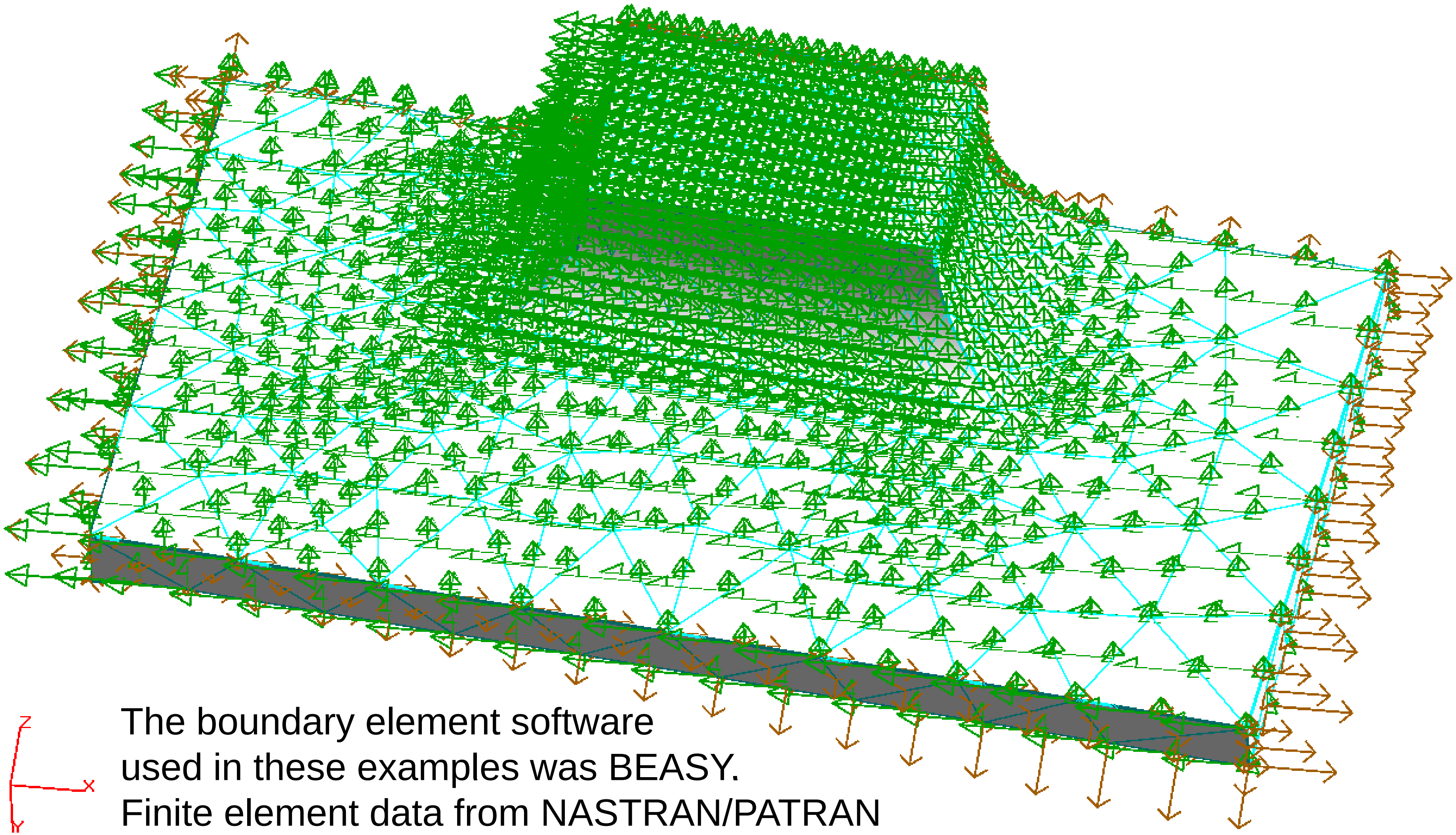
APPLICATION 1:
DAMAGE TOLERANT DESIGN

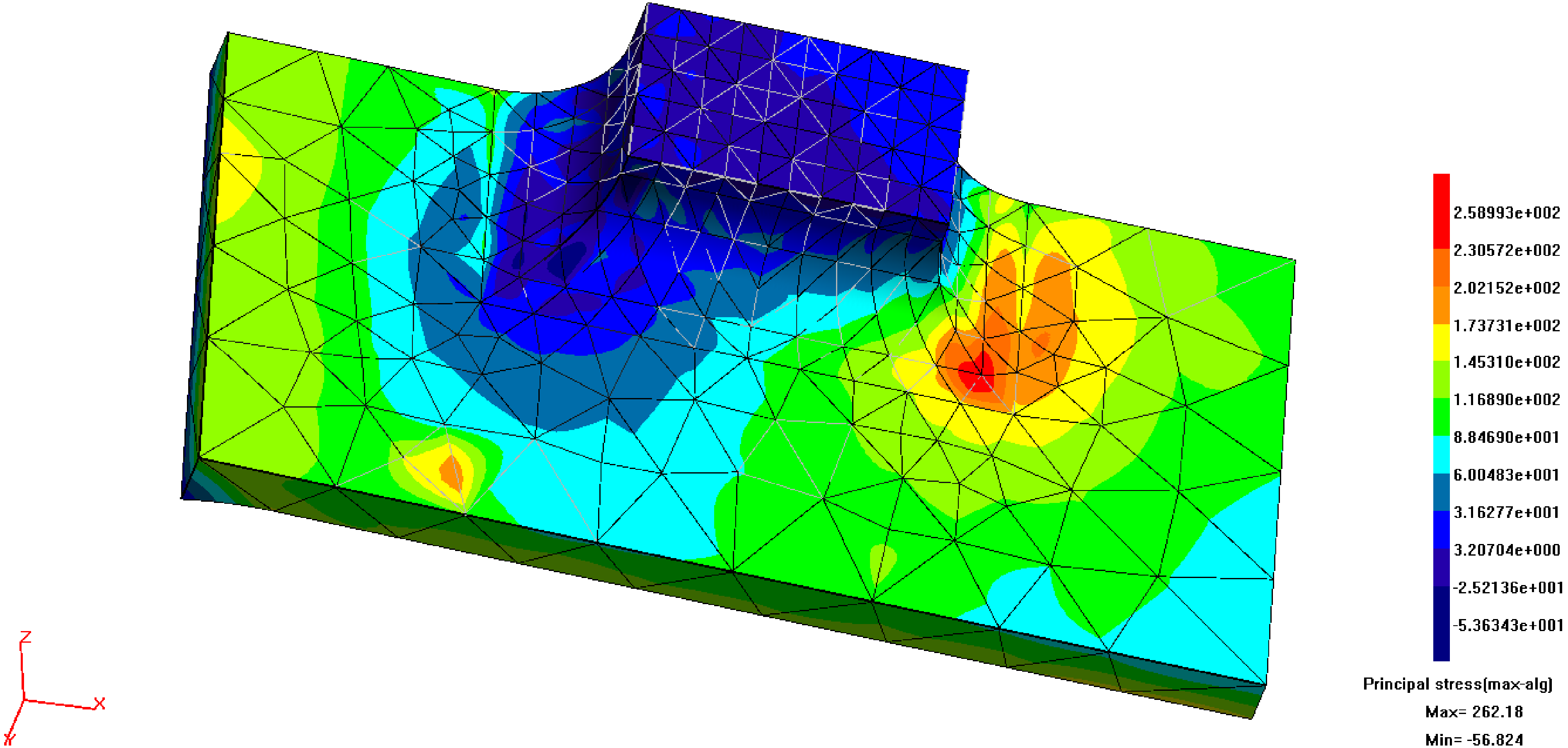
- Damage Tolerant Design – assume manufacturing defects exist from production and grow to failure during the life of the structure
- Will potential machining flaws at stress hotspots be non-propagating?
- Standard handbook stress intensity factors are time consuming to use in complicated geometry with bi-directional stress fields
- Boundary Elements (BE) can be used to determine whether or not the defect will grow, and by how much the local stress must be reduced to ensure zero growth
- Used alongside traditional SN methods and/or strain life methods this gives confidence that stress 'hotspots' have been designed out of the integrally machined part.

IMPORTED, SOLVED SUB-MODEL FROM FINITE ELEMENT RESULTS FILE AT ‘HOTSPOT’ LOCATION

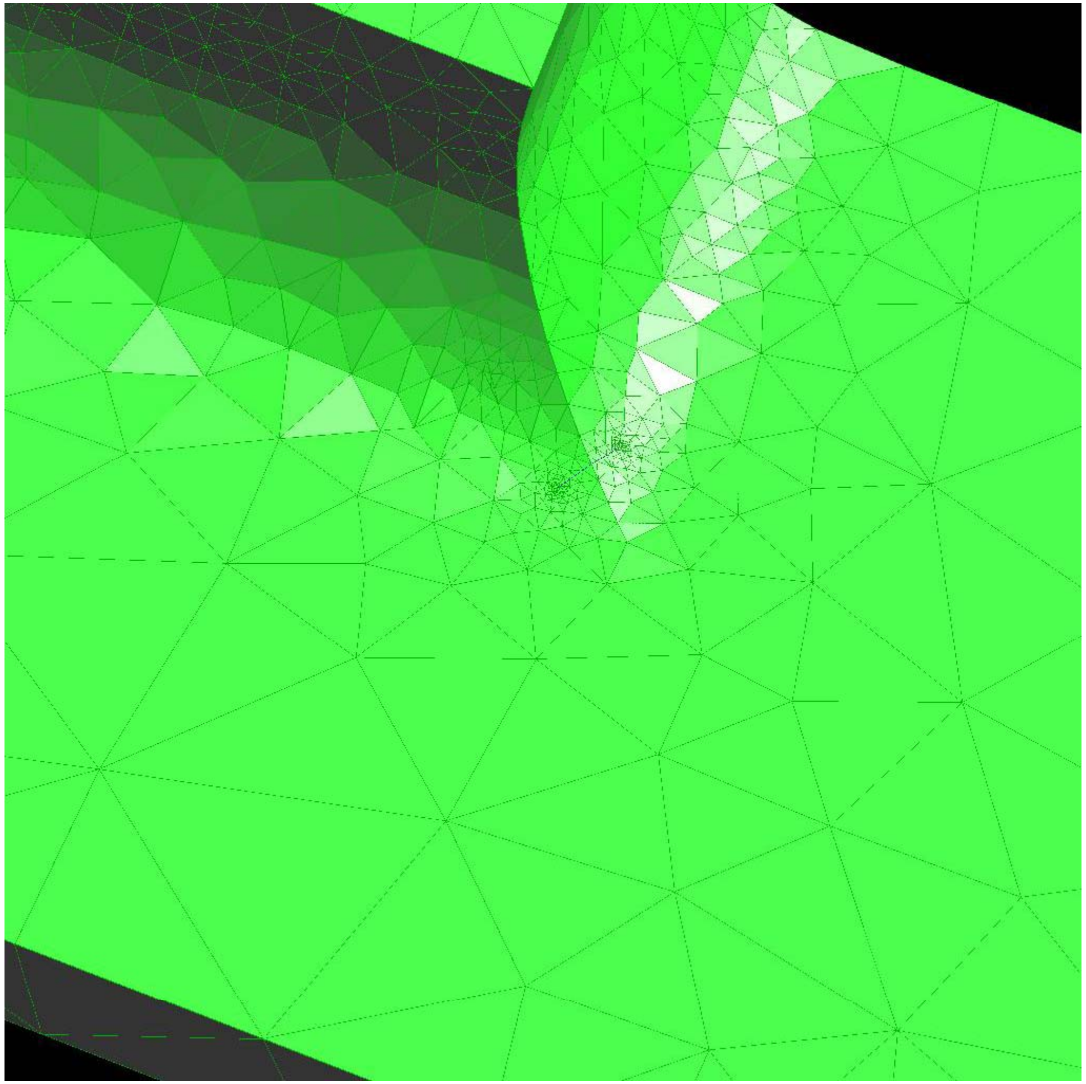


The boundary element software used in these examples was BEASY. Finite element data from NASTRAN/PATRAN and Strand7

CONVERTED TO BOUNDARY ELEMENT MODEL - UNCRACKED RUN REPLICATES FE RESULTS



SEMI ELLIPTICAL SURFACE CRACK INSERTED ONTO CUSP AT LOCATION OF PEAK STRESS

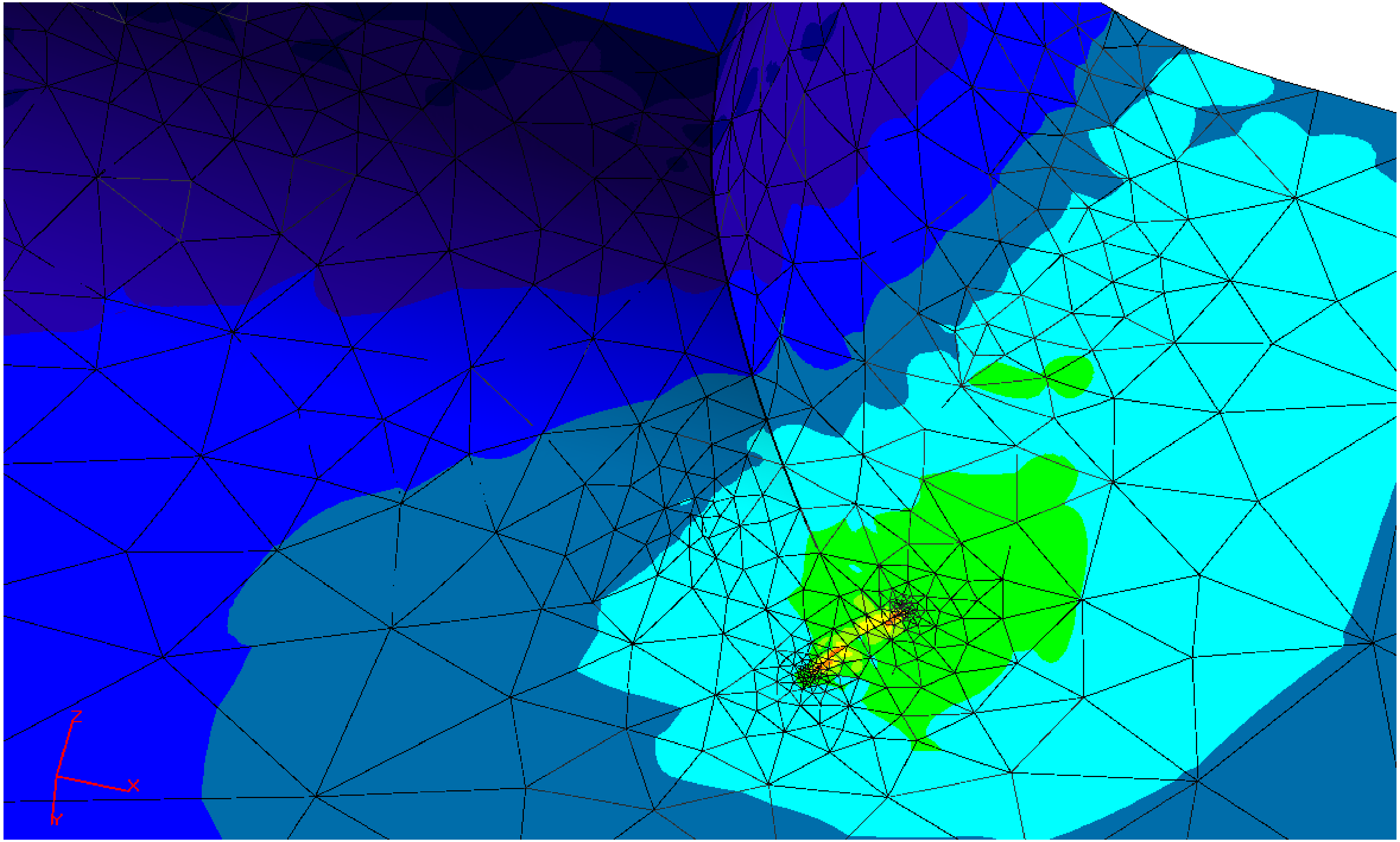


Standard library crack located at BE mesh point where P1 stress is highest

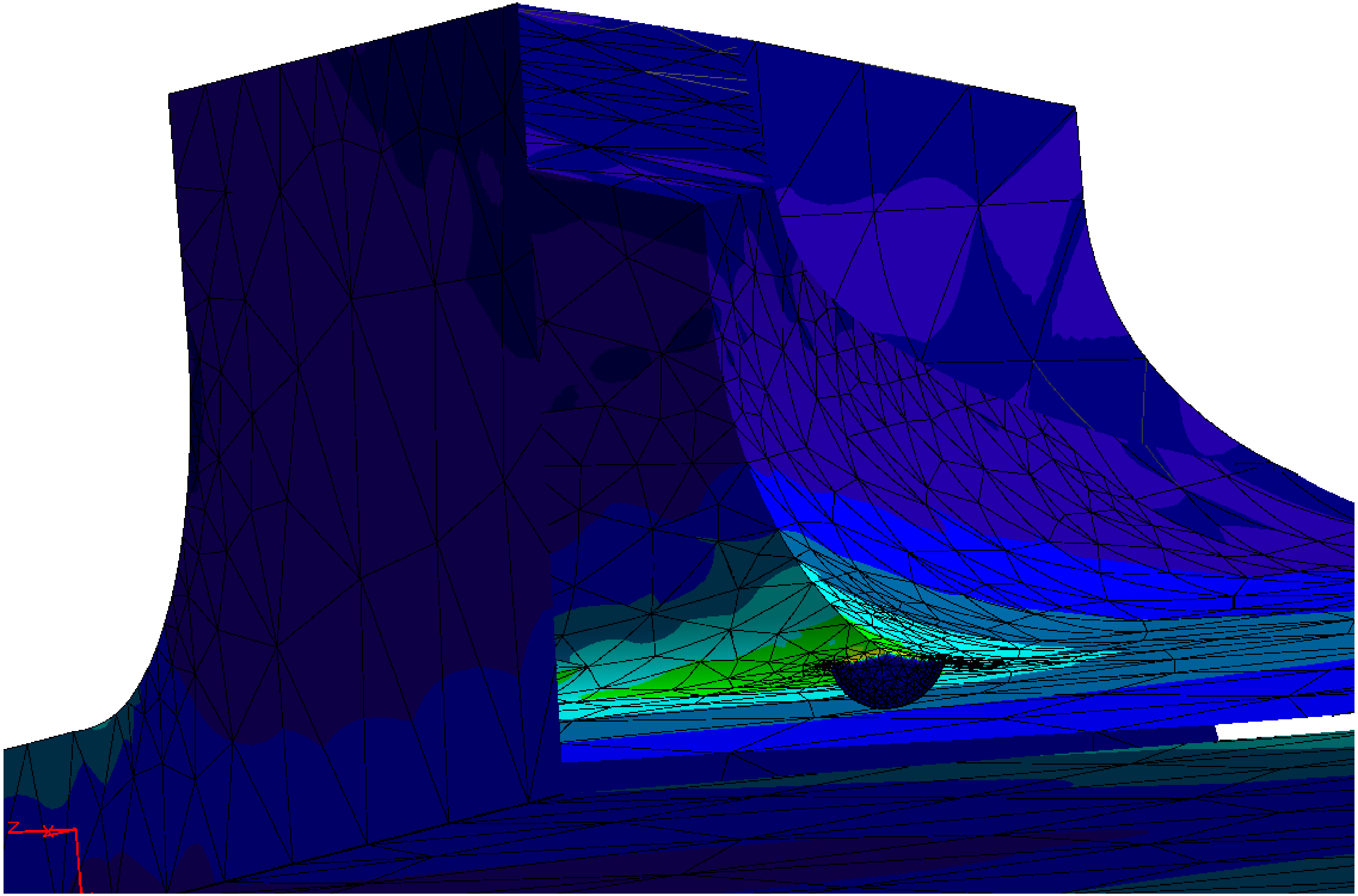
Crack oriented so that it is perpendicular to P1 stress vectors at the hotspot

Grown normal to surface, but this angle can also be varied if desired

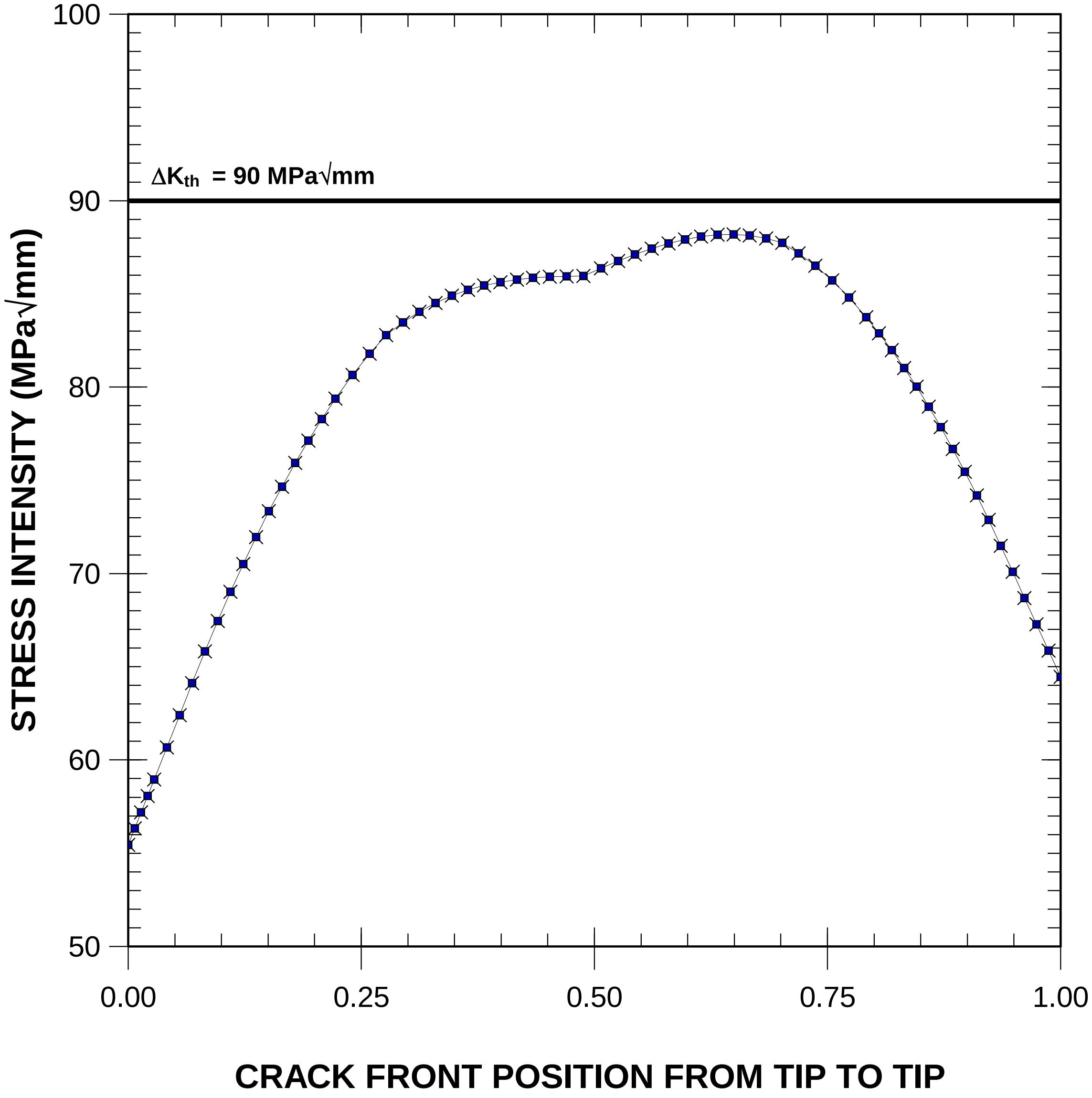
STRESS DISTRIBUTION AROUND CRACK (EXTERNAL VIEW)



INTERVAL VIEW OF CRACK BY USING A CLIP PLANE - SHOWS INSERTED SHAPE IN THE BODY



STRESS INTENSITY CALCULATED BY J-INTEGRAL METHOD ALONG CRACK FRONT



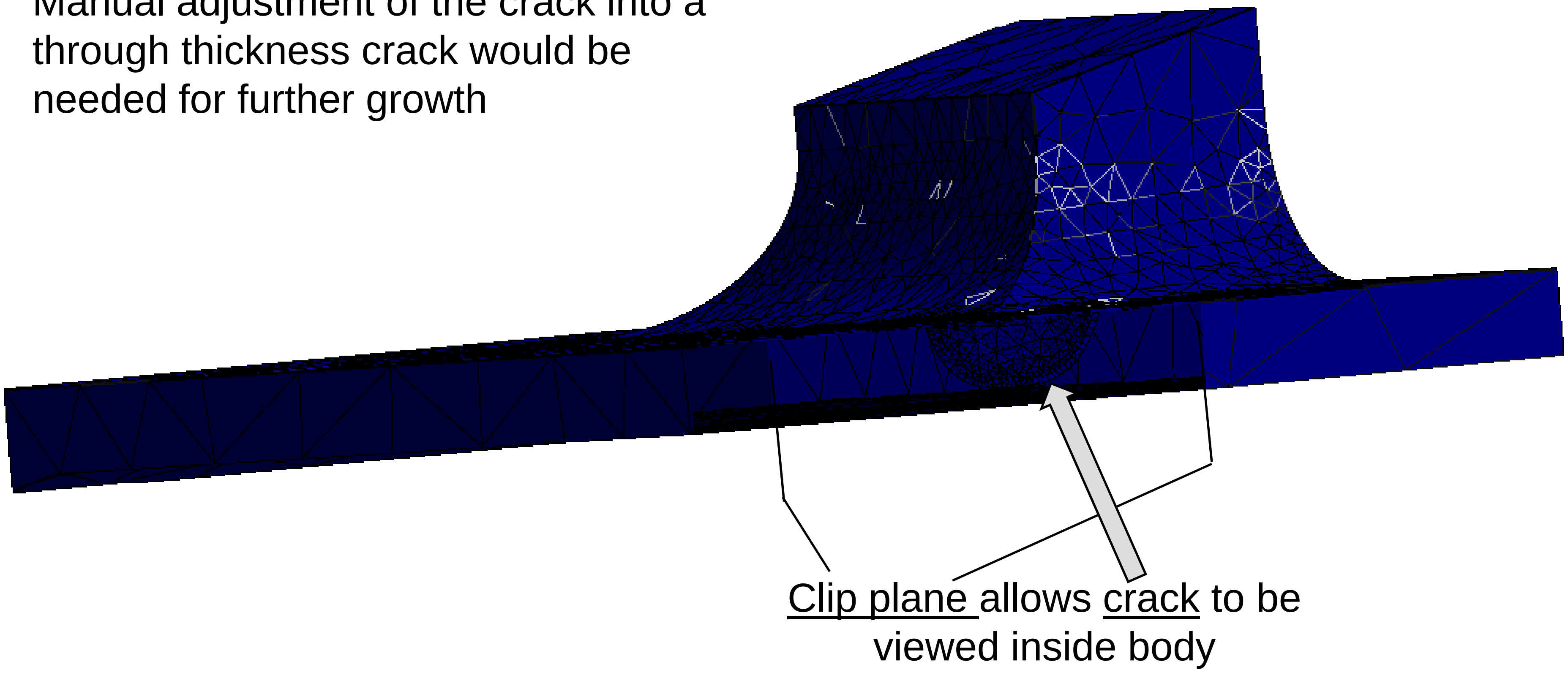
In this example the defect is just about non-propagating as the stress intensity is below the threshold ΔK

- What is the error range in stress?
- Carry out sensitivity studies
- Revise geometry
- In this example you would need to be very confident that the original FE is modelling the real structure correctly!

STRESSES INCREASED TO ALLOW THE DEFECT TO BE GROWN IN THE BEM USING A RATE LAW

Defect has grown to a just shy of a through thickness defect

Manual adjustment of the crack into a through thickness crack would be needed for further growth



APPLICATION 2:
ANALYSIS OF IN-SERVICE/TEST ITEM CRACKS

- Unexpected in-service or test item cracks need to be analysed as accurately as possible

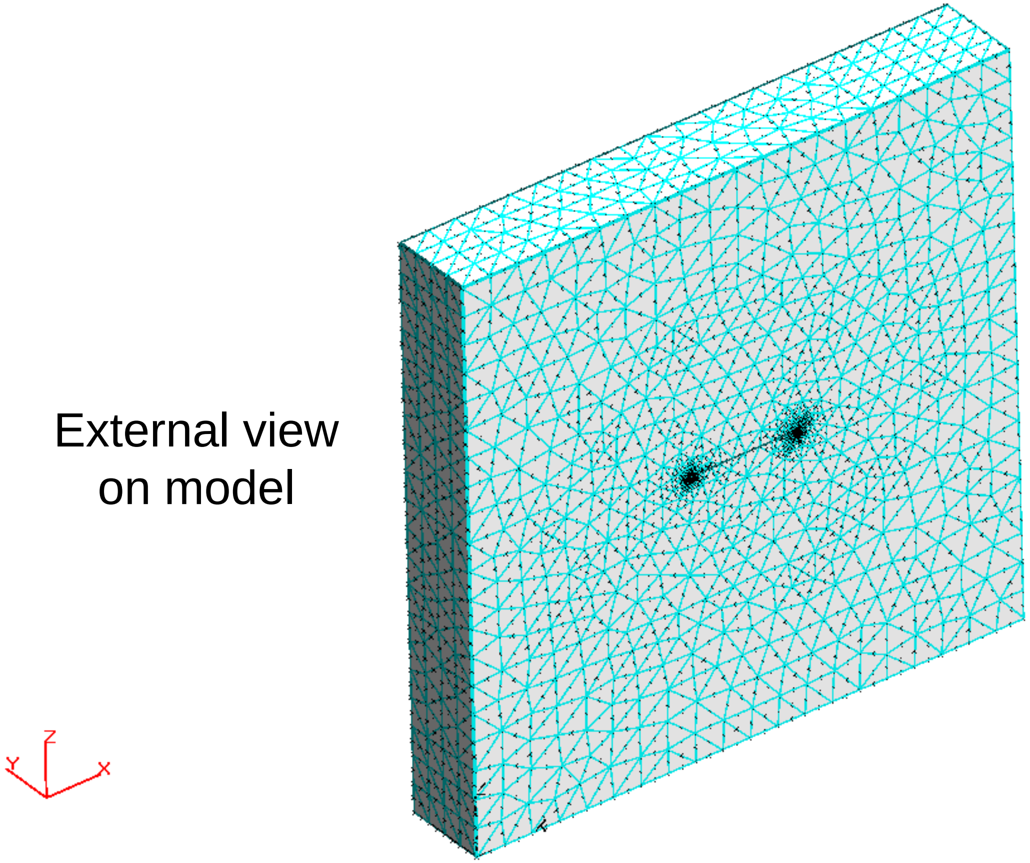
- The shape and aspect ratio are often different to those (if any) assumed during design and certification

- Standard handbook stress intensity factors sometimes don't cover these particular geometries

- Boundary Elements (BE) can be used to determine stress intensity factors along the crack front and remove one aspect of the uncertainty in matching the analysis to in-situ crack growth measurements or fracture surface striation counts

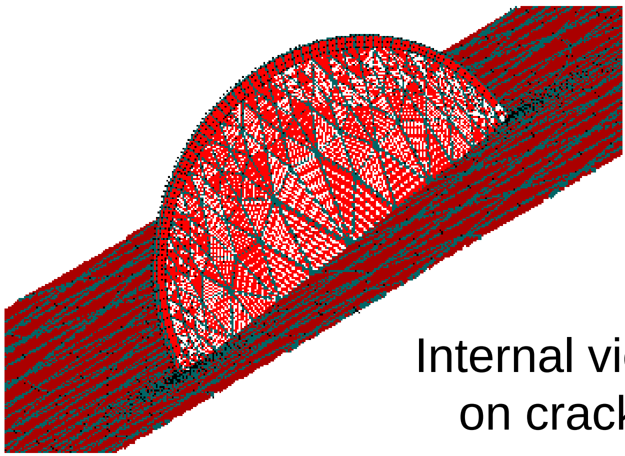
IMPORTED SUB-MODEL FROM FINITE ELEMENT RESULTS FILE

External view
on model



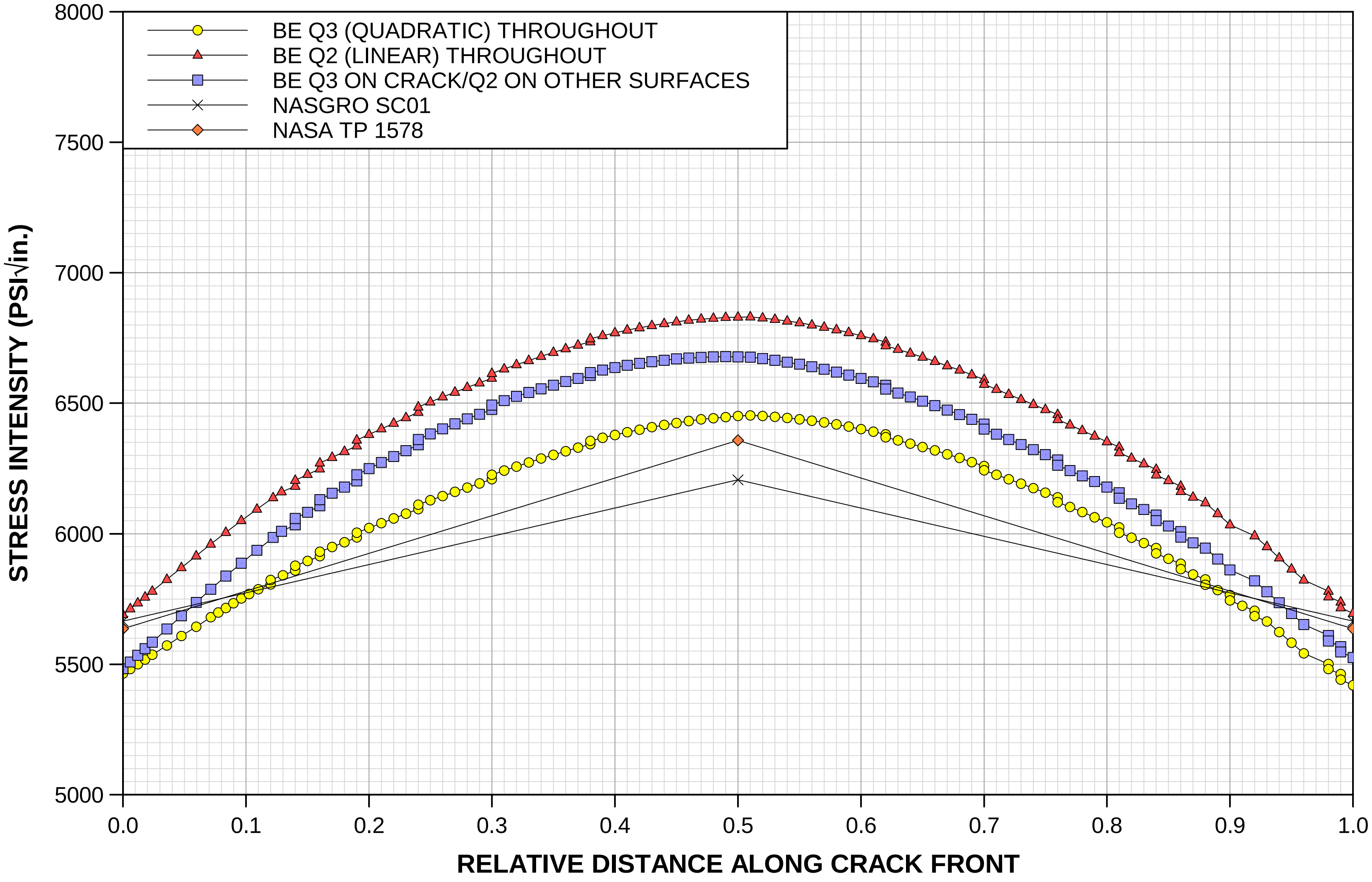
Calibrate the BEM using handbook solutions to ensure mesh density and element order will be OK

NASGRO SC01 is replicated in this BEM, along with the original data from NASA TP 1578



Internal view
on crack

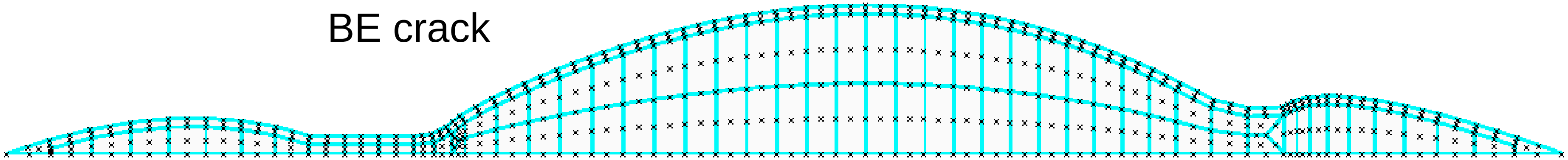
SENSITIVITY STUDY FOR BEM OF STANDARD CRACK GEOMETRY WITH STANDARD SOLUTIONS



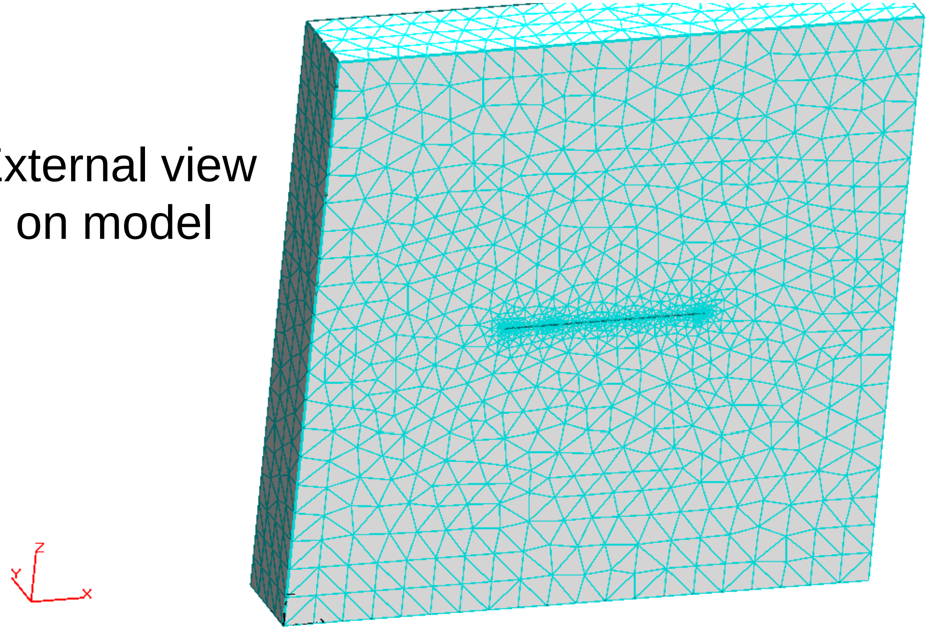
A similar sensitivity study is carried out with different mesh densities, to optimise the mesh density and element order but still give sensible run times

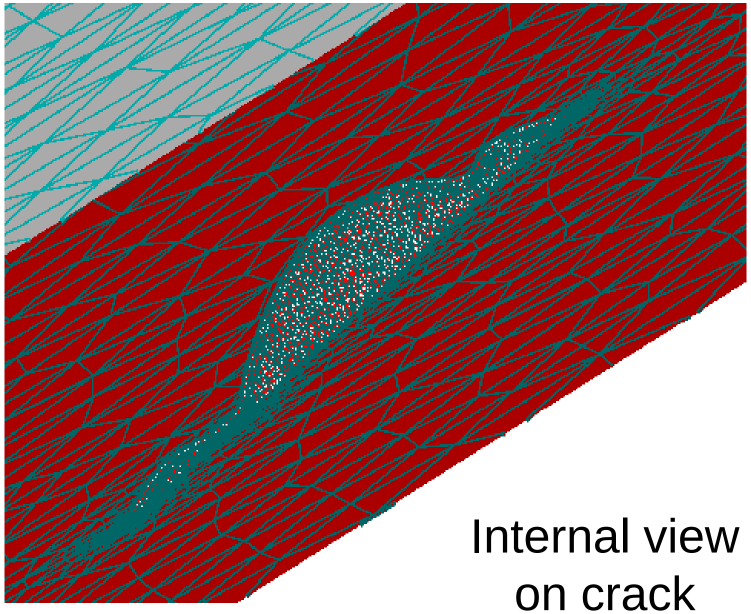
MODEL CRACK FOUND IN-SERVICE AND INSERT INTO TEST PLATE

BE crack



External view
on model





Internal view
on crack

Use appropriate element order and
mesh density as determined by
standard geometry investigation –
once checked the crack can be used in a sub
model of the real structure

APPLICATION 3:
INFLUENCE OF LUG SHAPE AND PIN FIT ON SIF

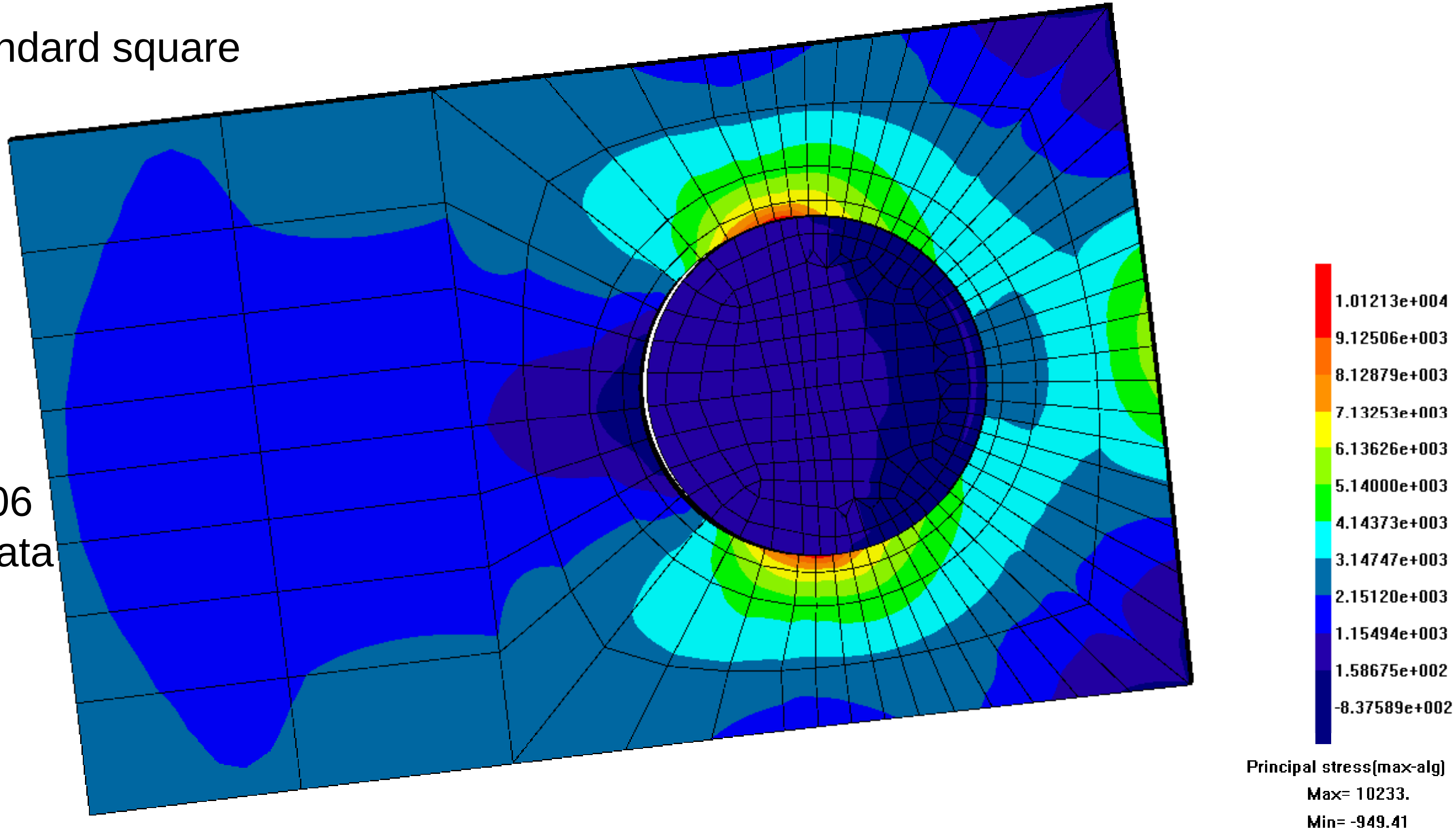
- It is a well known fact that both pin clearance and lug shape affects the stress concentration factor and peak stress location in a lug. Stress concentration factors have been published to quantify these effects, for example ESDU 81006.

- The same parameters also affect the stress intensity factors (SIFs) of cracks in a lug

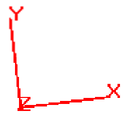
- In this study a constant crack aspect ratio has been used to investigate the effect of different lug shape on the stress intensity factors of corner cracks in a lug. Pin fit ranged from various amounts of clearance (for KT comparison) to perfect fit (for stress intensity factor comparison)

STRESS CONCENTRATION FACTORS FROM BE COMPARED TO ESDU 81006 AND HEYWOOD

BEM of standard square ended lug
W = 2.0 in.
D = 1.0 in.
c = 1.0 in.
t = 0.25 in.

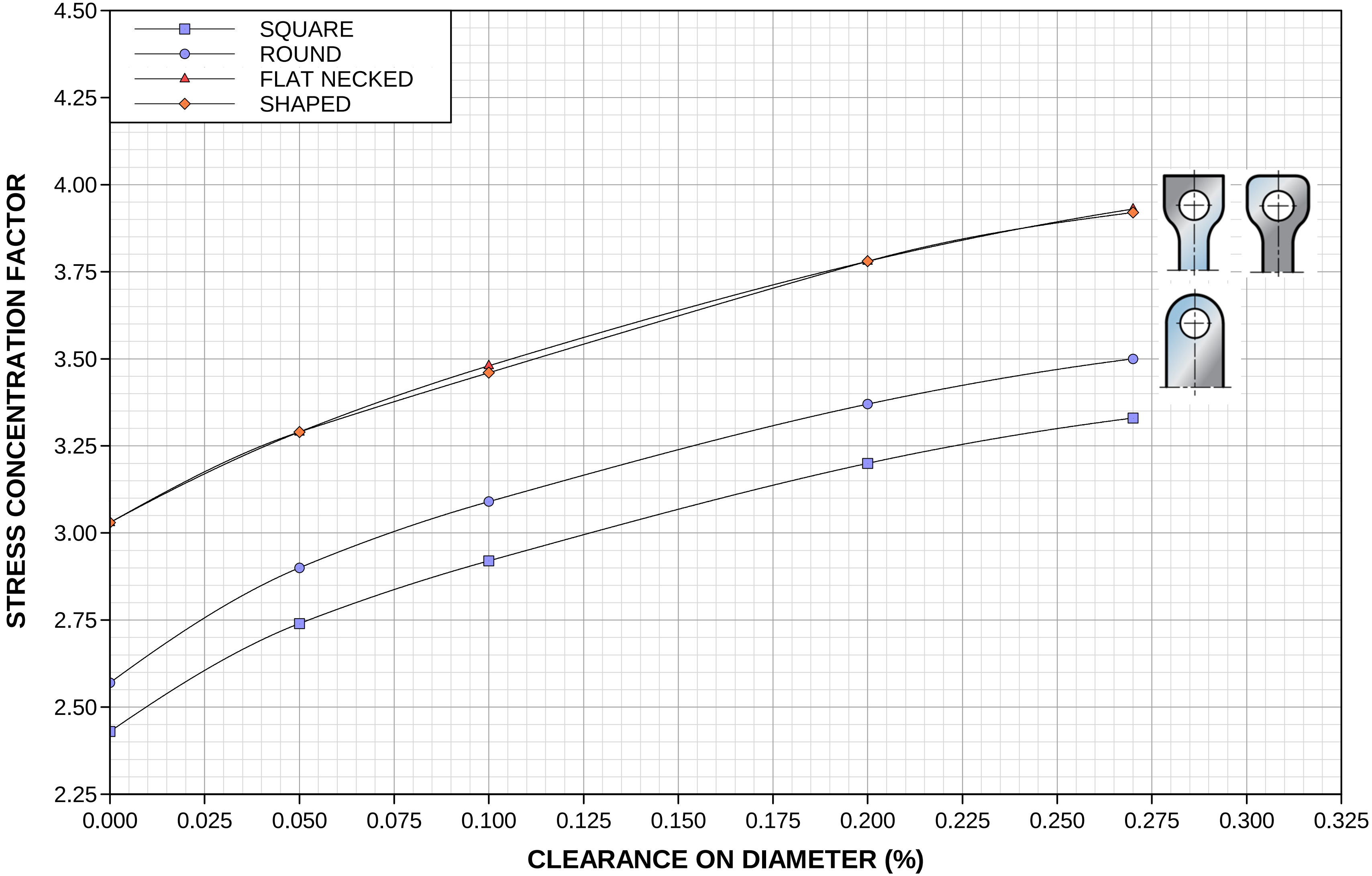


ESDU 81006 based on data from 1948

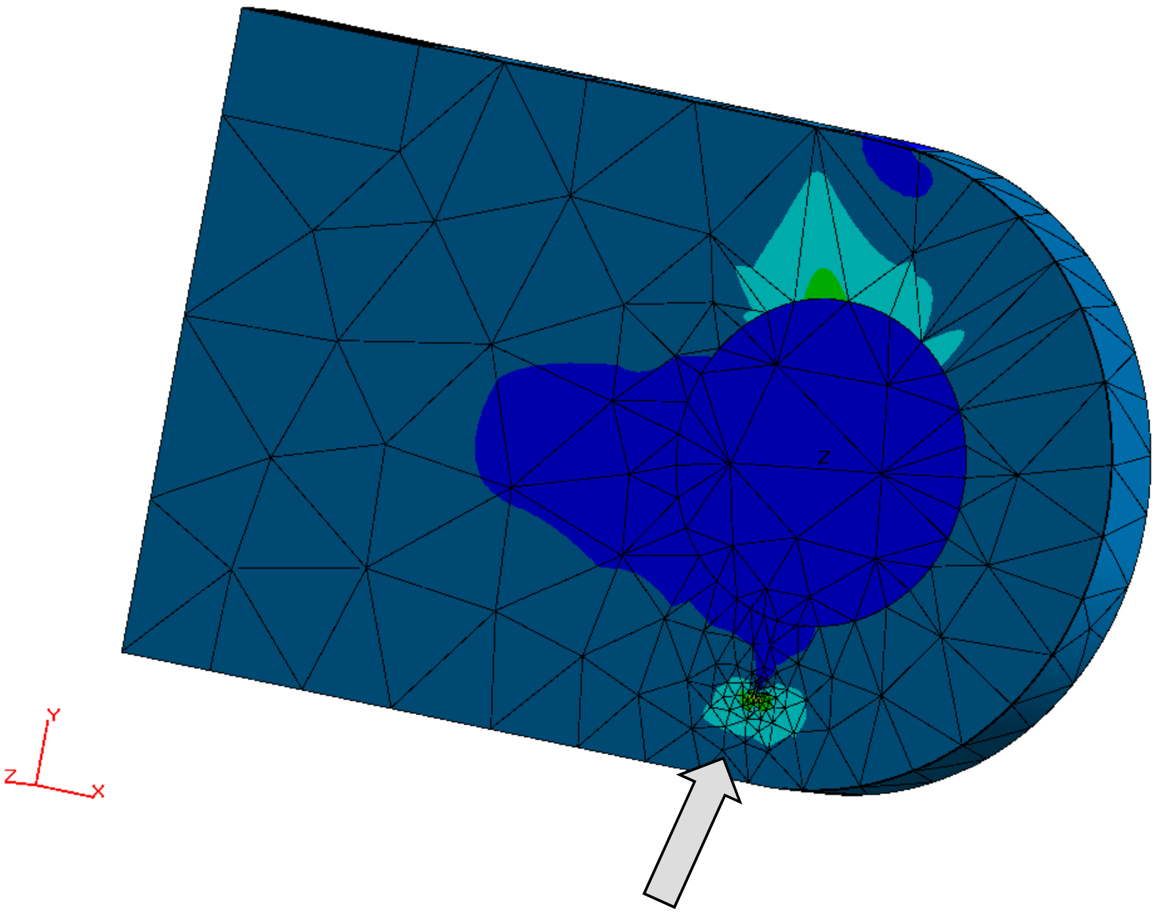


CLEARANCE (%)	KT(BE)	CLEARANCE (%)	KT(reference)
0.0	2.42	0.0	N/A
0.1	2.88	<0.1	2.60/2.75 (ESDU 81006/HEYWOOD) [FROM THE SAME 1948 DATA!]
0.2	3.13	0.2	3.00 (ESDU 81006)

THE EFFECT OF LUG SHAPE AND PIN FIT ON THE STRESS CONCENTRATION FACTOR OF A LUG



STRESS INTENSITY FACTOR DERIVATION FROM BOUNDARY ELEMENT MODEL (BEM)



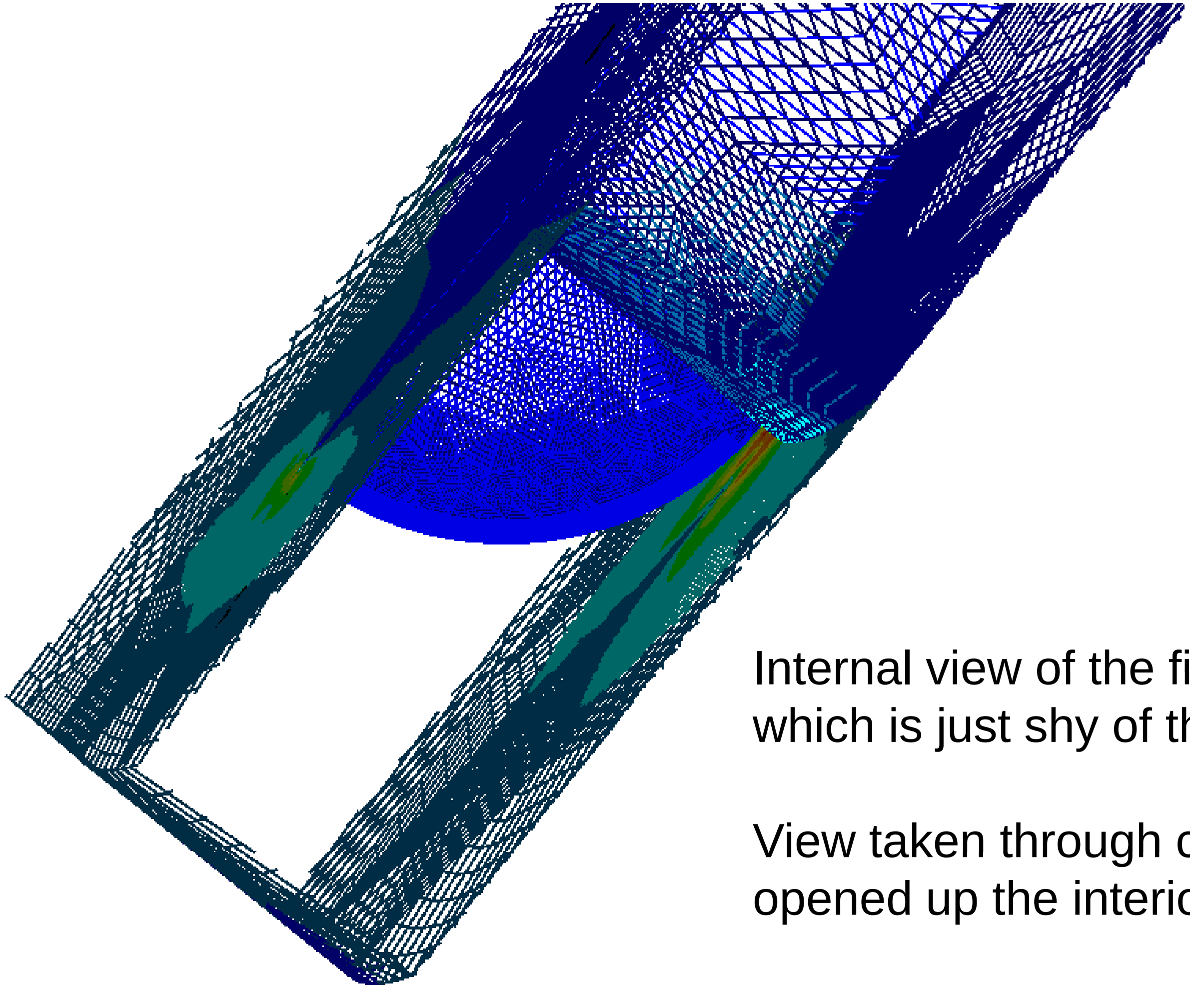
Single corner crack, constant aspect ratio of a/c = 1.0 for a range of crack sizes

BEM of perfect fit pin in standard round ended lug under axial load

This is compared to the stress intensity factor for NASGRO CC03, based on FE modelling in the 1970/80s, hence contact not used and lug load simulated by a bearing pressure on the bore

The bearing pressure in this FE work is assumed to have been un-changed by the presence of the crack, i.e. the pin retains perfect contact even as the ligament loses stiffness

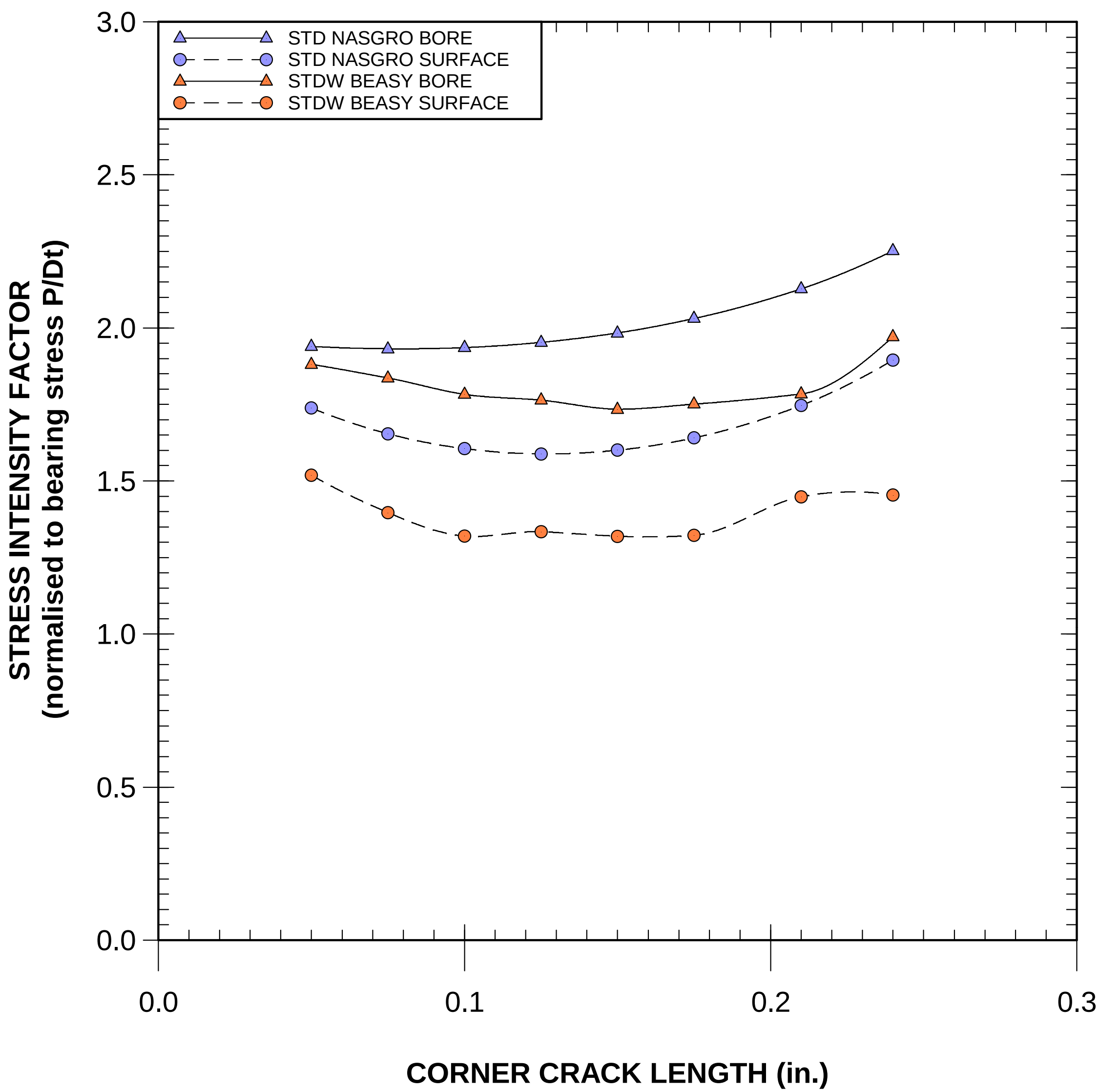
IMPORTED SUB-MODEL FROM FINITE ELEMENT RESULTS FILE



Internal view of the final crack length, which is just shy of through thickness.

View taken through clip plane which has opened up the interior of the model

STRESS INTENSITY FACTORS DOWN BORE OF HOLE FROM BEM COMPARED TO NASGRO

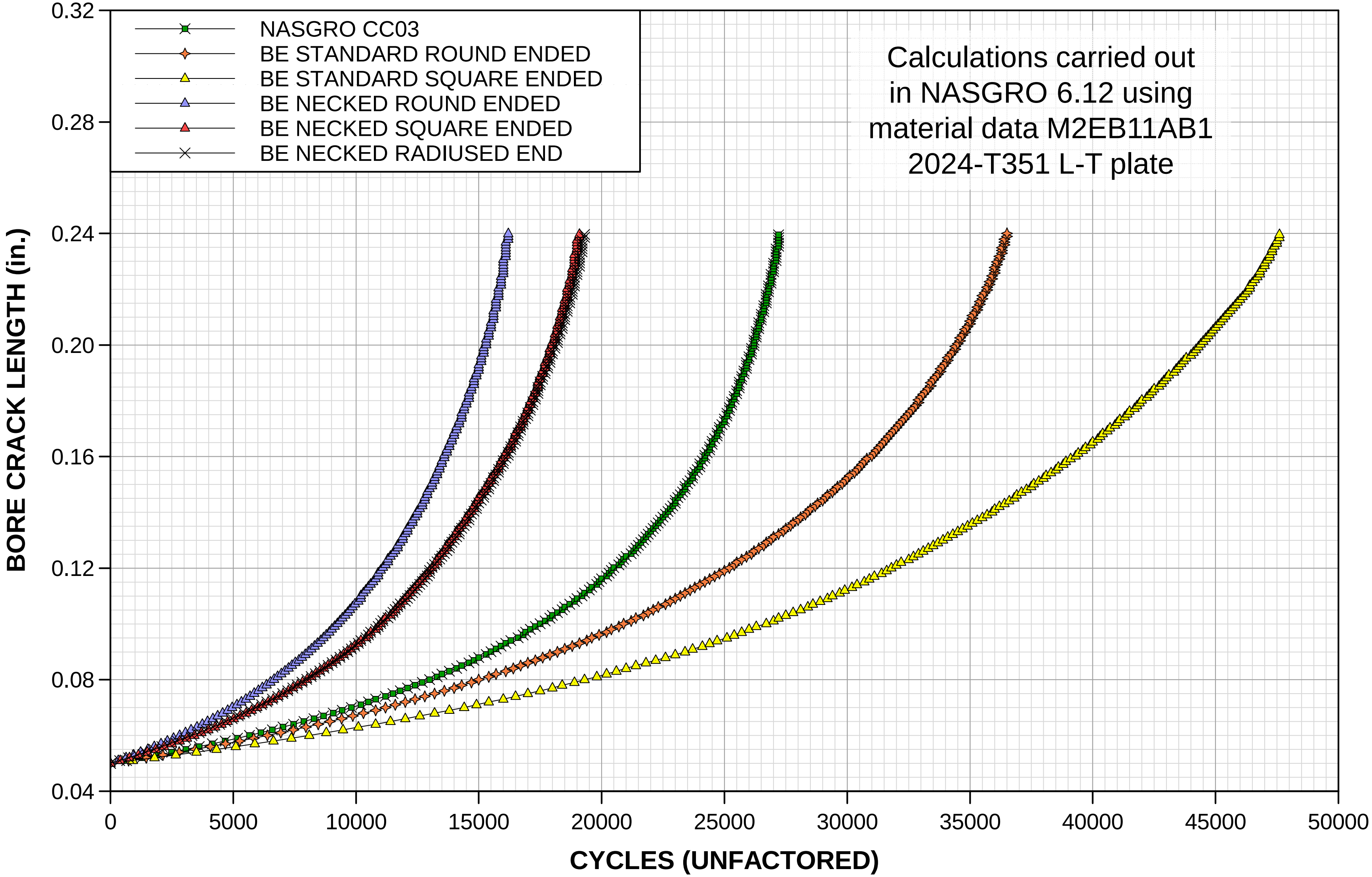


BEM of perfect fit pin in standard round ended lug under axial load

The SIF is influenced by the stiffness change in the cracked ligament, i.e. as the crack gets bigger more load is taken by the uncracked side, as indicated by the divergence between the BE and NASGRO values

Note also the BE values are 'raw' data – the NASGRO SIF is taken from equations which were fitted empirically to the data

LUG SHAPE INFLUENCES STRESS GRADIENTS HENCE CYCLES TO GROW TO THROUGH THICKNESS



IN CONCLUSION

- Stress concentrations found on integrally machined items can be investigated using BE and any necessary action taken
- Cracks found in-service and on test items can be readily analysed using BE methods
- The standard handbook solution for a lug might be overly conservative when compared to an analysis which includes contact
- The effect of lug shape (and pin fit) should always be taken into account when analysing lugs, as some shapes will increase local stresses and gradients relative to the handbook assumption, and hence give lower crack growth lives and residual strength