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DEFINING A PROCESS FOR STRESS REDUCTION IN THE KEEL TRAY INTERFACE IN UNICOMPARTMENTAL KNEE REPLACEMENT TIBIAL COMPONENTS

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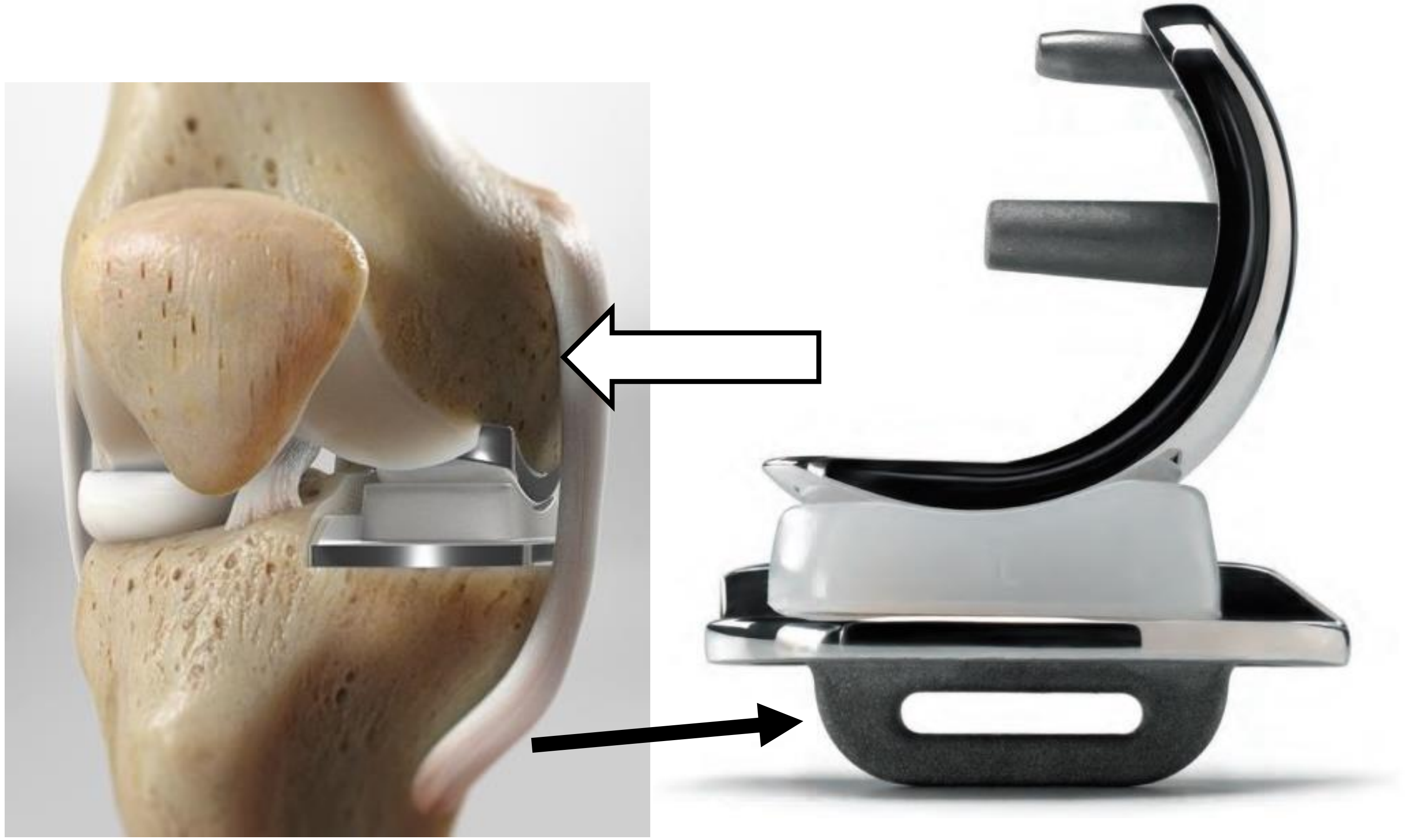
The Oxford Unicompartmental Knee replacement

- 3 Part device
  - Femoral component
  - Meniscal bearing
  - Tibial component

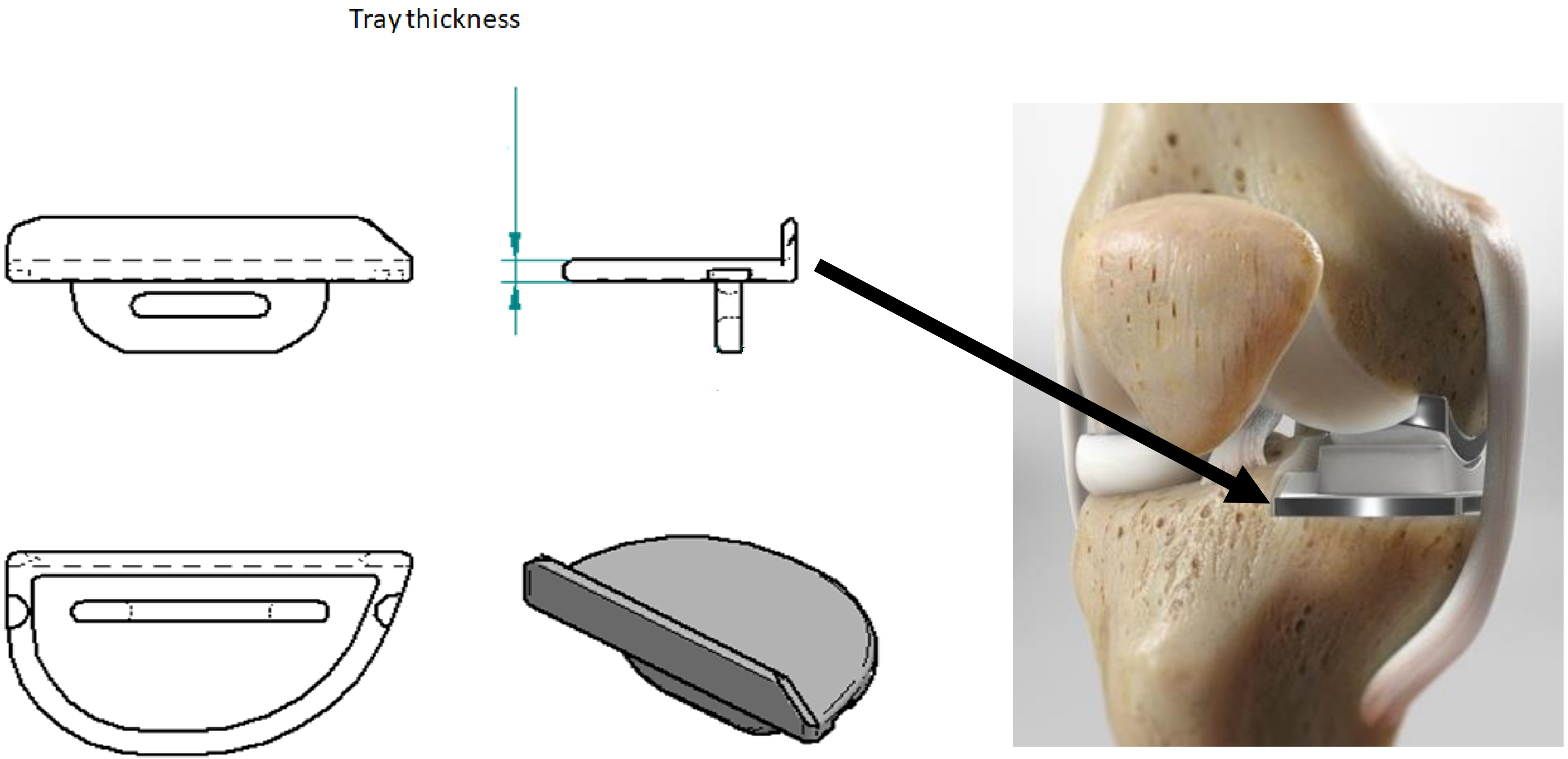
- Design improvement of the tibial section using finite element non-parametric shape optimisation.



Design Driver

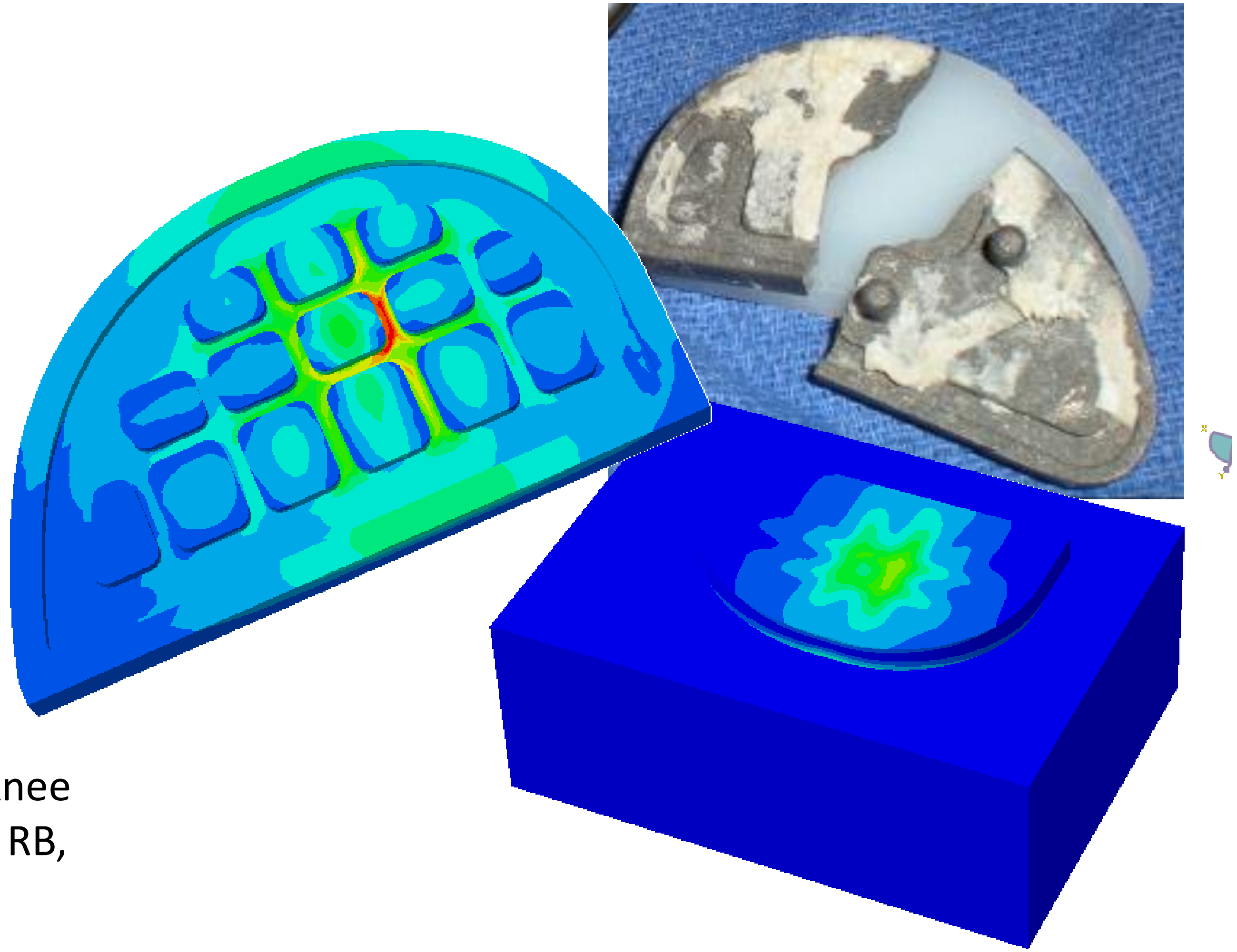
- Minimum bone resection is advantageous

- This can be achieved through reducing the tray thickness



Tray Failure

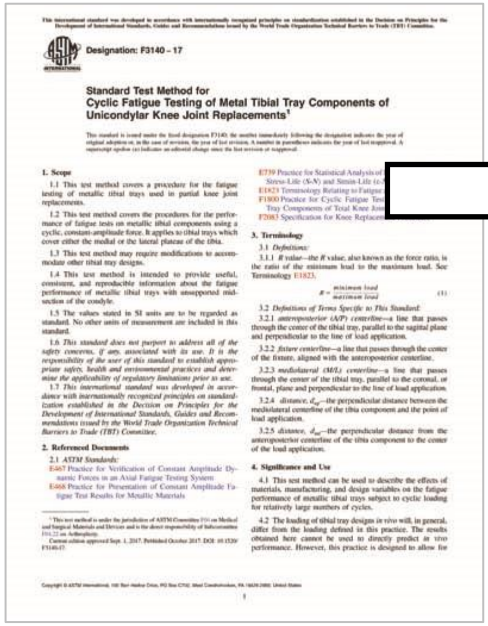
- Structural performance and durability constrain geometric design freedom
- Hasn't ever happened to an Oxford Unicompartmental Knee, but has happened with other devices.



Initial experience of the Journey-Deuce bicompartmental knee prosthesis. Palumbo BT, Henderson ER, Edwards PK, Burris RB, Gutiérrez S, Raterman SJ. *J Arthroplasty* 2011; 26 (6) Suppl 1: 40-45.

ASTM testing

- Test specification
  - Test vs real life vs simulation trichotomy
  - ASTM test doesn't replicate real world usage
  - Almost into codes based design here
  - But its probably the best test case we can apply..
- Finite element models of the test can provide design insights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Standard Test Method for Cyclic Fatigue Testing of Metal Tibial Tray Components of Unicondylar Knee Joint Replacements[1]

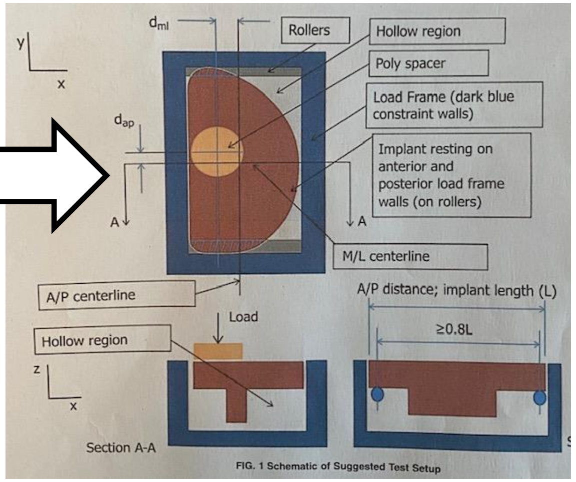
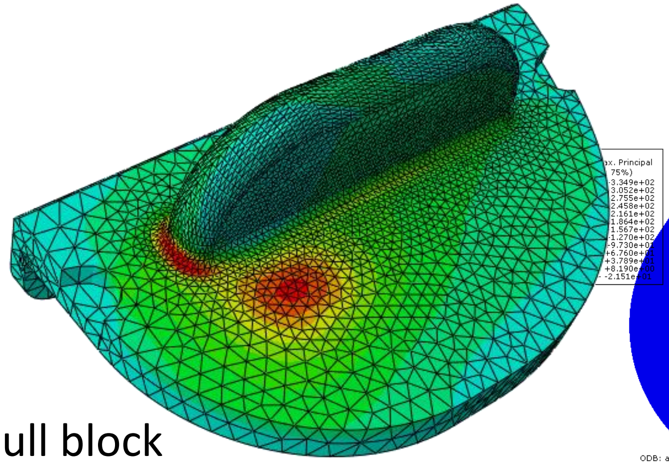
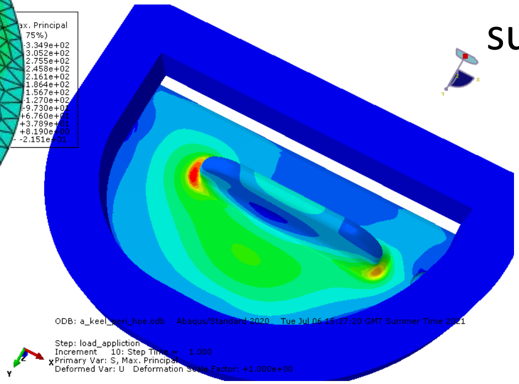


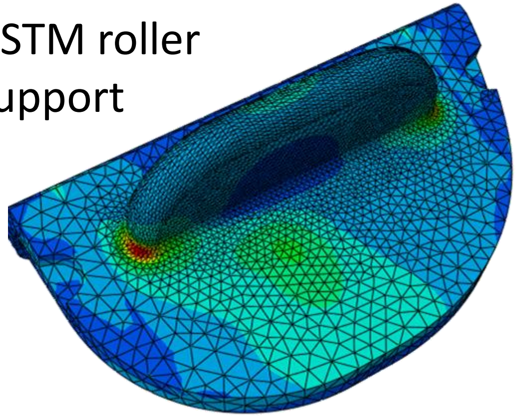
FIG. 1 Schematic of Suggested Test Setup



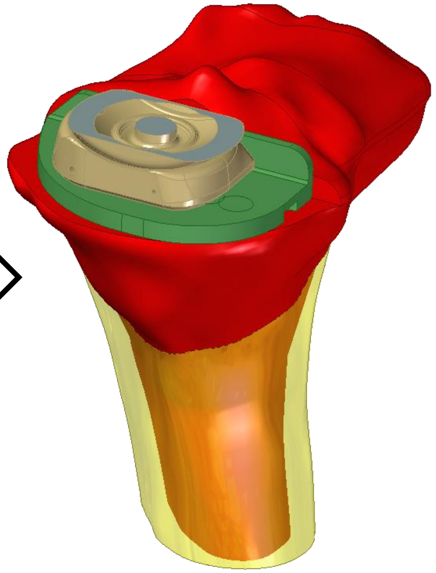
Full block support



Peripheral support



ASTM roller support

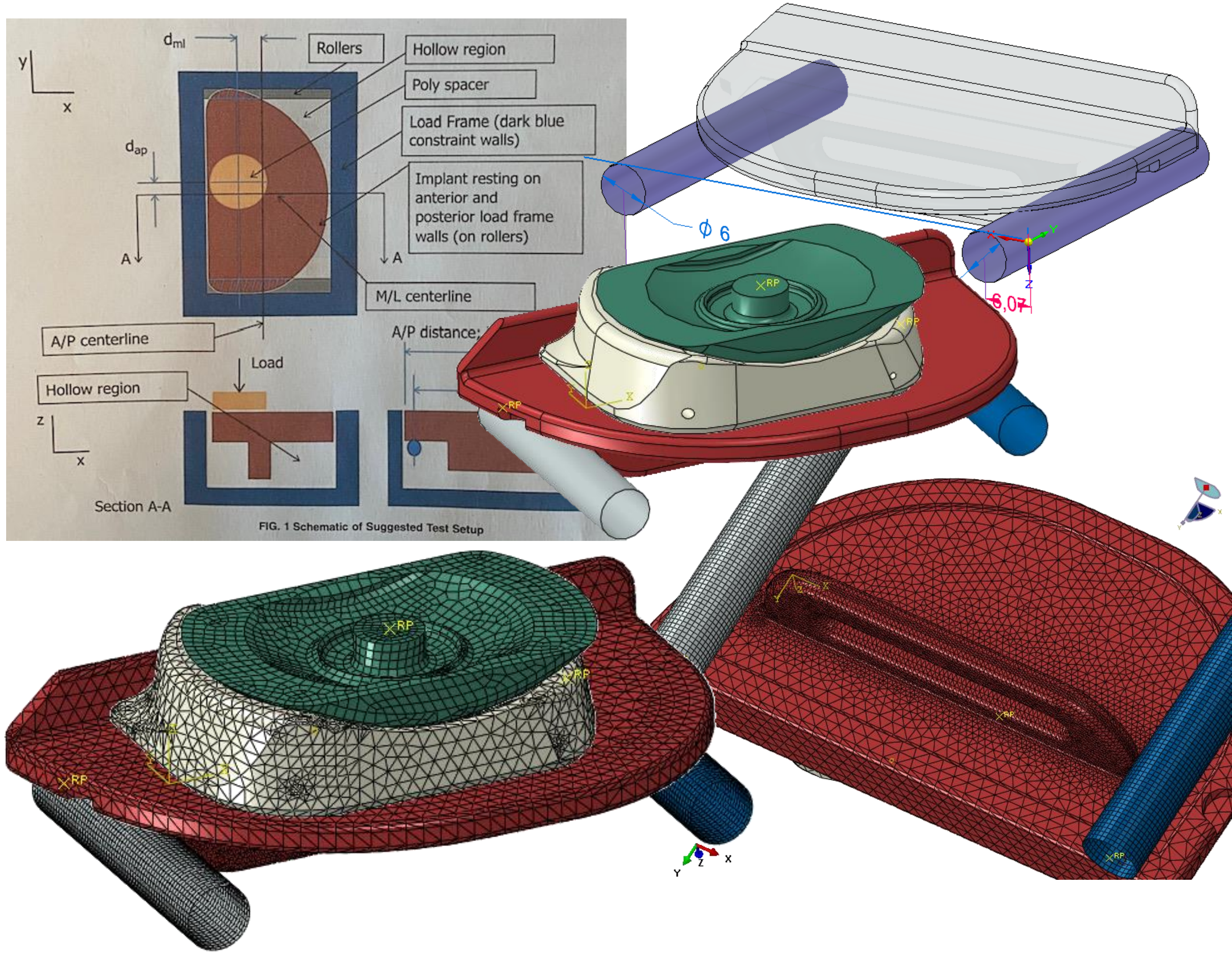


Simulating the ASTM test

- CAD models: NX and Solid Edge
- FEA models: Abaqus CAE and solver.

- Geometry:
  - Implant geometry used without simplification
  - Bearing and Femoral component – used to apply load in realistic manner
  - Rollers – discrete rigid surfaces
  - Femoral device – reduced geometry, discrete rigid surface
- Contact:
  - Surface to surface contact

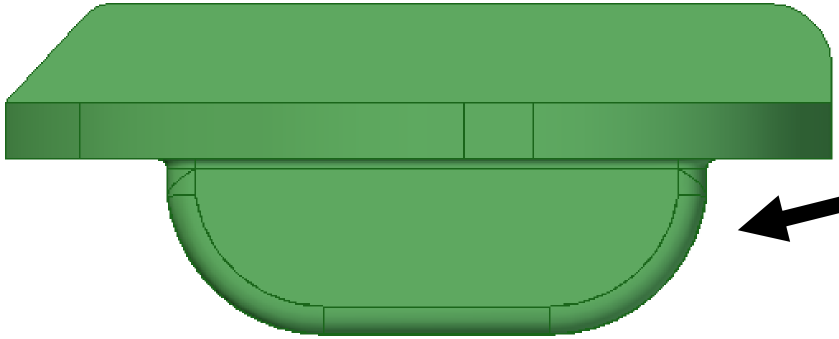
- Higher order tetrahedral elements in all deformable components.
- High levels of local mesh refinement

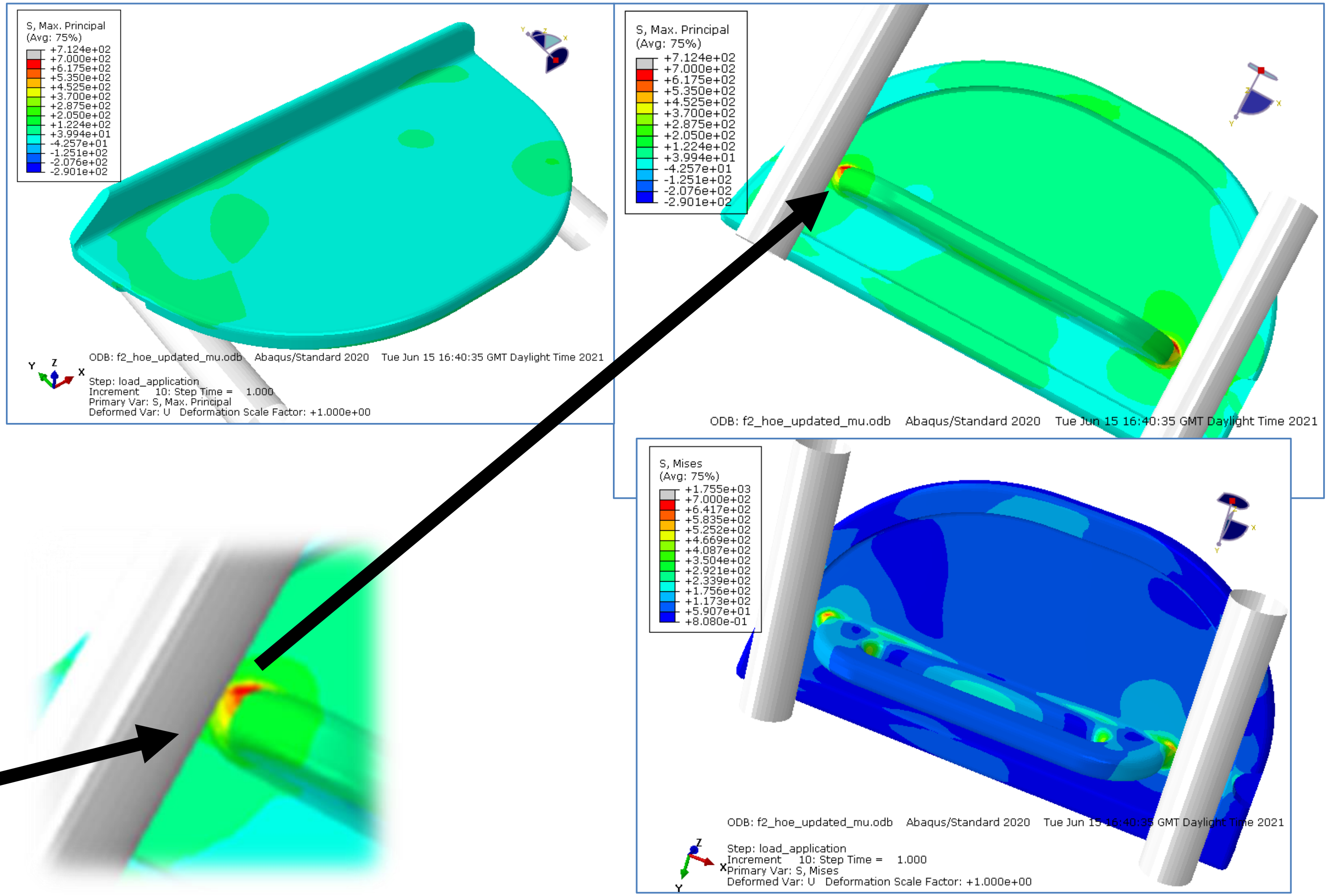


Simulating the ASTM test

- A range of sizes were analysed - stress results were always dominated by the stress in the keel tray intersection.

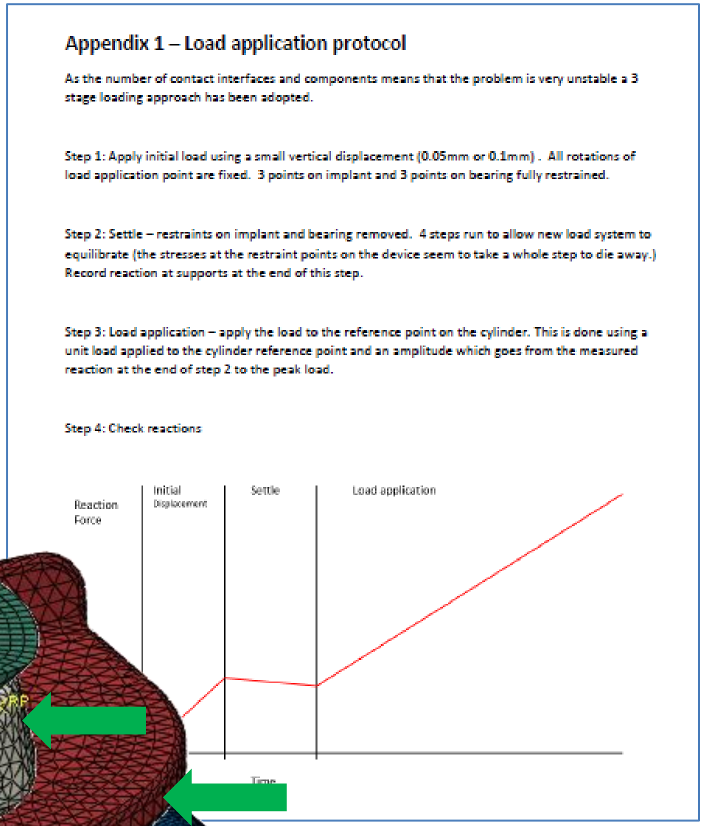
- We didn't have any fatigue allowable's for the material, or knock down factors for surface finish etc
- So in this study we used the results of a device know to pass the test as a benchmark
- But this is a workflow presentation on design improvement processes..





Simulating the ASTM test

- Challenges
  - Solution timescales – typically 4-24hrs depending on model geometry, contact convergence etc.
  - Instability – loading protocol developed to control



Appendix 1 – Load application protocol

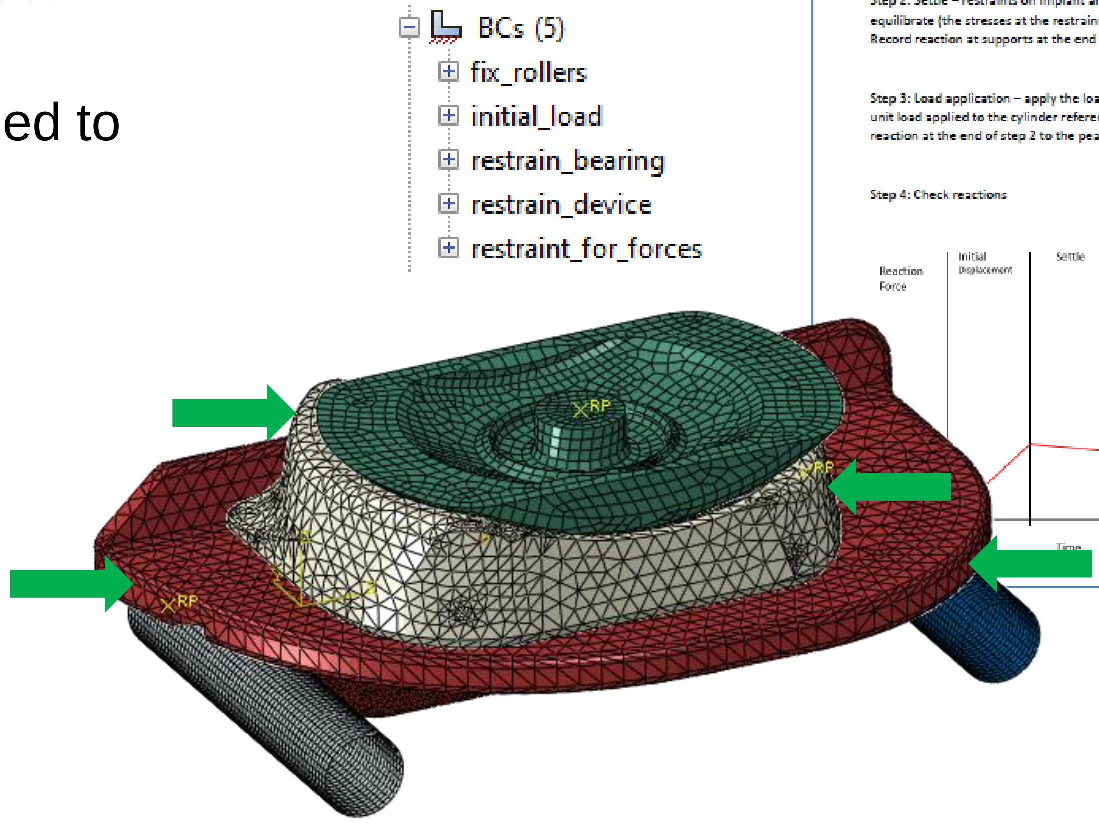
As the number of contact interfaces and components means that the problem is very unstable a 3 stage loading approach has been adopted.

Step 1: Apply initial load using a small vertical displacement (0.05mm or 0.1mm) . All rotations of load application point are fixed. 3 points on implant and 3 points on bearing fully restrained.

Step 2: Settle – restraints on implant and bearing removed. 4 steps run to allow new load system to equilibrate (the stresses at the restraint points on the device seem to take a whole step to die away.) Record reaction at supports at the end of this step.

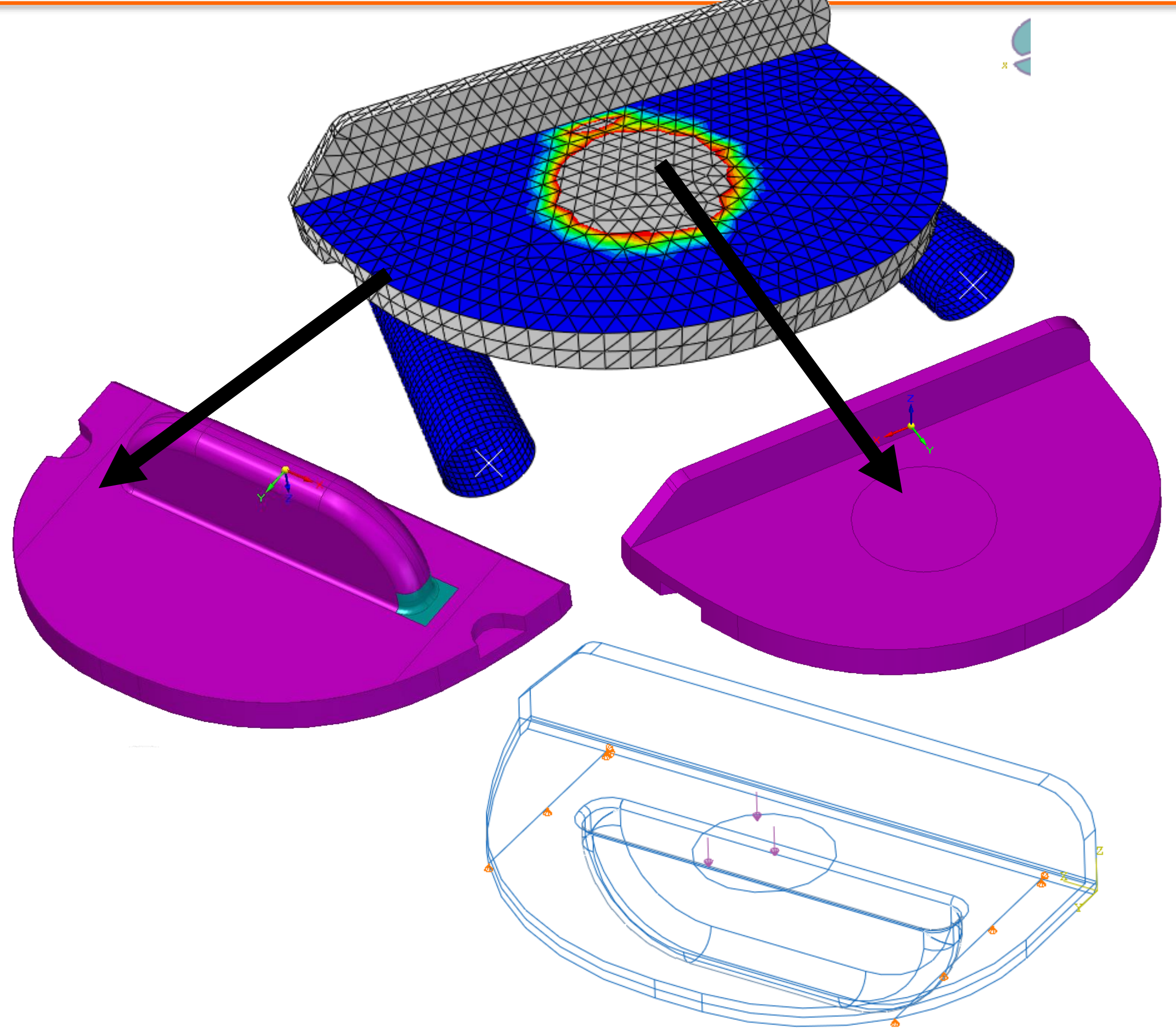
Step 3: Load application – apply the load to the reference point on the cylinder. This is done using a unit load applied to the cylinder reference point and an amplitude which goes from the measured reaction at the end of step 2 to the peak load.

Step 4: Check reactions



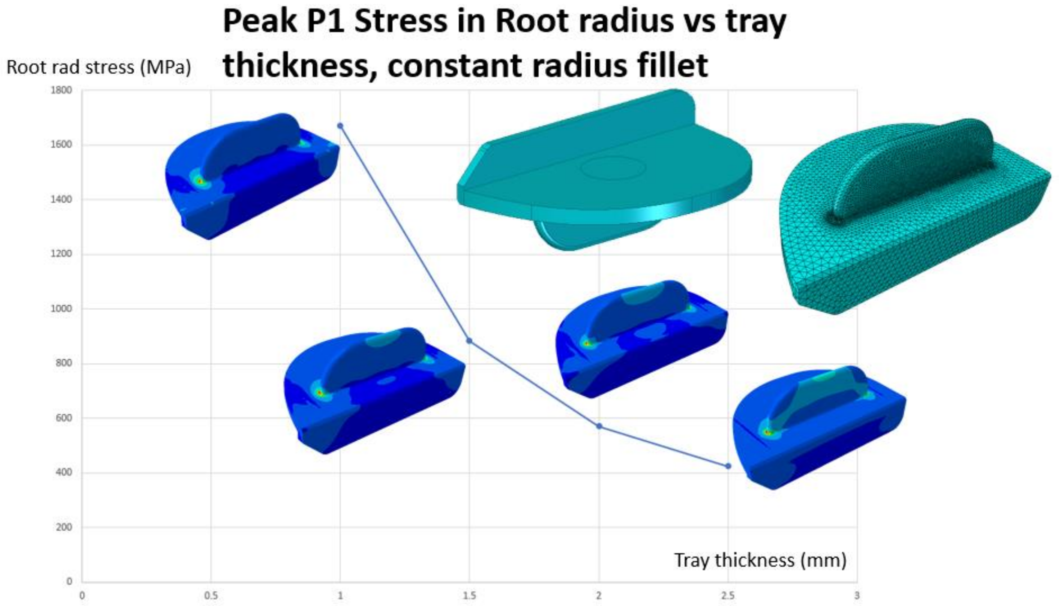
The need for a rapid solution

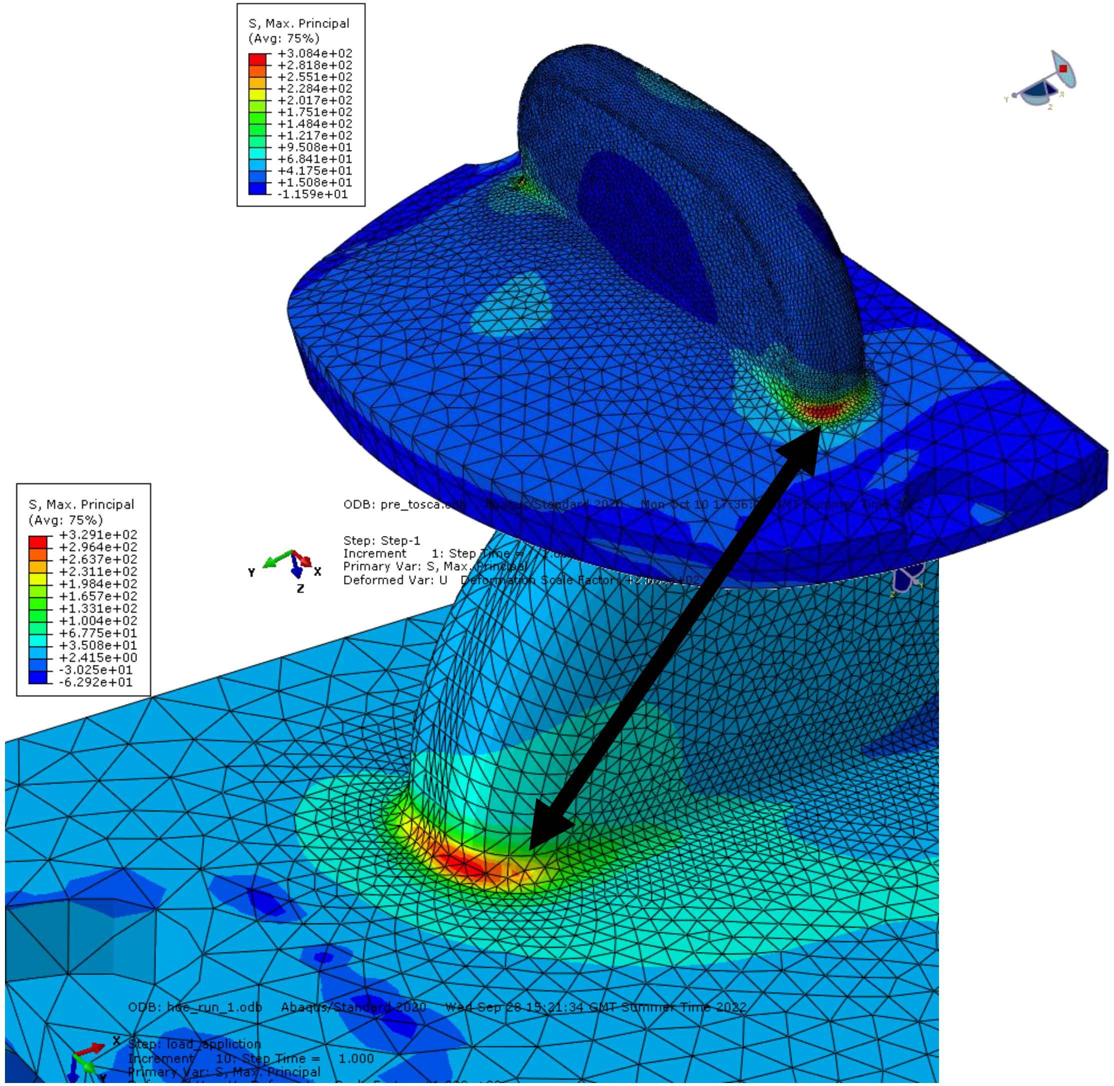
- Design improvement means we need to investigate the designspace, but each point is computationally very expensive.
- Reduce model complexity to increase solution speed with minimal reduction in solution accuracy.
  - Replace contact regions with line constraints or load patch (size taken from contact pressure region on contact model).
  - Redraw simplified geometric representation – not simplify original.
- Solution times fall from many hours to several minutes.



The rapid solution?

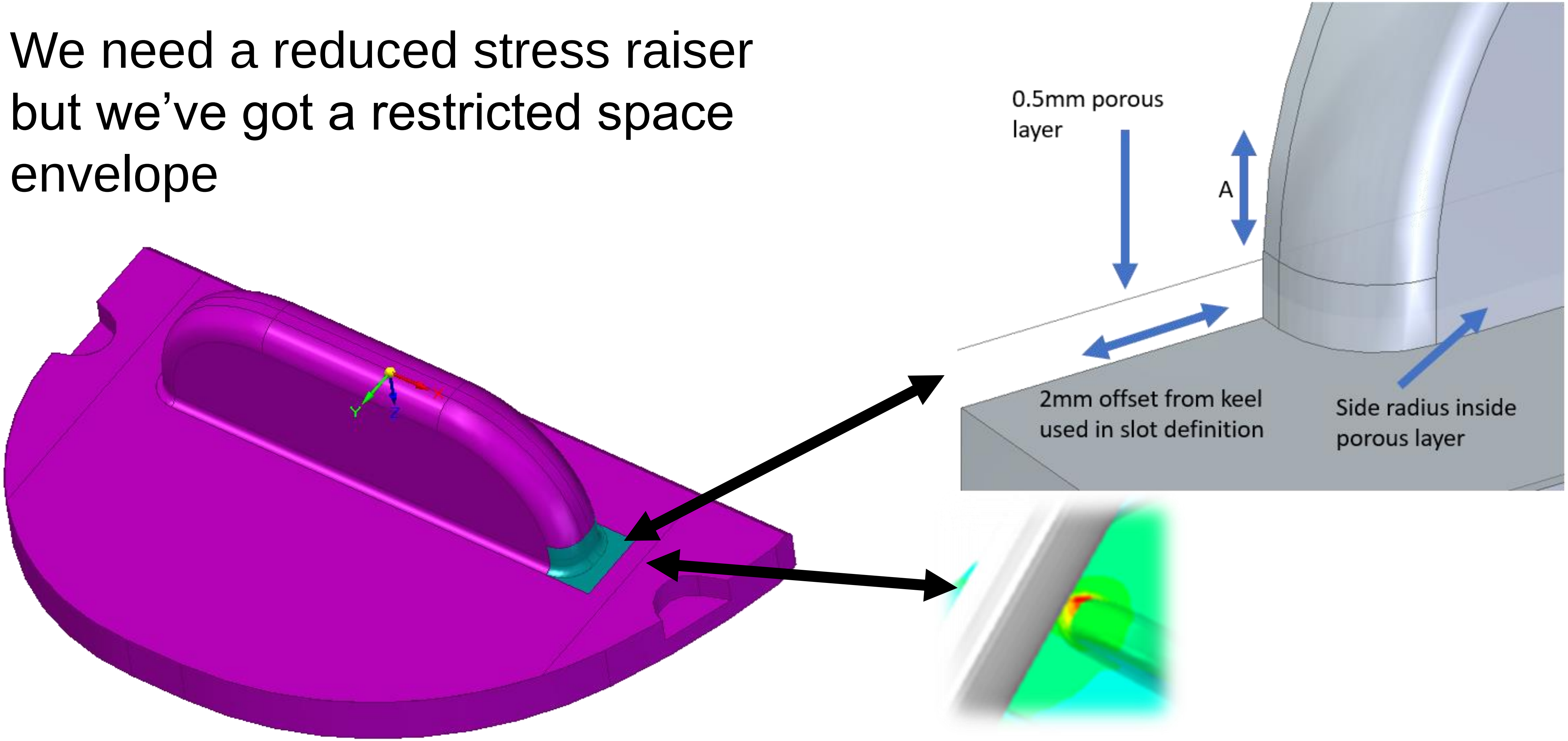
- Less than 10% difference between complex contact model and simplified case
- Changing model geometries is rapid and straightforward. (And enables automation)





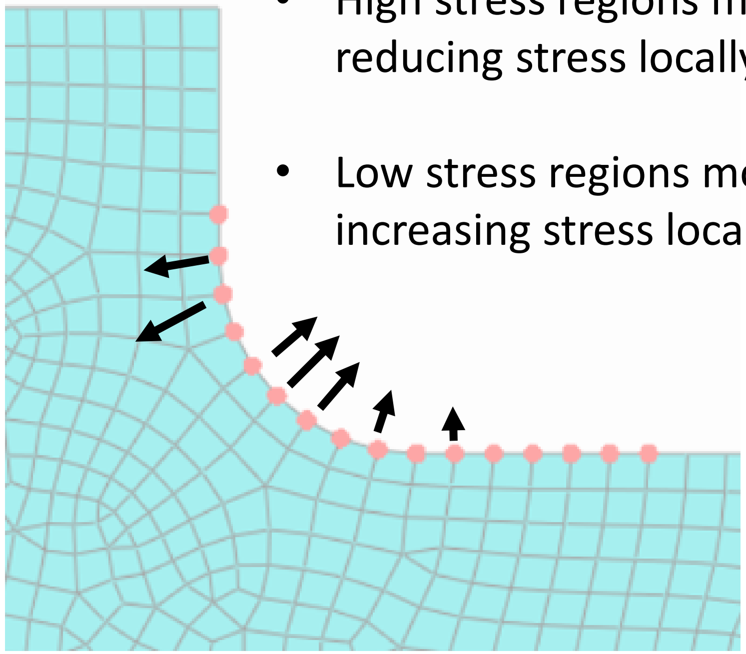
Looking at the design envelope

- We need a reduced stress raiser but we've got a restricted space envelope



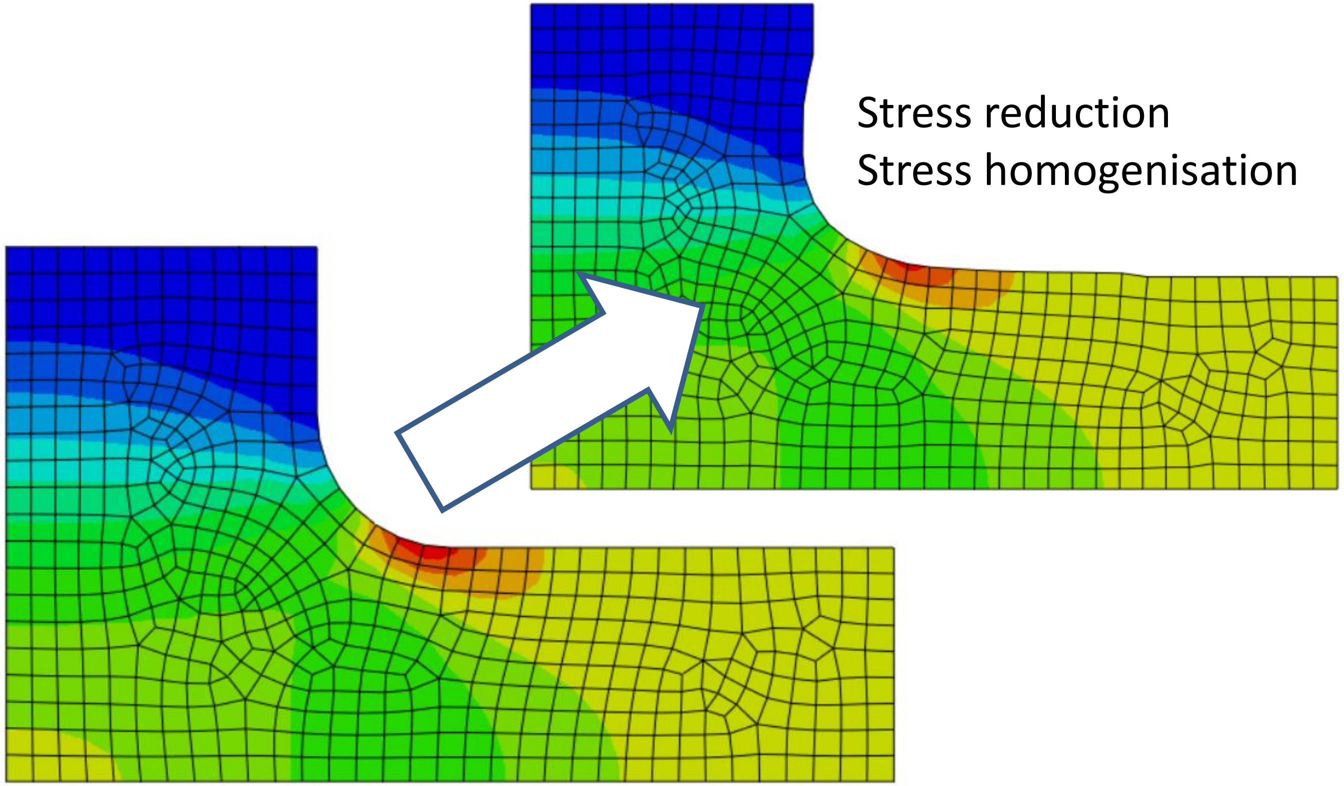
Optimising the fillet radius

- Bigger fillet radius works, but exceeds the design restriction region
- Non-parametric shape optimisation offers a way forwards.



- High stress regions move out, reducing stress locally

- Low stress regions move in, increasing stress locally



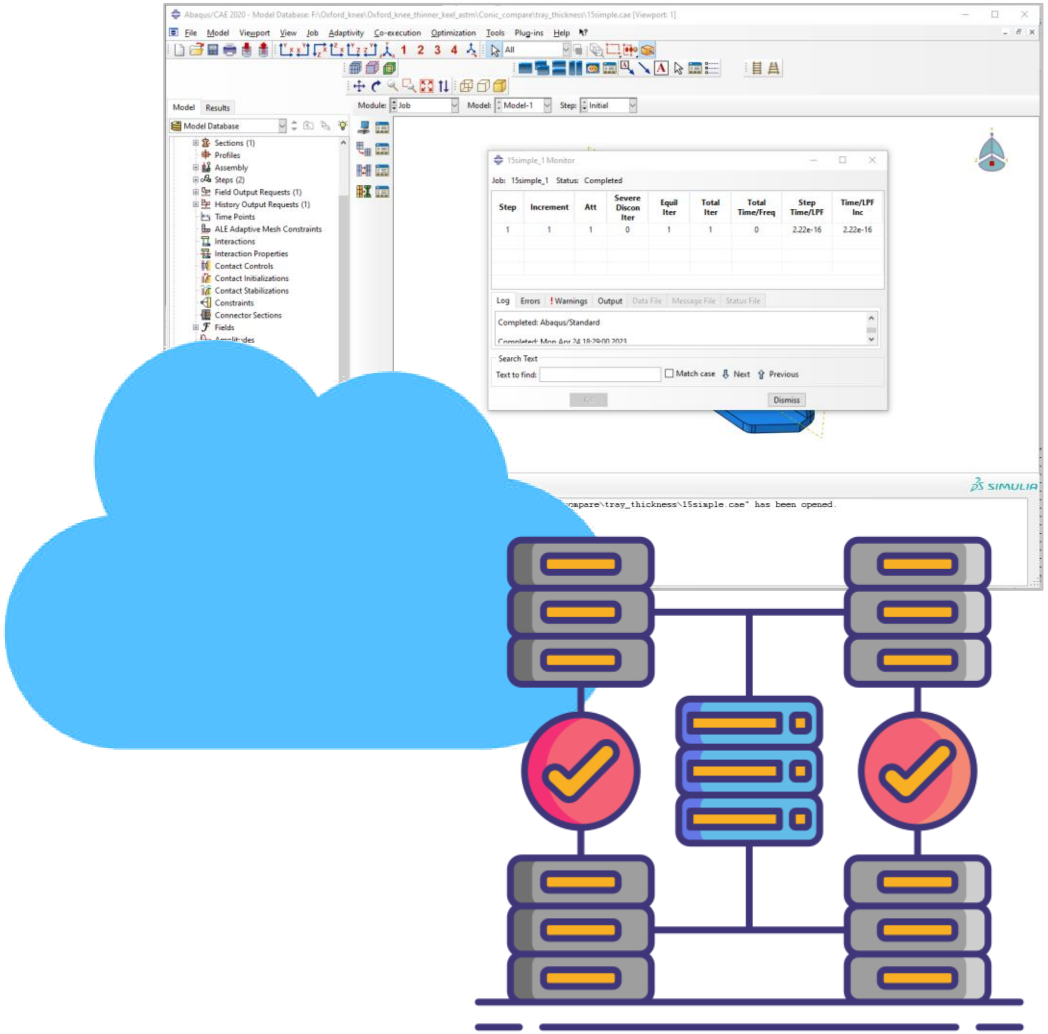
Some solve time metrics

- Multicore solution of contact model: min 4hrs
- Number of solution cycles for optimisation: approx. 60
- Number of optimisation cycles to achieve useful solution: typically 4

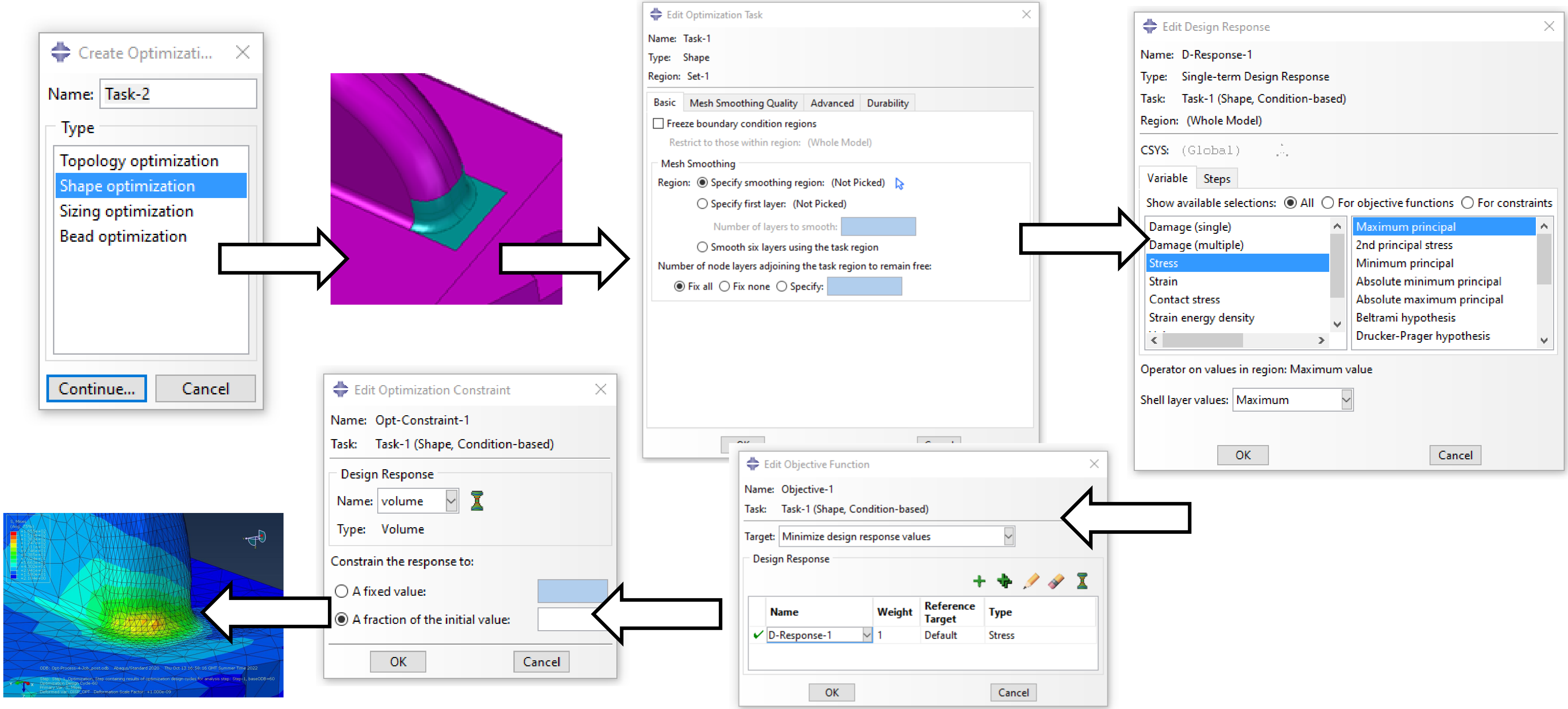
- Which gives us 960 hours solve time
- **40 days**

- It’s a sequential process so cloud, cluster, parallel, GPU won’t help you.

- Which effectively means this is unsolvable without a simplified model



Implementation of the process Abaqus /TOSCA



Results of non-parametric optimisation

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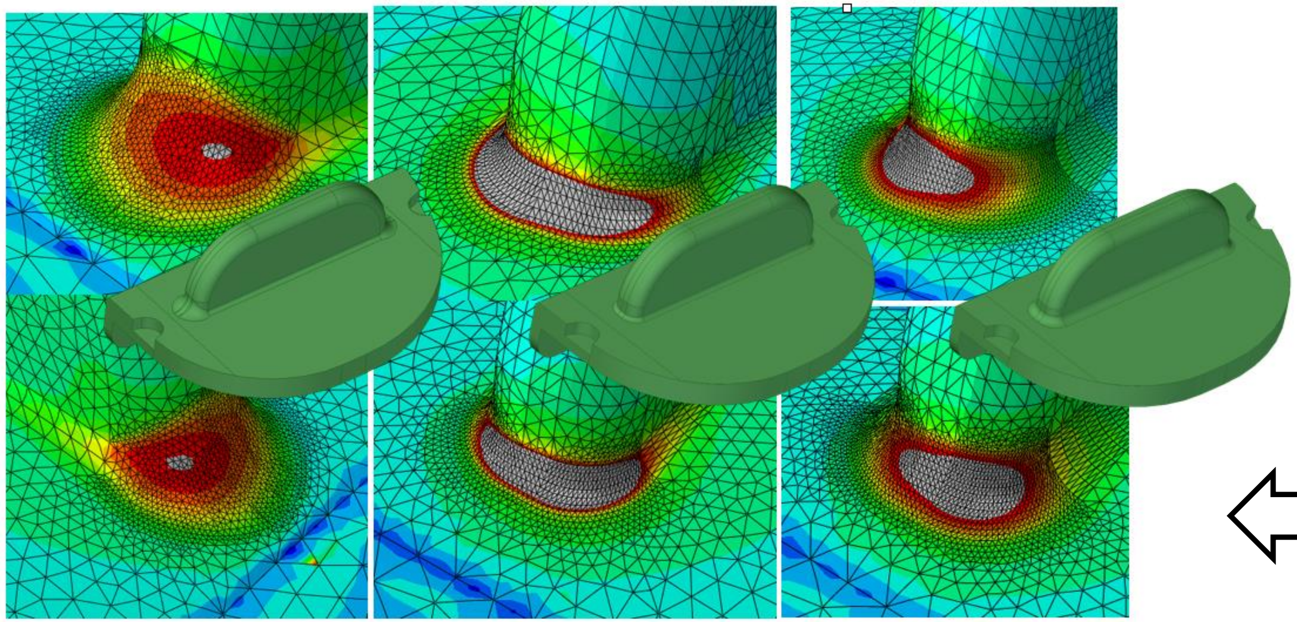
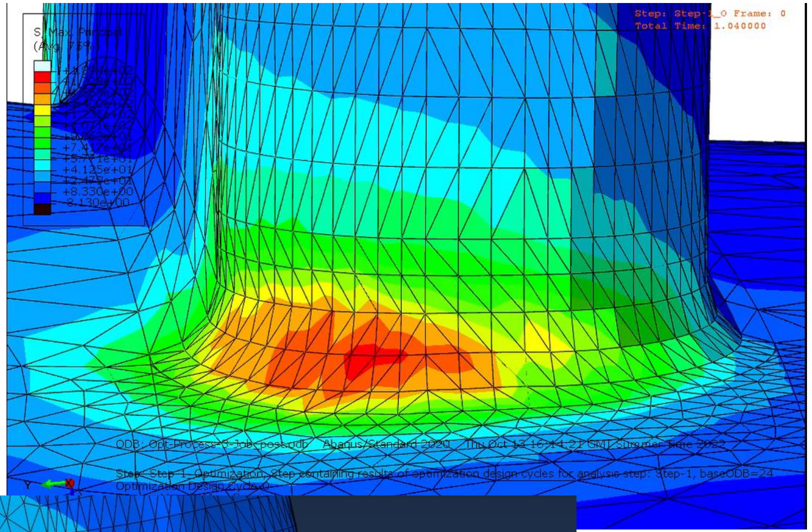
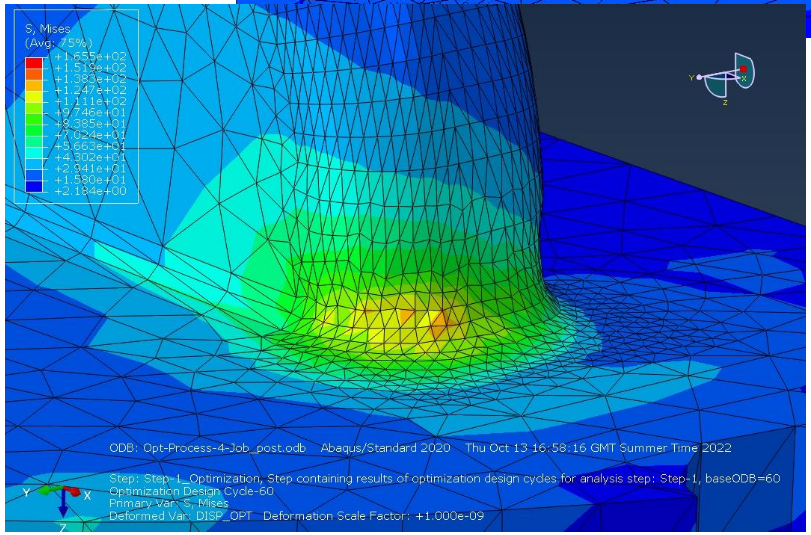
- Non-parametric shape gives significant stress reduction and significant reduction in stress gradient

2mm to 0.5mm fillet | 0.5mm fillet | 1mm fillet



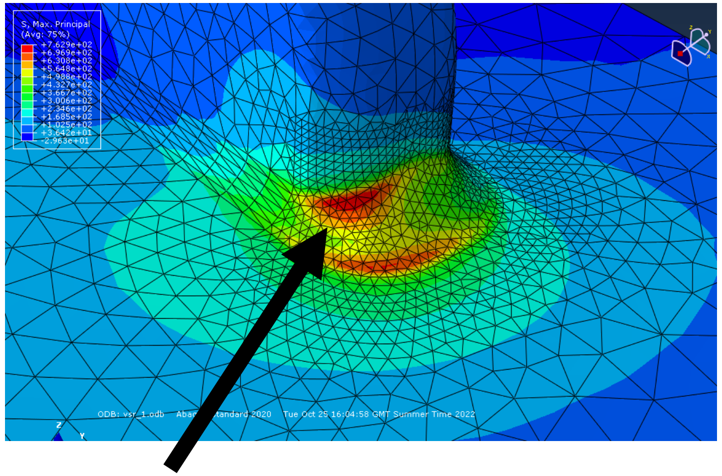
Peak – 142MPa | Peak – 250MPa | Peak – 175MPa



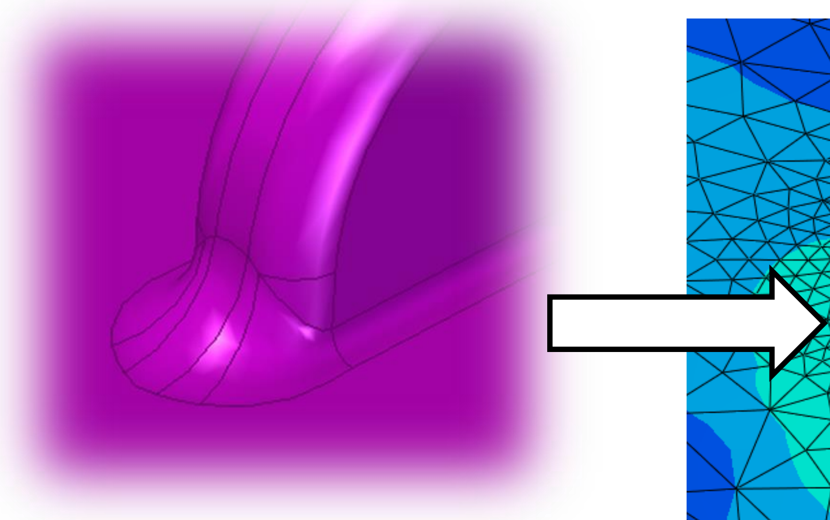


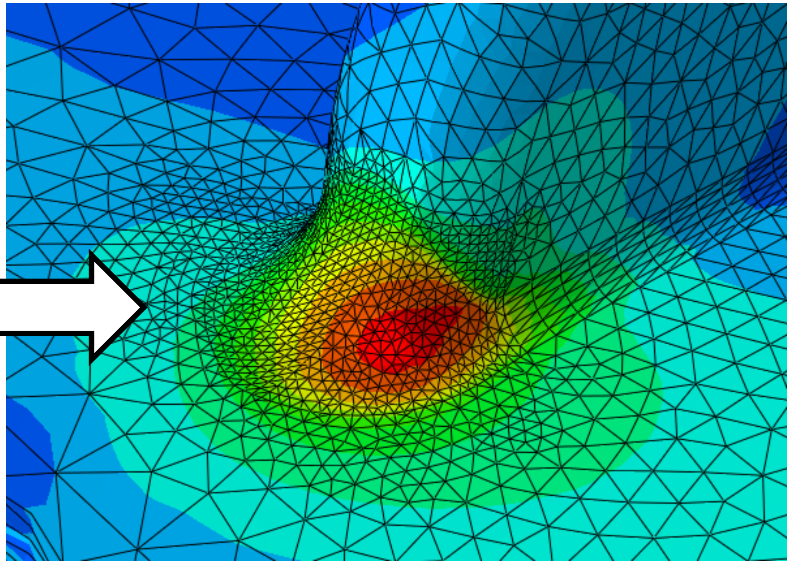
Transferring the shape data

- To be useful we have to convert the non-parametric nodal positions into parametrically defined forms which can be scaled across the range of device sizes.
- Defining a CAD model form that didn’t re-introduce stress raisers proved challenging



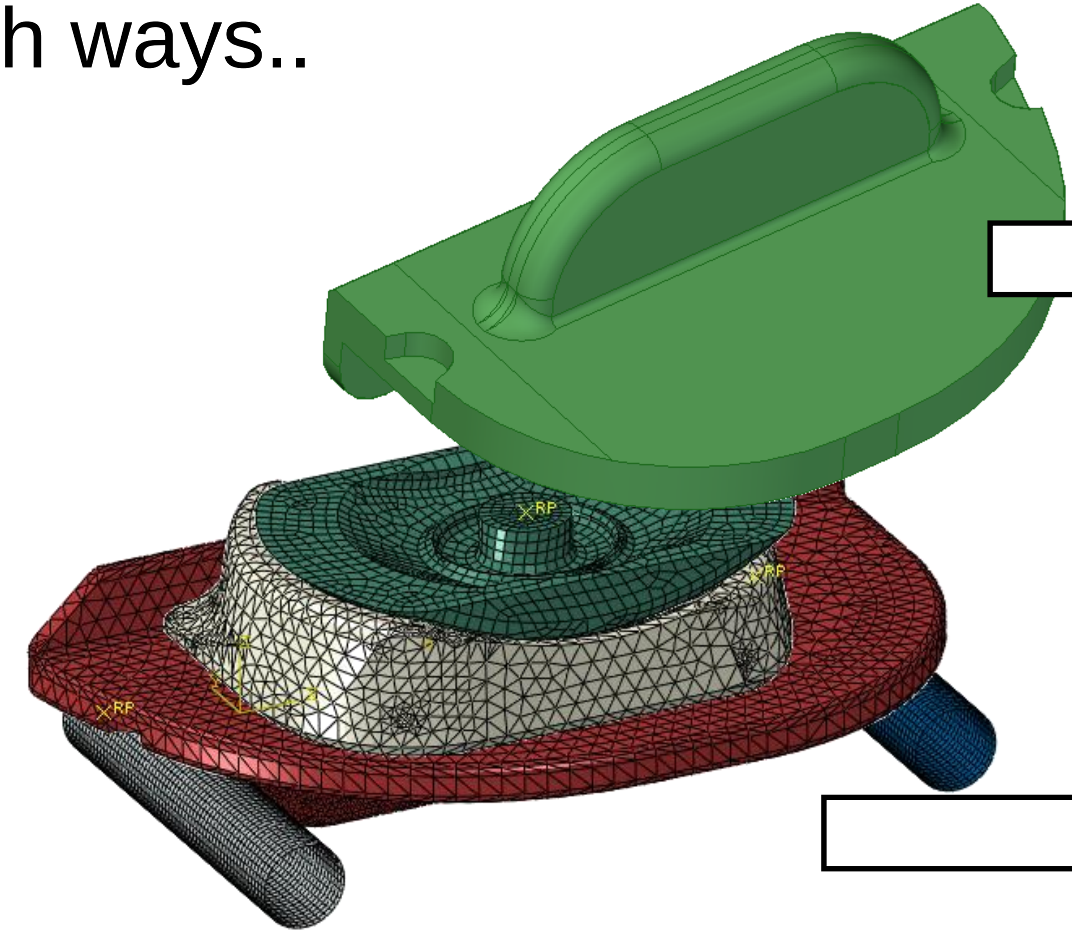
Lack of tangency in this region has reintroduced a stress raiser.

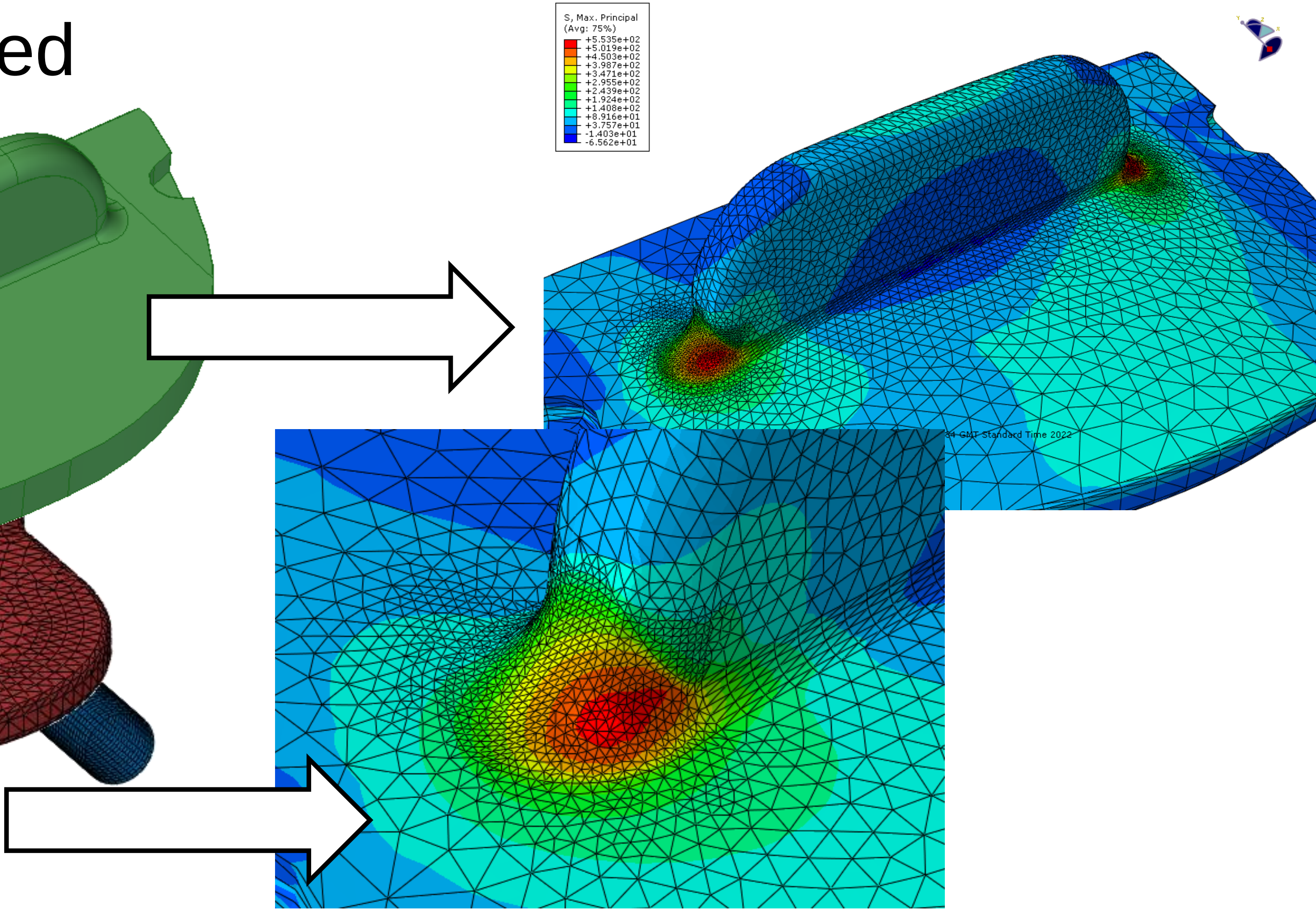




“Validate” simple model using complex interaction model

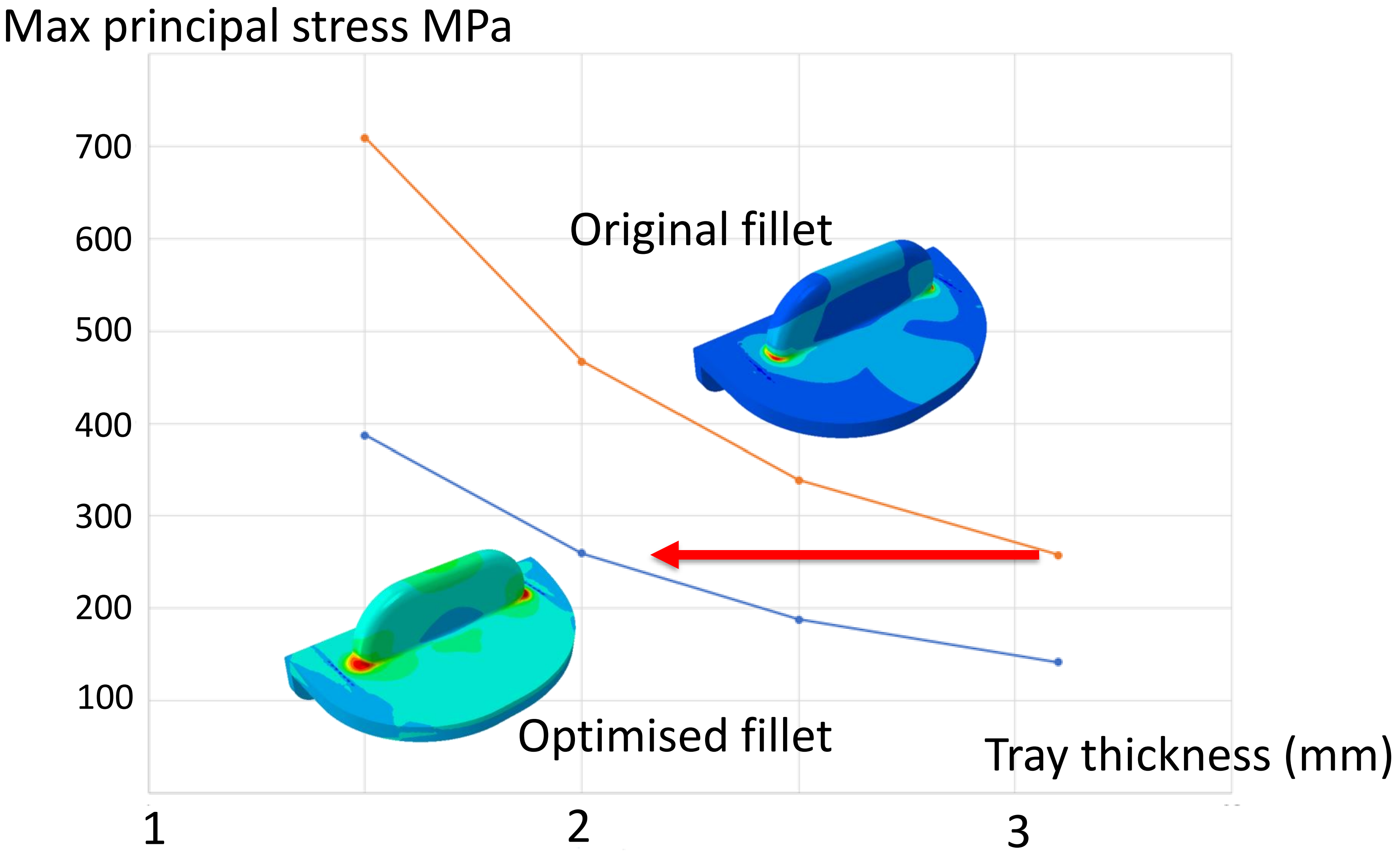
- Optimised design analysed both ways..





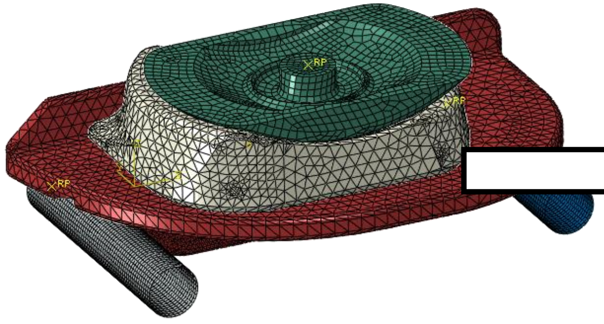
Tray thickness results

- New fillet geometry reduces stress across a range of tray thicknesses.
- Critically allowing a reduction of tray thickness without increase in stress level.

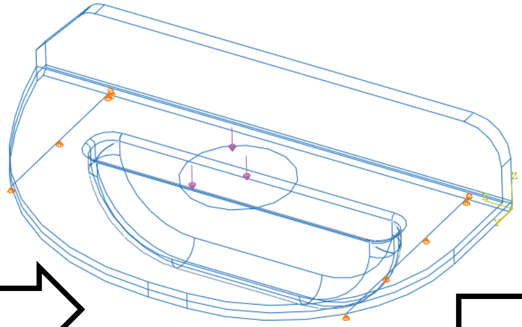


Process Map

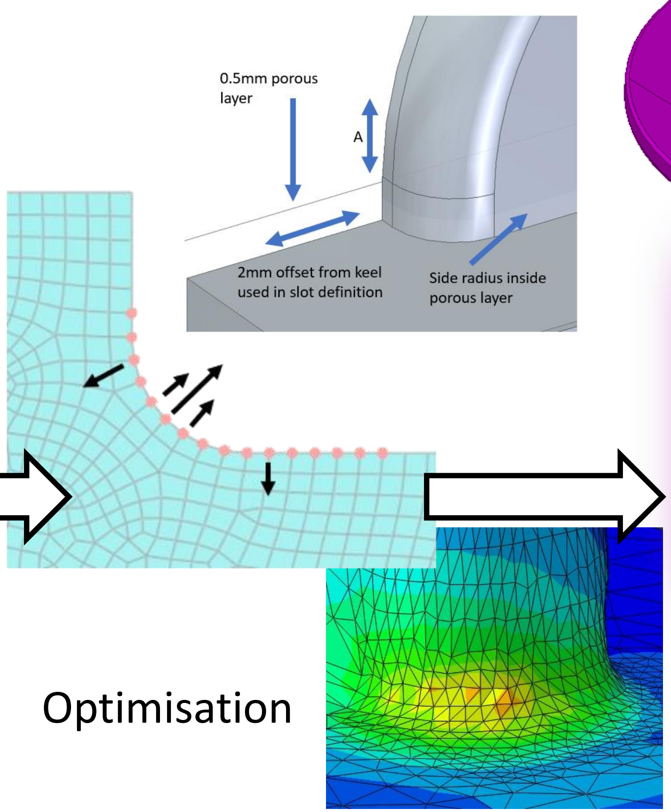
- Mapped process reduces optimisation timescales and effort to industrially relevant levels.



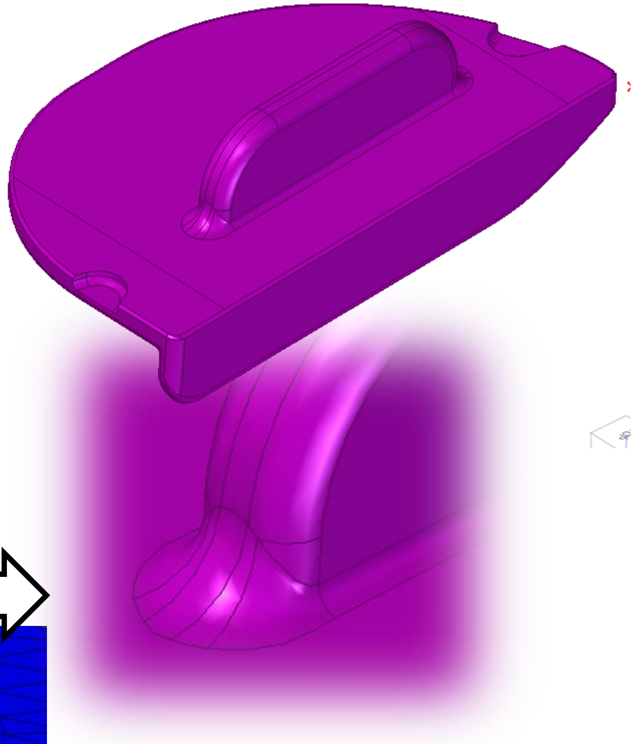
Create detailed FEA model



Idealised FEA representation



Optimisation



Implementation and parametrisation in CAD

Conclusion

- Non-parametric shape optimisation of the critical radius has unlocked regions of the designspace, improving component performance. The new fillet radius has allowed us to create a safe design with a thinner tray.
- This technology (and other optimisation and design space exploration techniques) can only be applied when simulation models are optimised and reduced in order to create meaningful, industrially relevant, analysis timescales.