-1.2, 99.9997
crackedBlock-1.3, 100.003
crackedBlock-1.4, 90.8995
crackedBlock-1.5, 99.9997
crackedBlock-1.6, 99.9676
crackedBlock-1.7, 91.1936
crackedBlock-1.8, 99.4275
crackedBlock-1.9, 100.
crackedBlock-1.10, 100.
crackedBlock-1.11, 100.
crackedBlock-1.12, 100.
crackedBlock-1.13, 100.
crackedBlock-1.14, 100.
crackedBlock-1.15, 100.
crackedBlock-1.16, 100.
crackedBlock-1.17, 100.
crackedBlock-1.18, 100.
crackedBlock-1.19, 100.
crackedBlock-1.20, 100.
crackedBlock-1.21, 99.9997
crackedBlock-1.22, 100.
crackedBlock-1.27, 97.1686
crackedBlock-1.28, 97.471
crackedBlock-1.29, 100.
crackedBlock-1.30, 99.9997
crackedBlock-1.31, 100.
crackedBlock-1.32, 100.
crackedBlock-1.33, 100.
crackedBlock-1.34, 99.9997
crackedBlock-1.35, 100.
crackedBlock-1.36, 100.
```

Issues in field importation

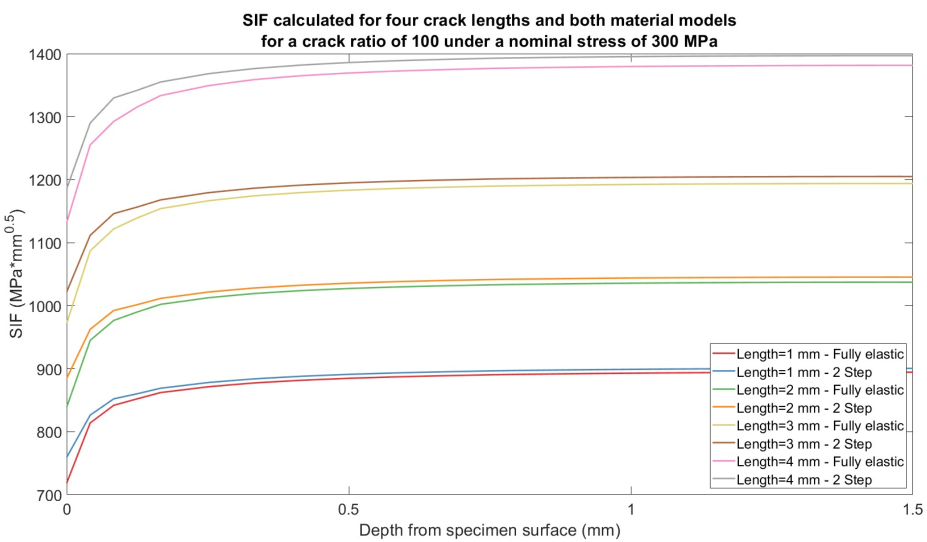
– Neither point cloud or mesh-to-mesh method truly
s

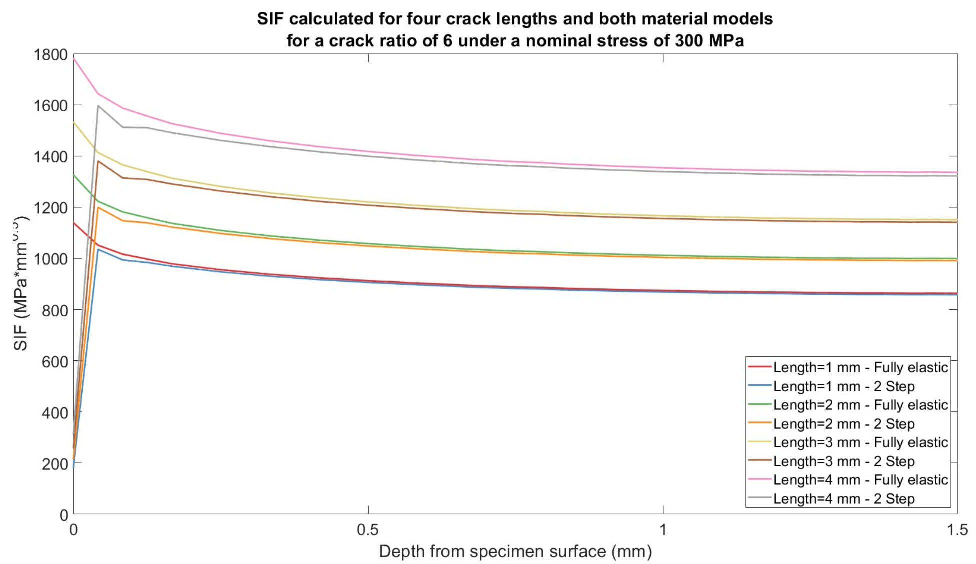



Viewport: 1 ODB: c:/temp/SEN_Plastic_step.odb
SDV2
100.010E+00
97.508E+00
95.007E+00
92.505E+00
90.003E+00
87.502E+00
85.000E+00
82.498E+00
79.997E+00
77.495E+00
74.993E+00
72.492E+00
69.990E+00
Reduced integration linear brick element
Viewport: 2 ODB: c:/temp/SEN_Plastic_step_QuadElements.odb
Reduced integration quadratic brick element
Viewport: 3 ODB: c:/temp/SEN_Plastic_step_FullyIntElements.odb
Fully integrated linear brick element


Viewport: 1 ODB: c:/temp/Test2Step_2D.odb
SDV2
(Avg: 75%)
109.827E+00
108.444E+00
104.680E+00
100.915E+00
97.151E+00
93.386E+00
89.622E+00
85.858E+00
82.093E+00
78.329E+00
74.565E+00
70.800E+00
67.036E+00
63.271E+00
56.907E+00
Y
X
Field calculated during the plastic step
Viewport: 2 ODB: c:/temp/Test2Step_2D_Elast.odb
SDV2
(Avg: 75%)
108.444E+00
104.680E+00
100.916E+00
97.151E+00
93.387E+00
89.622E+00
85.858E+00
82.093E+00
78.329E+00
74.565E+00
70.800E+00
67.036E+00
63.271E+00
Y
X
Prescribed field for elastic step

Low stress state : 300 MPa for 1mm pre-crack





Low stress state : 300 MPa for 1mm precrack (continued)