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27/06/23

Multiaxial Crack Growth Prediction

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Supervisor: Professor David Nowell

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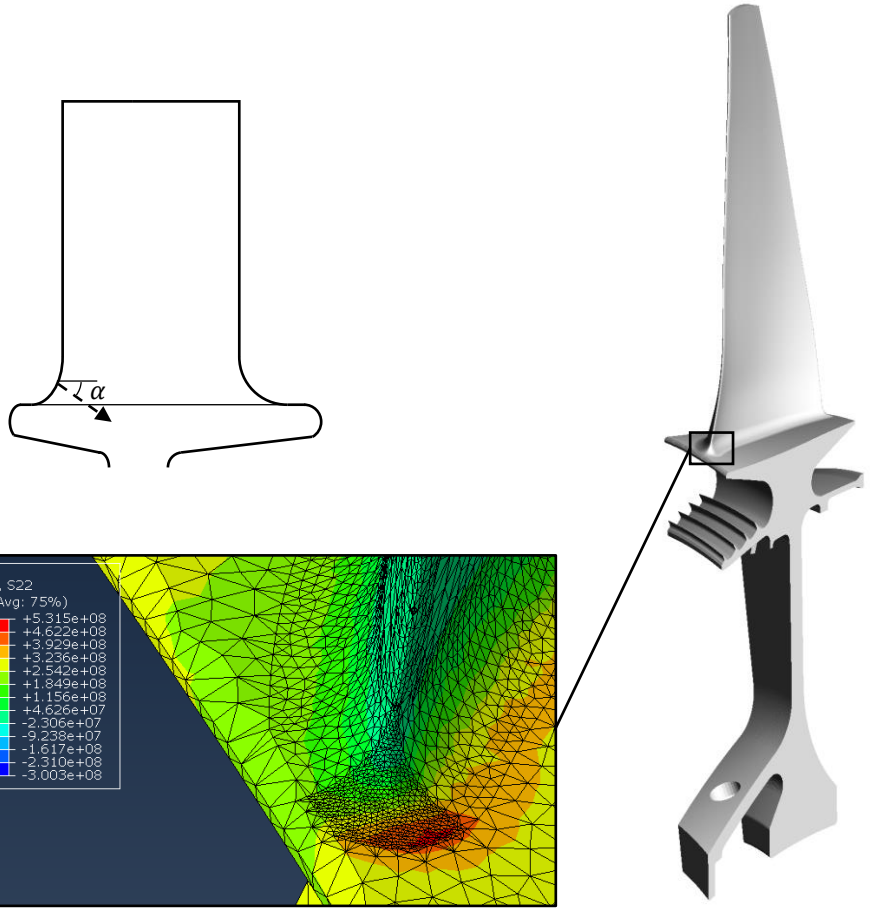
Problem overview

- Foreign object damage (FOD) in the fillet region of the leads to crack growth
- Depending on the location of the crack it may propagate to the bore of the disk



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Objectives

- Design an experimental geometry to replicate the features of non-proportional crack propagation in aeroengine disks
- Carry out experiments to establish practical growth trajectories under controlled conditions
- Develop an improved criterion for the prediction of crack direction and, if possible, growth rate

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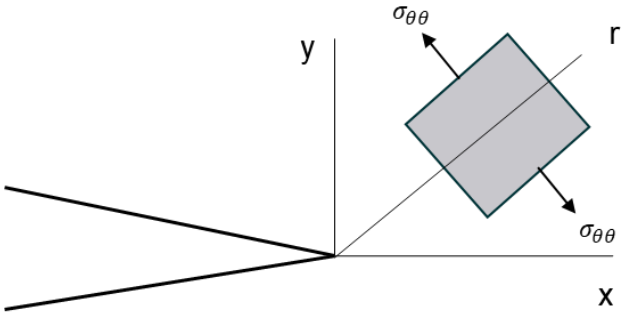
Crack growth mechanism



- Different crack direction criteria available
- Correct criterion is material dependent
- Transition between criteria is possible
- Maximum tensile stress:
  - $\sigma_{\theta\theta} = \frac{1}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \left[\Delta K_I \cos\left(\frac{\theta}{2}\right) - \frac{3}{2} \Delta K_{II} \sin(\theta)\right]$

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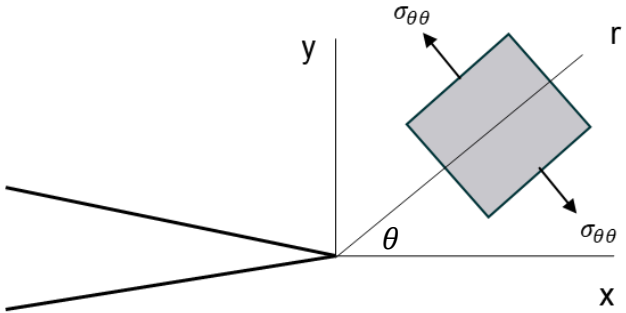
Non-proportional loading

- Non-proportional loading affects growth rate and trajectory
- Variable mode-mixity
  - Multiple local load maxima in one cycle
- Crack tip shielding



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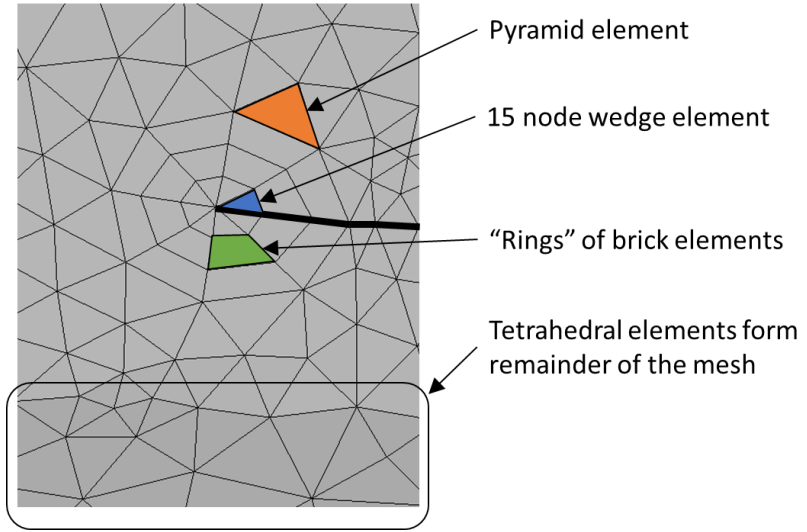
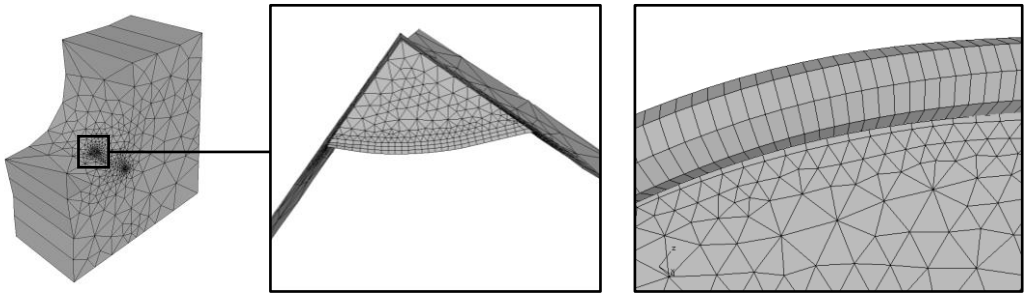
Crack modelling approach

- Contour integral to compute stress intensity factors (SIFs) in Abaqus + FRANC3D
- Incremental crack growth through remeshing
- Limited non-proportional crack growth modelling





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Crack modelling approach

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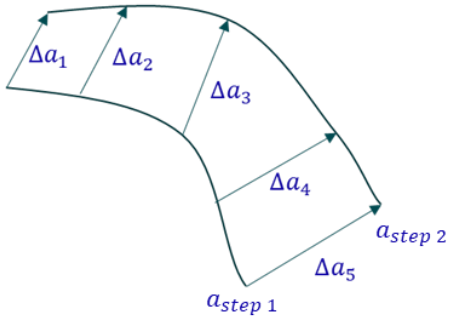

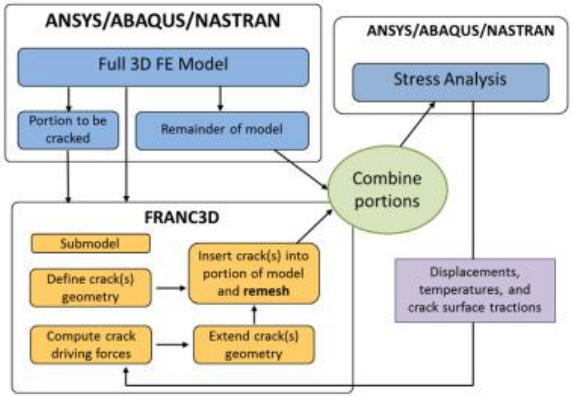

FRANC3D workflow [1]

[1] P. A. Wawrzynek, B. J. Carter, and A. R. Ingraffea, “Advances in simulation of arbitrary 3D crack growth using FRANC3D/NG,” 12th Int. Conf. Fract. 2009, ICF-12, vol. 1, pp. 344–354, 2009.

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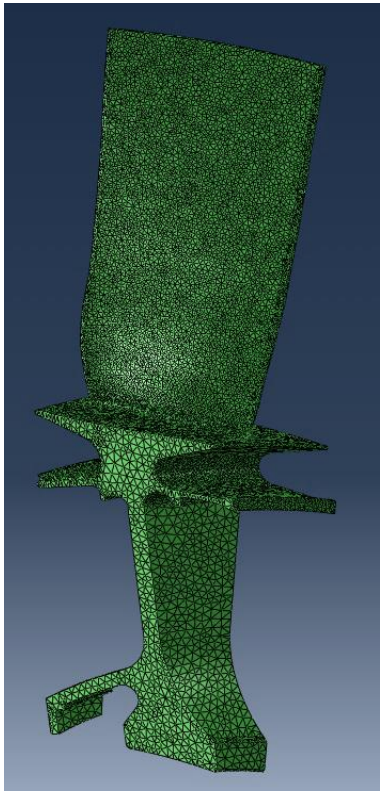
Loading

- Crack is subject to mixed-mode I/II/III loading

- LCF loading: rotational and thermal loads
- HCF loading: vibration



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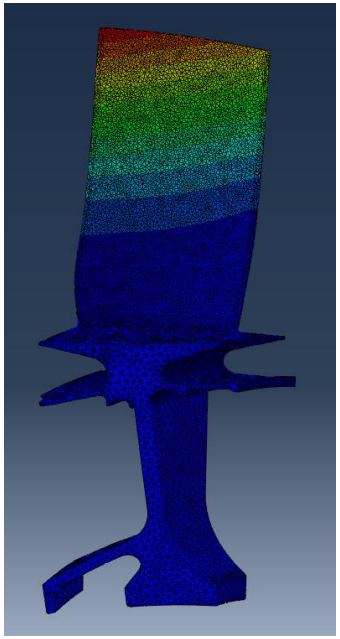
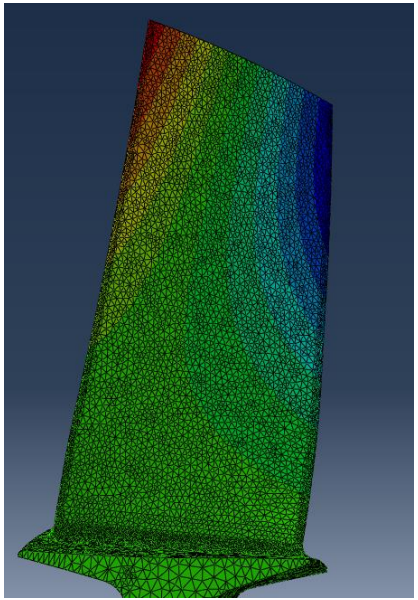
Mode shapes

- Static mode shapes:
  - 1st flap: 198.15 Hz
  - 1st torsion: 672.46 Hz





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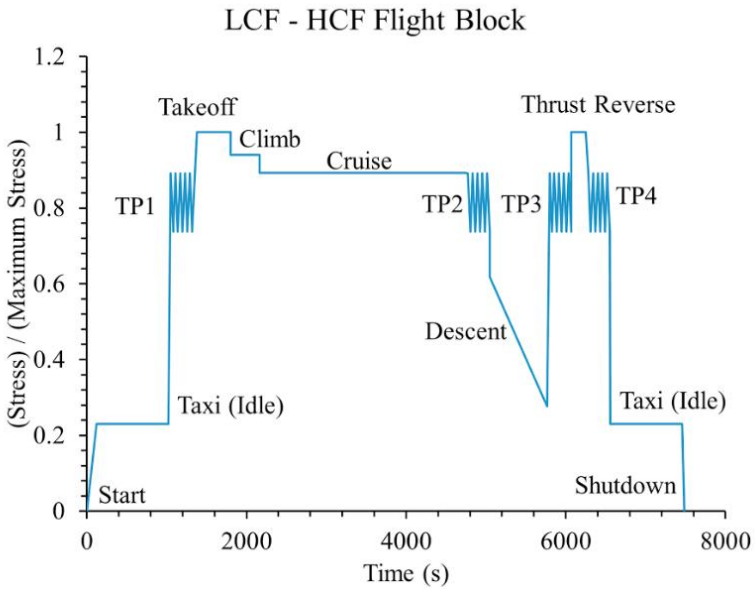
Crack growth mechanism

- Combination of high-cycle and low-cycle loading
- Previous work on compressor blades showed HCF to be the primary mechanism of fracture [2]
- Initial LCF growth until HCF threshold
- Subsequent HCF + LCF



Minor cycle of 'Descent-Thrust Reverse-Taxi' and a major cycle of 'Start-Takeoff-Shutdown' [1]

[2] D. Mangardich, F. Abrari, and Z. Fawaz, "Modeling crack growth of an aircraft engine high pressure compressor blade under combined HCF and LCF loading," *Eng. Fract. Mech.*, vol. 214, no. April, pp. 474–486, Jun. 2019, doi: 10.1016/j.engfracmech.2019.04.028.

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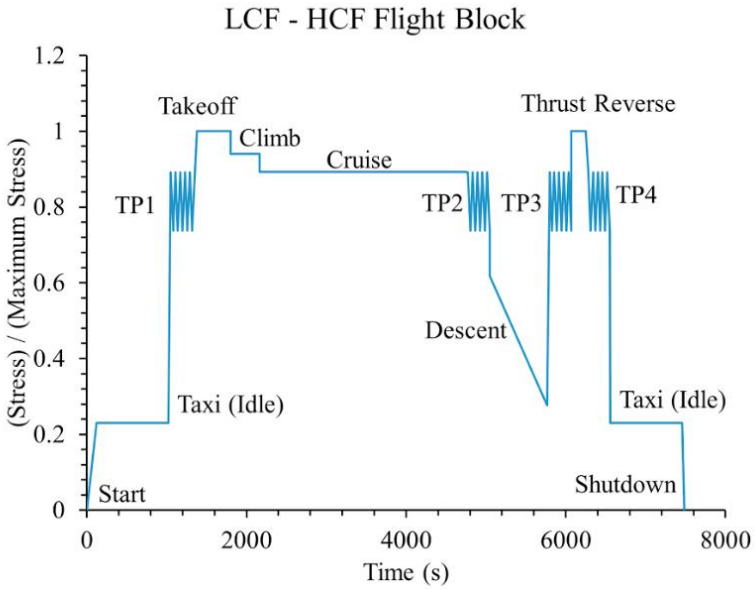
Crack growth mechanism

- Transition from short crack to long crack behaviour at 50 μm for Ti alloys [3]
- 125 μm assumed initial crack depth



Minor cycle of 'Descent-Thrust Reverse-Taxi' and a major cycle of 'Start-Takeoff-Shutdown' [1]

[3] Nicholas T. Chapter 4: LCF-HCF Interactions. High Cycle Fatigue - A Mechanics of Material Perspective. Ohio: Elsevier; 2006

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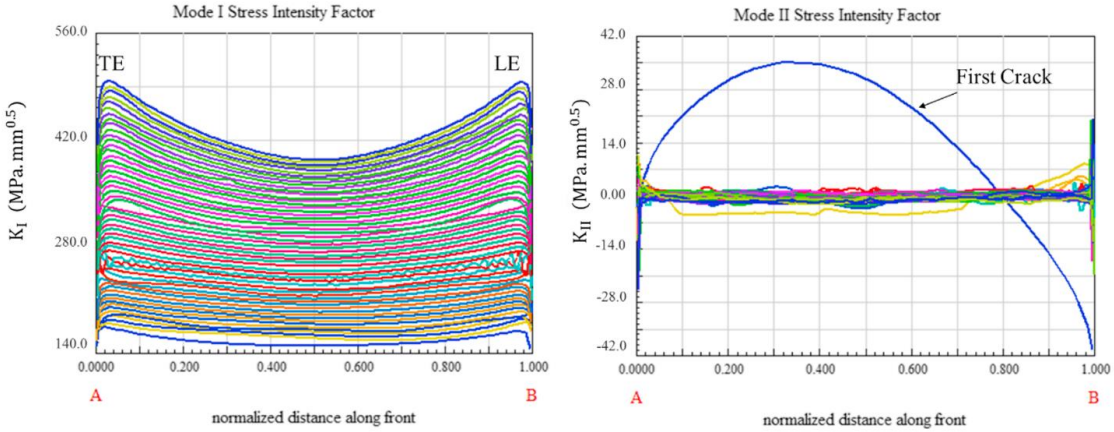
Crack growth simulation

- Crack growth simulation of LCF component completed in FRANC3D + Abaqus
- Crack paths kink to satisfy MTS leading to $\Delta K_{II} = 0$



Mode I and II stress intensities along first 55 crack fronts under pure LCF loading (A=TE, B=LE) [1]

[1] P. A. Wawrzynek, B. J. Carter, and A. R. Ingraffea, “Advances in simulation of arbitrary 3D crack growth using FRANC3D/NG,” 12th Int. Conf. Fract. 2009, ICF-12, vol. 1, pp. 344–354, 2009.

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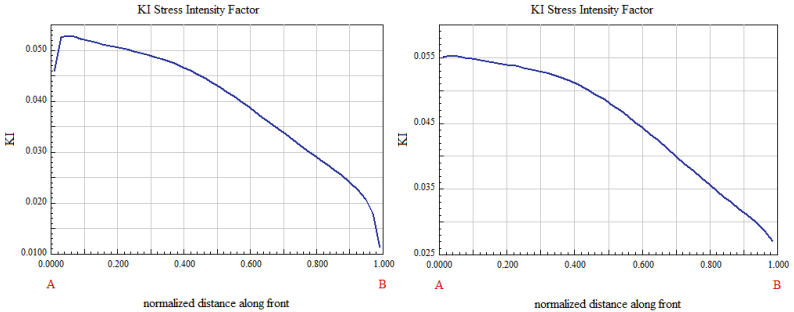
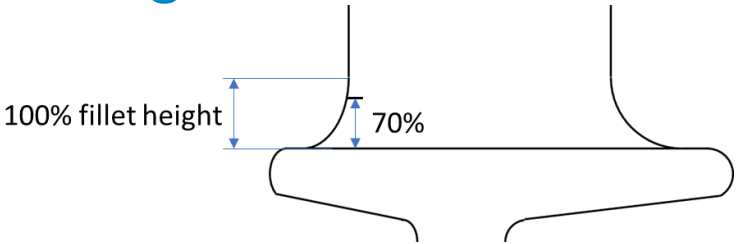
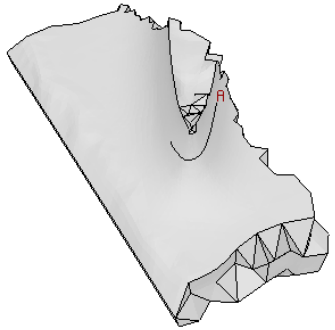
Blisk crack propagation – 70% fillet height

- Assumed that loading may be simplified to:
  - Steady: rotational body forces
  - Cyclic: first flap mode vibration
- Inserted semi-elliptical flaw at 70% “fillet height”



K_I under LC loads for crack growth under consecutive steps





Pressure side labelled ‘A’

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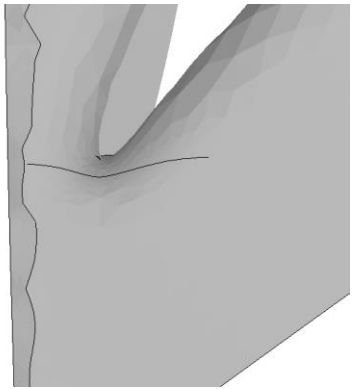
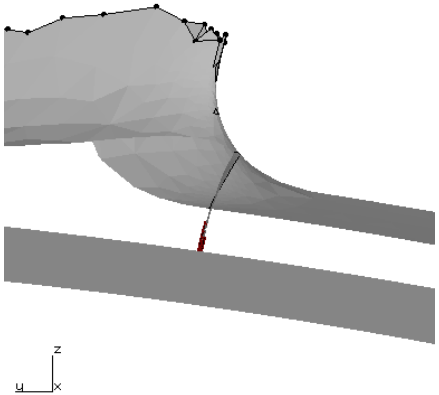
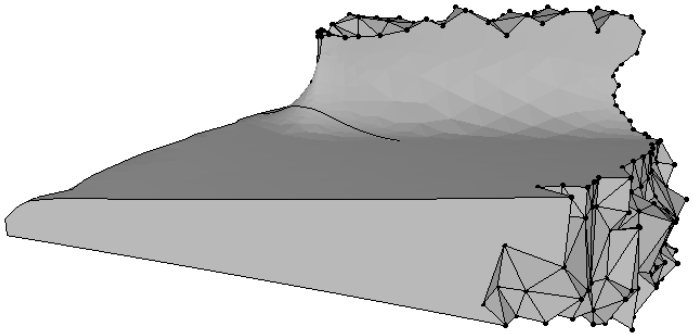
Blisk crack propagation – 20% fillet height

- Inserted semi-elliptical flaw at 20% “fillet height”
- Immediate growth towards bore







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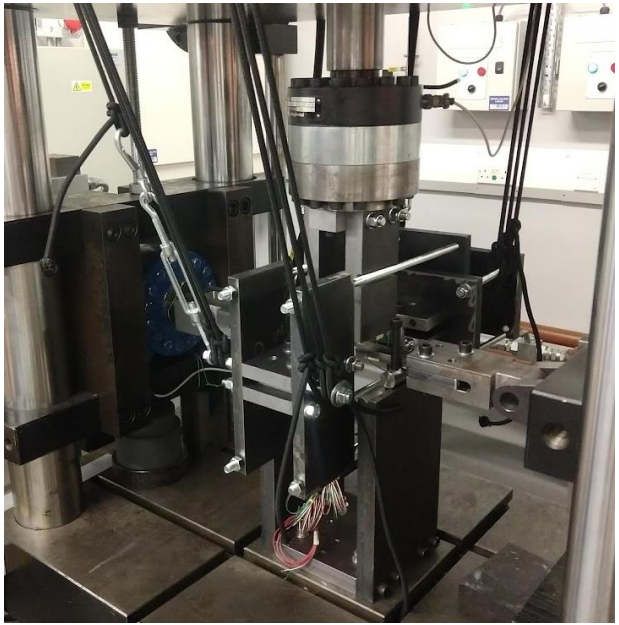
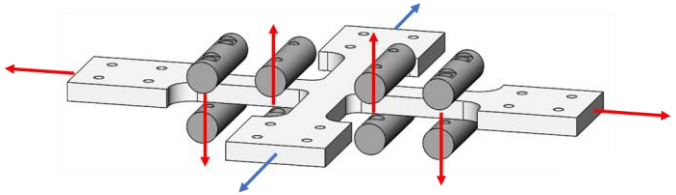
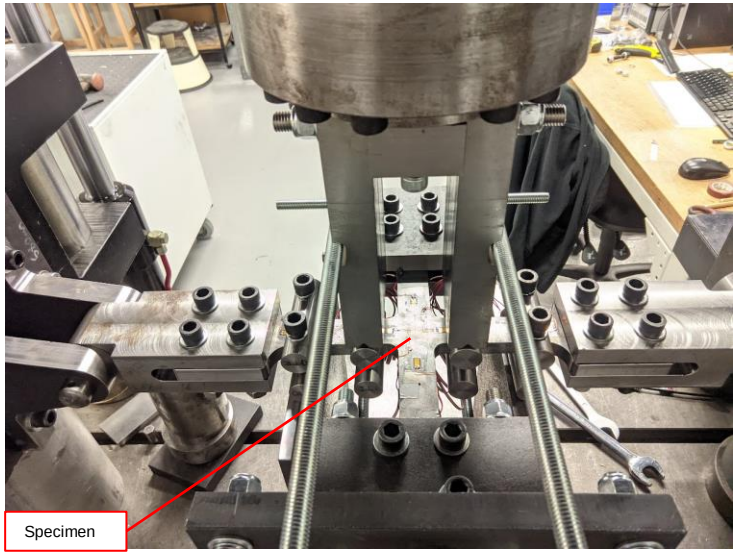
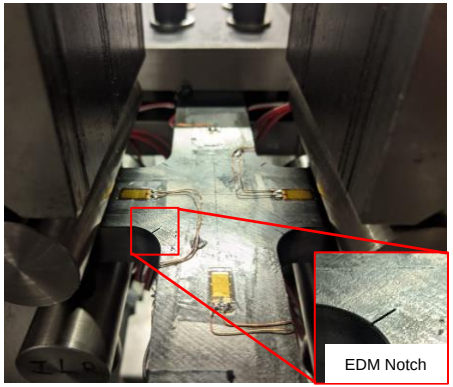
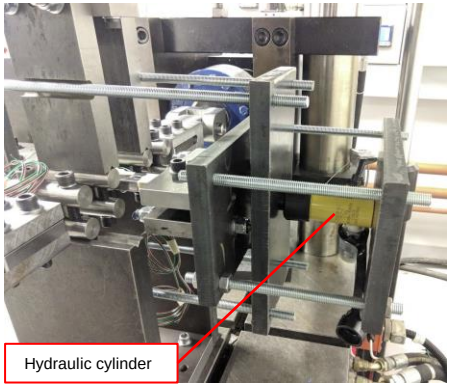
Biaxial test rig











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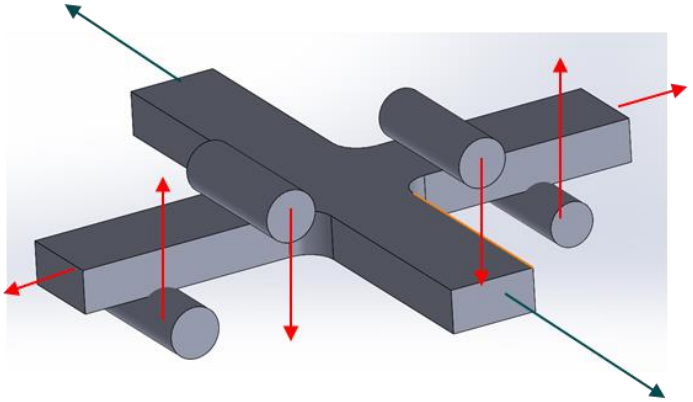
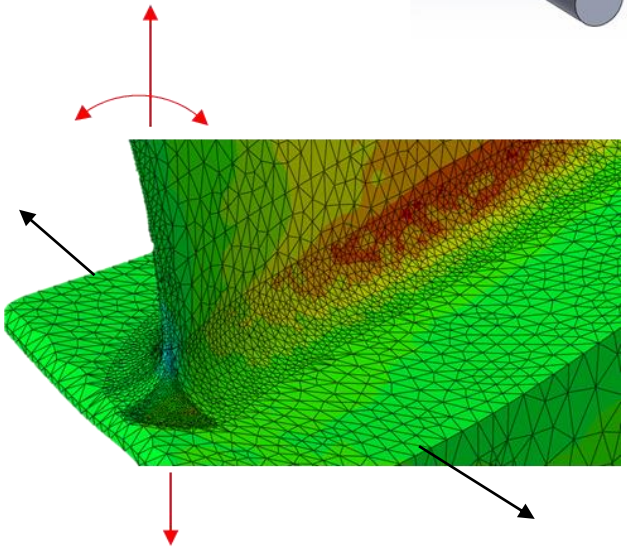
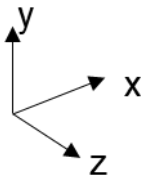
Test sample

- Cruciform sample for biaxial machine
- Tests performed on mild steel S275 and titanium alloy Ti-6Al-4V
- Loading directions
  - X: biaxial machine
  - Y: biaxial machine
  - Z: hydraulic fixture







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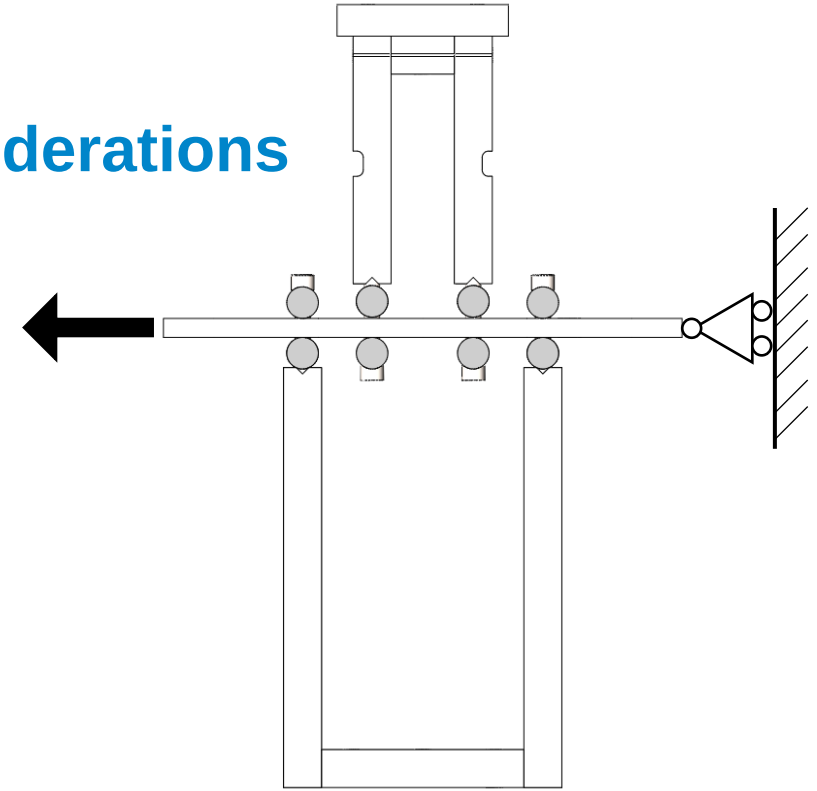
Four-point bending design considerations

- Biaxial machine
  - 1 actuator per axis
  - Specimen is not centred during loading
- Risk of fretting wear at loading pins
  - Requires horizontal compliance



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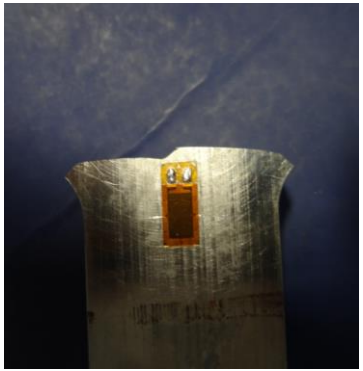
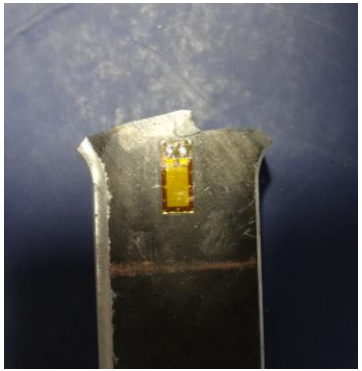
Test settings

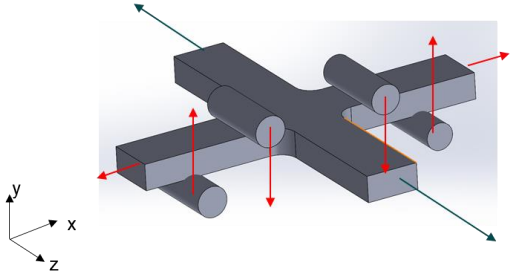
- Loads adjusted to influence crack trajectory



Test 1



Test 3



Test Number	Material	x load [kN]	y load (cyclic) [kN]	z load [kN]	N_f
1	Mild steel S275	30.1	14.5	8.7	500,884
2	Ti-6Al-4V	20.1	14.5	8.7	261,306
3	Mild steel S275	20.1	9.5	15.4	839,458
4	Ti-6Al-4V	20.1	9.5	15.4	72,400

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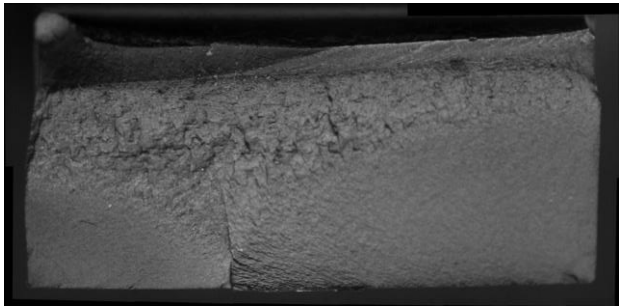
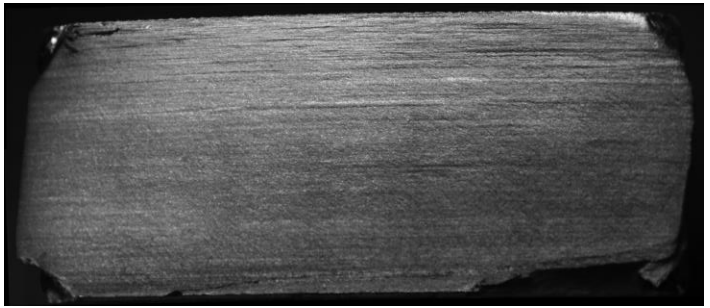
Results – fracture surfaces

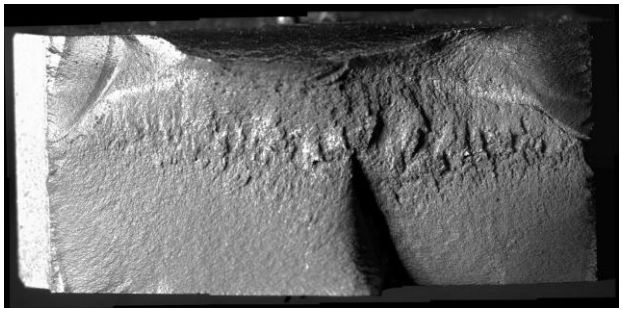
Test 1
Steel S275



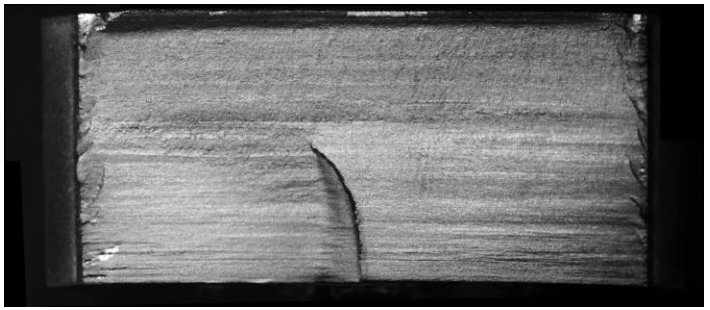
Test 2
Ti-6Al-4V



Test 3
Steel S275



Test 4
Ti-6Al-4V



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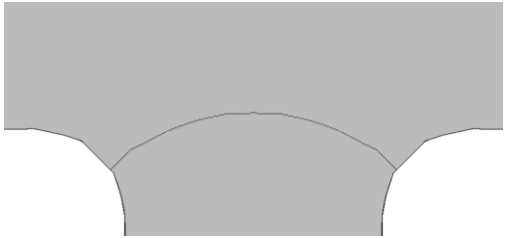
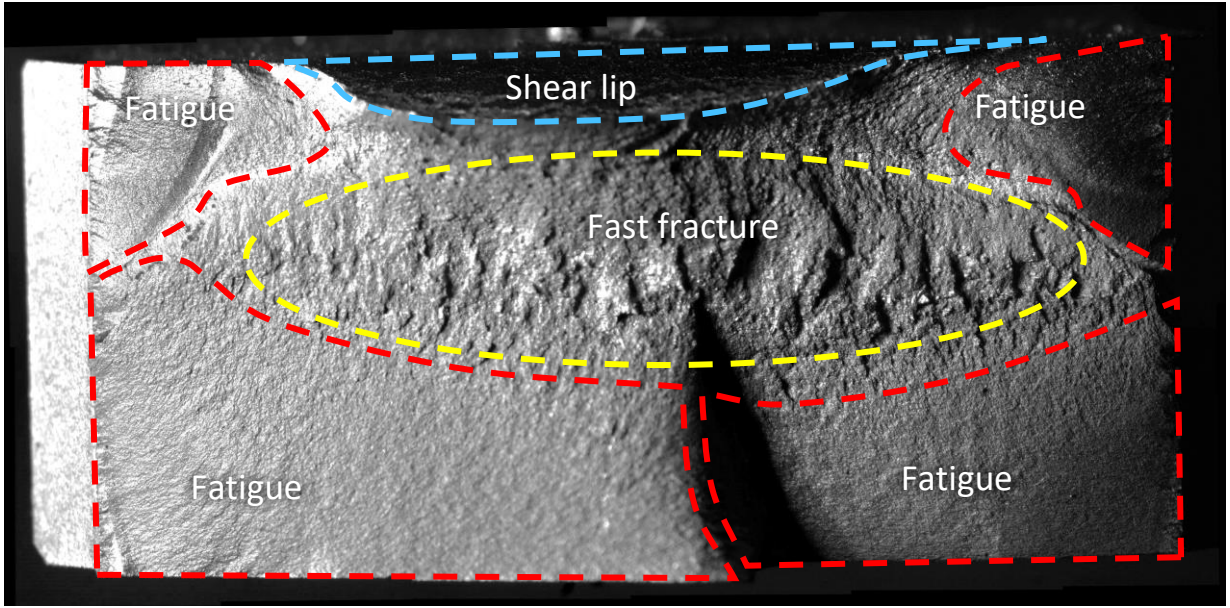
Results – fracture surfaces





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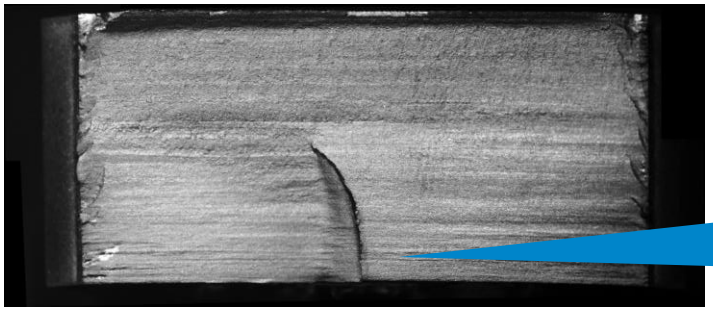
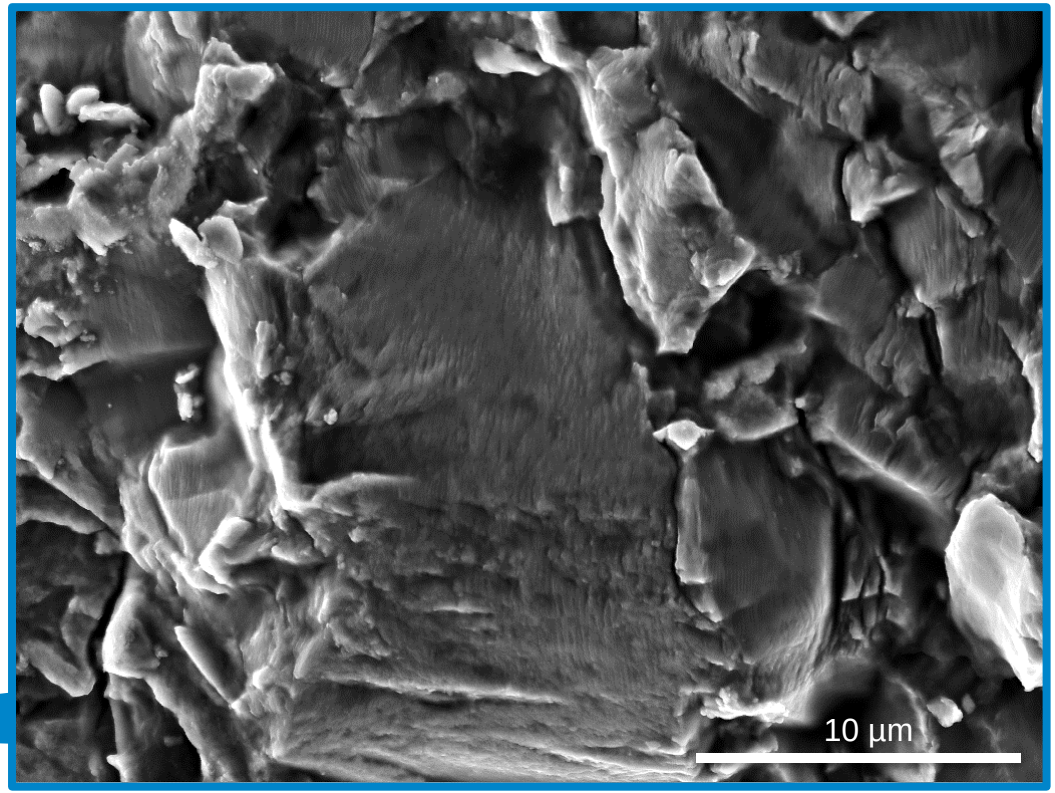
Test 4 fracture surface

- Highly faceted surface due to rolling process
- Striations visible in SEM micrograph





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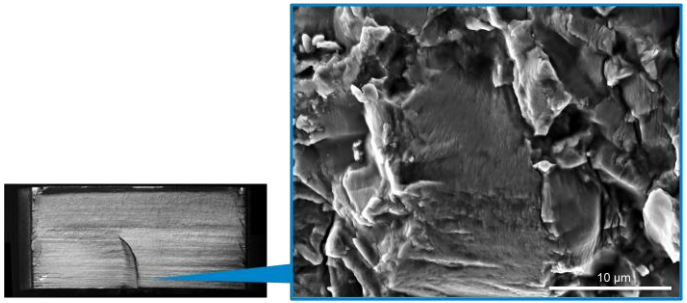
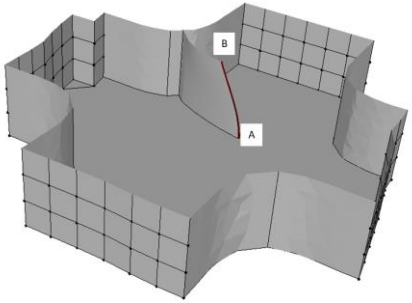
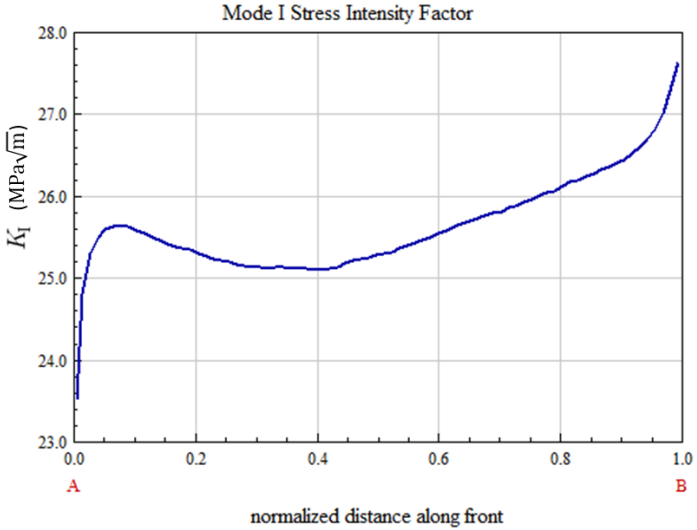
Test 4 fracture surface

- 0.18 µm approximate average striation size in region of interest
- 0.081 µm predicted crack growth per cycle







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Summary

- Multiaxial fatigue tests have been completed on notched cruciform specimens
- Directionality of rolled Ti-6Al-4V must be understood further

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Future work

- Complete cruciform tests crack deflection angles
- Complete tests with single-notched and double notch specimens
- Complete SENB tests on Ti-6Al-4V specimens to determine directionality of rolled material