Thermomechanical fatigue crack initiation in disc alloys using a damage approach

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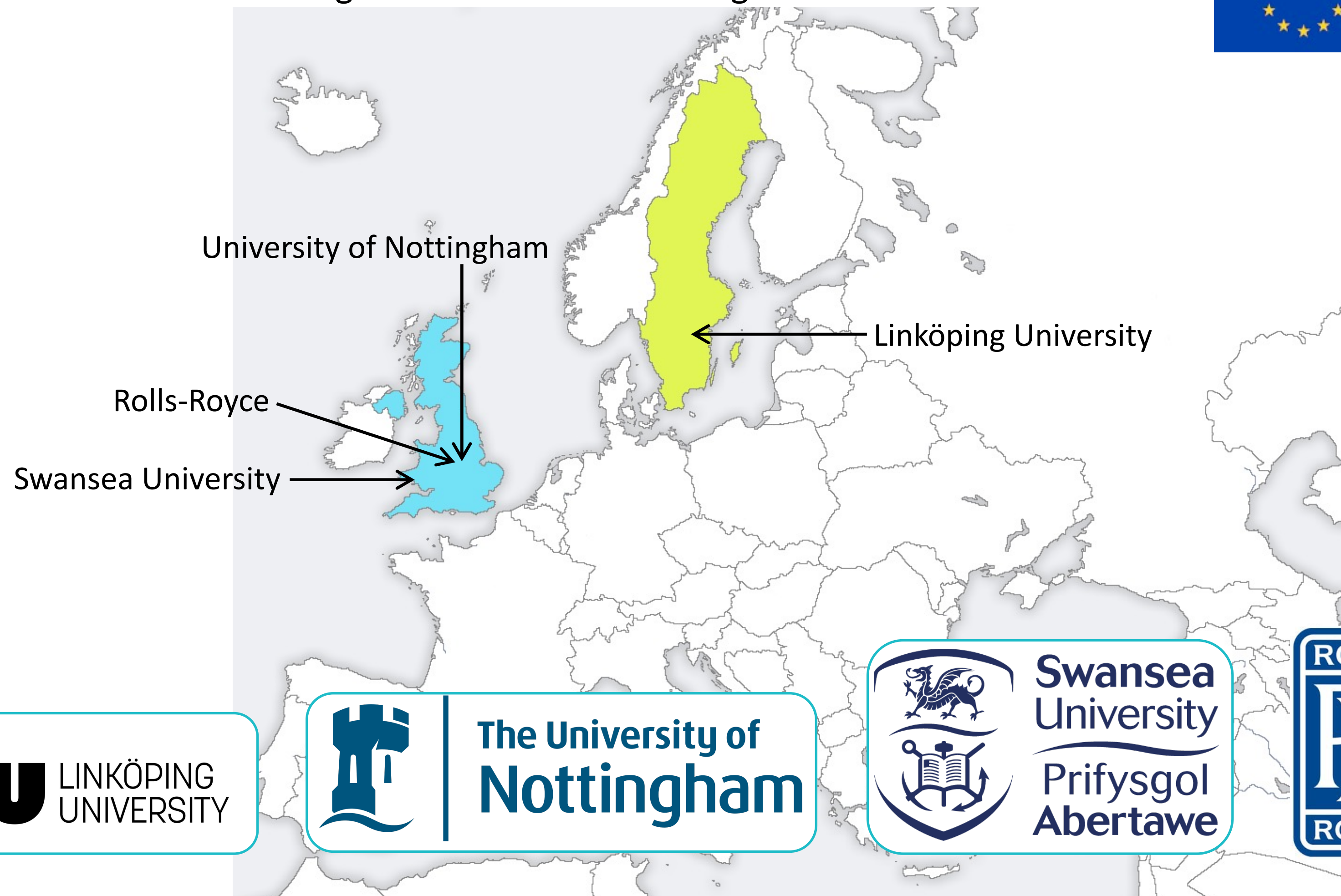
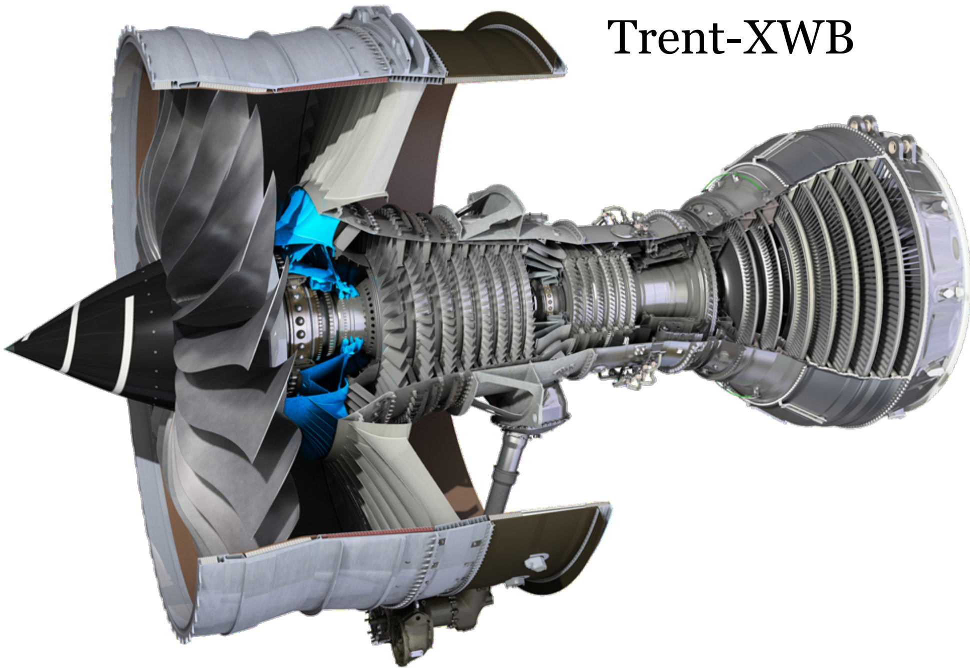
DevTMF – Horizon 2020 – CleanSky 2

Development of Experimental Techniques and Predictive Tools to Characterise **T**hermo**M**echanical **F**atigue Behaviour and Damage Mechanisms



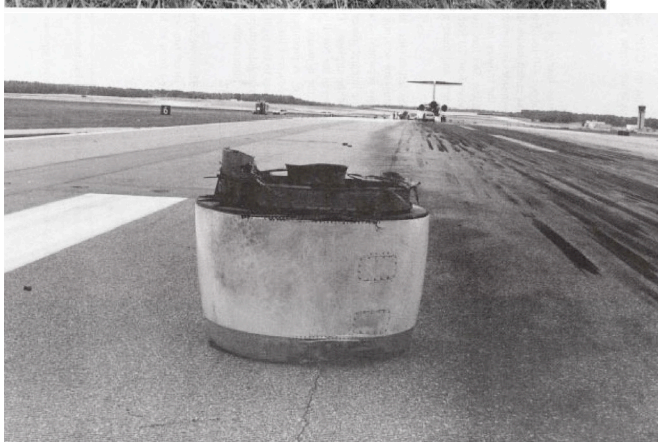
Gas turbine



Trent-XWB

SGT-800

Failure is not an option



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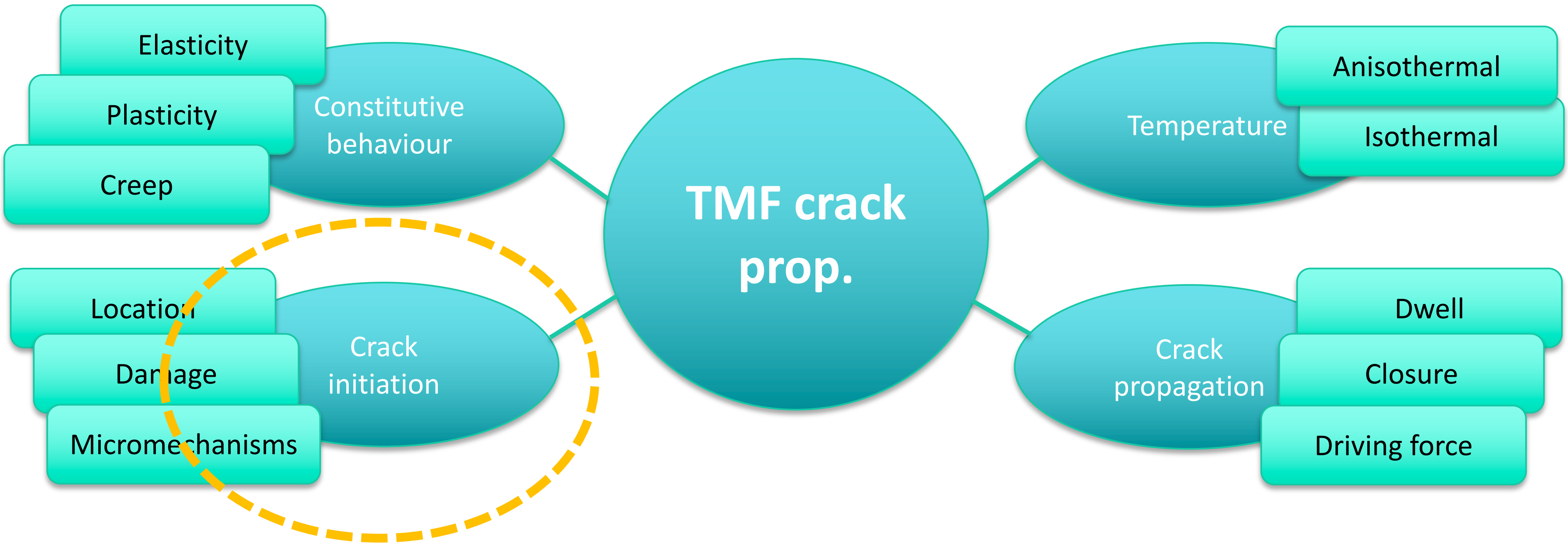

Elasticity
Plasticity
Creep
Constitutive behaviour
TMF crack prop.
Temperature
Anisothermal
Isothermal
Location
Damage
Micromechanisms
Crack initiation
Crack propagation
Dwell
Closure
Driving force

TMF crack initiation experiments

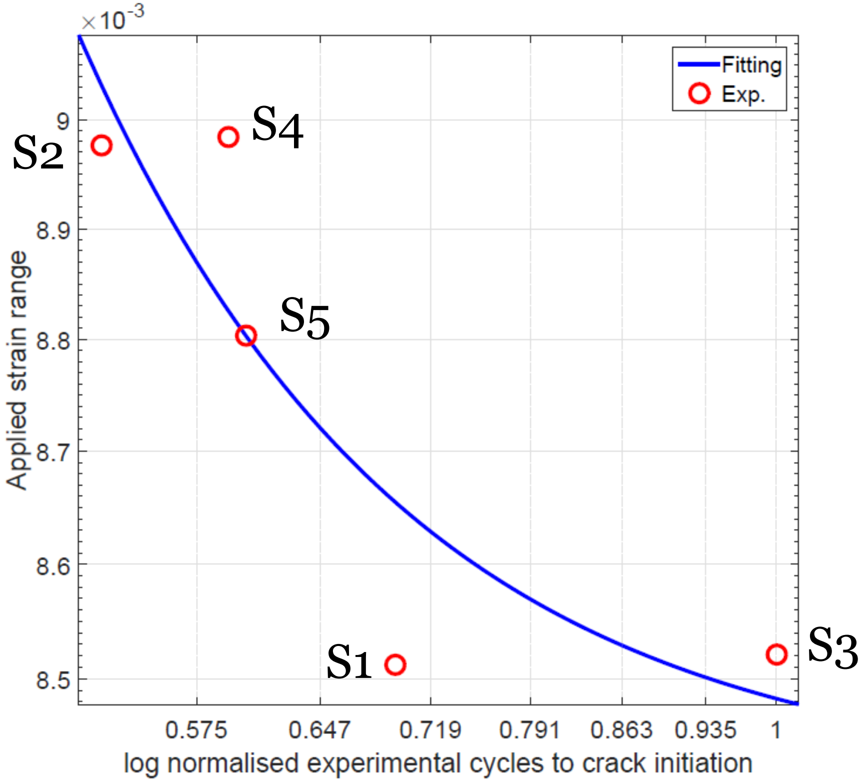
- Polycrystalline Ni-base disc alloy: RR1000
- Smooth round specimens
- Engine relevant load cycle:
  - ”OP”-TMF: 300 – 675˚C
  - Hold-time: 30s

10% load-drop

Specimen	Diameter [mm]	$\Delta\varepsilon_{mech}$ [%]	Normalised N_i
$S1$	7.61	0.8512	0.695
$S2$	7.60	0.8976	0.526
$S3$	7.62	0.8521	1.000
$S4$	7.60	0.8984	0.593
$S5$	7.61	0.8803	0.604

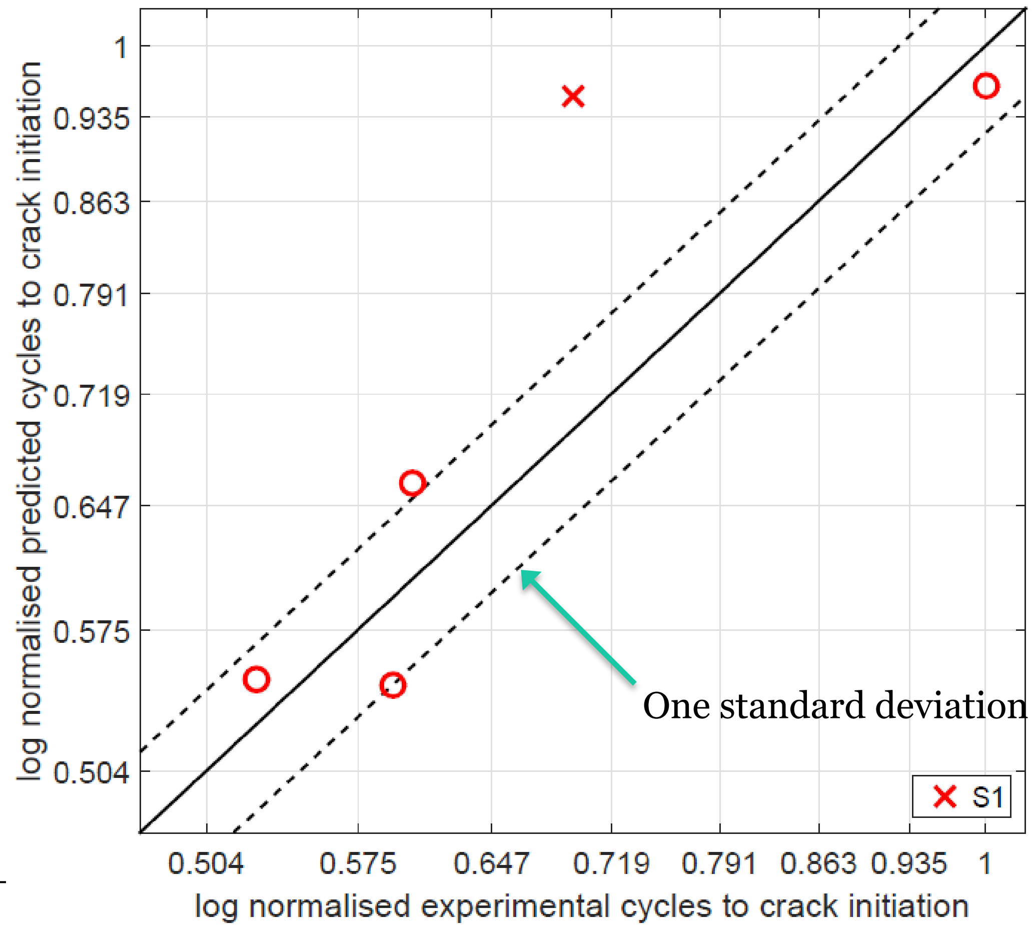
Experimental lives

- Obtained lives
- How to model this?
- Fatigue damage model:
  - Memory surface
  - Memory stress
  - Plastic strain energy
  - Endurance limit



Resulting model prediction

- Model fitted to four
- S1: Verification
  - Off by factor 1.37



Constitutive behaviour

User-defined material model

$$f = \sigma_{eq}^{vM}\left[\hat{\sigma}_{ij} - B_{ij}\right] - r - \sigma_Y$$

$$\dot{B}_{ij}^{k} = c_k\left(a_k \dot{\varepsilon}_{ij}^{vp} - B_{ij}^{k}\dot{\lambda}\right),\ k = 1,2$$

$$\dot{r}_1 = q_1\dot{\lambda}$$

$$\dot{r}_2 = h\left(q_2 - r_2\right)\dot{\lambda}$$

$$\dot{\varepsilon}_{ij}^{vp} = \begin{cases} 0 & , f \leq 0 \\ \dot{\lambda}\frac{\partial f}{\partial \sigma_{ij}} & , f > 0 \end{cases}$$

$$\dot{\lambda} = \left(\frac{f}{\eta}\right)^{m}$$

Crack initiation

- Add-on to user-defined material model

User-defined material model generates internal variables

↓

Fatigue damage model

$$g = \sqrt{\hat{\sigma}_{ij}\hat{\sigma}_{ij}} - \sqrt{\frac{2}{3}}\sigma_{mem} \leq 0$$

$$\dot{\sigma}_{mem} = \sqrt{\frac{3}{2}}\mathcal{H}[g]\left\langle \frac{\hat{\sigma}_{ij}\dot{\hat{\sigma}}_{ij}}{\sqrt{\hat{\sigma}_{pq}\hat{\sigma}_{pq}}} \right\rangle - \beta\left(1 - \mathcal{H}[g]\right)\left(\sigma_{mem} - \sigma_{end}\right)\dot{\lambda}$$

$$\dot{\omega} = \langle \sigma_{mem} - \sigma_{end} \rangle^{\alpha}\,\dot{\psi}^{p}$$

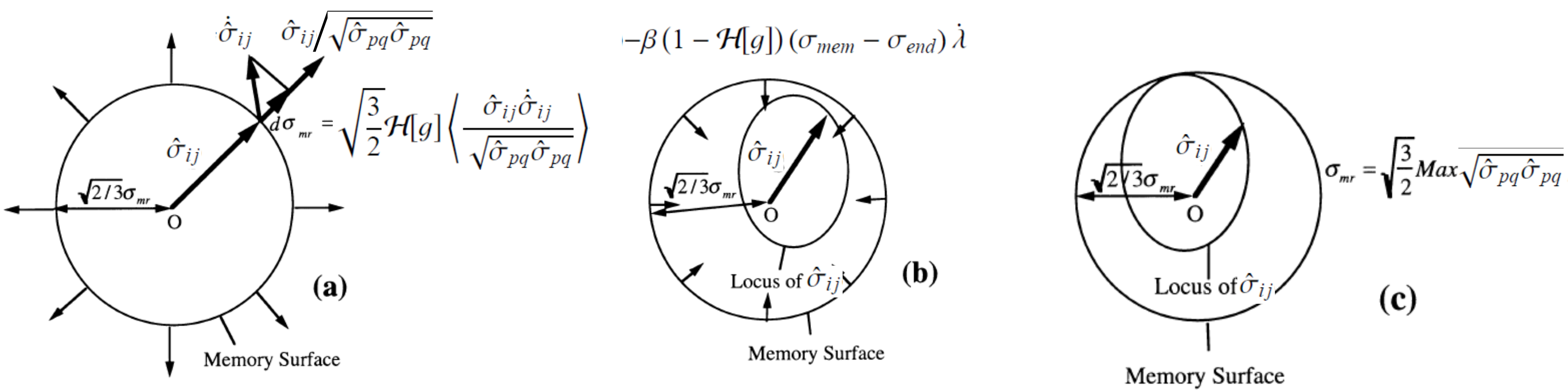
$$\dot{\psi}^{p} = \mathcal{H}[\sigma_{kk}]\,\sigma_{eq}^{vM}\,\dot{\lambda}$$

Fatigue damage model adopted from *Jiang 2000*

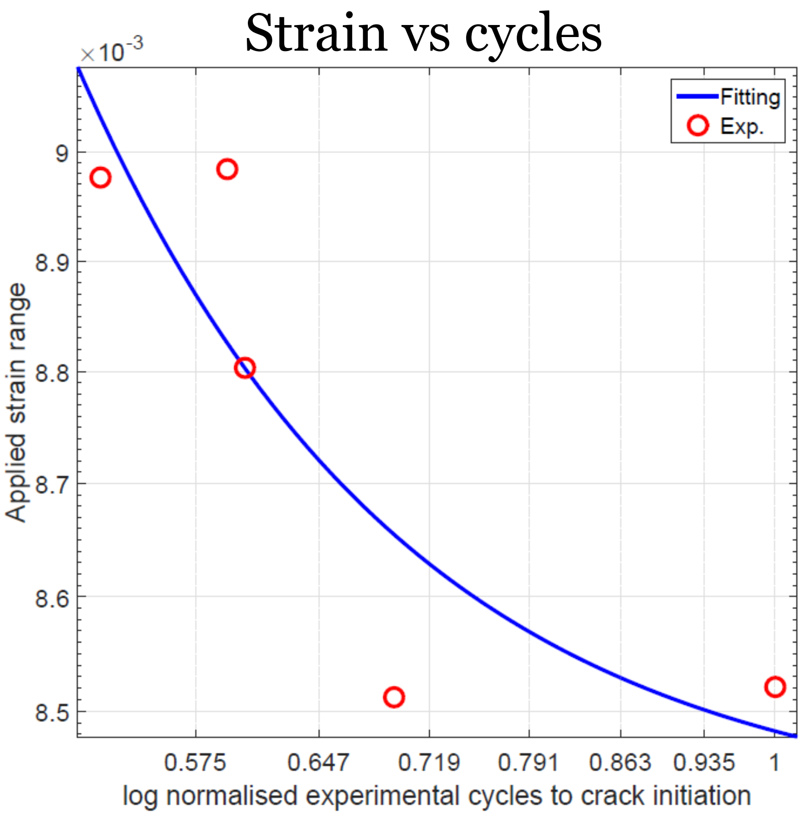
Memory surface

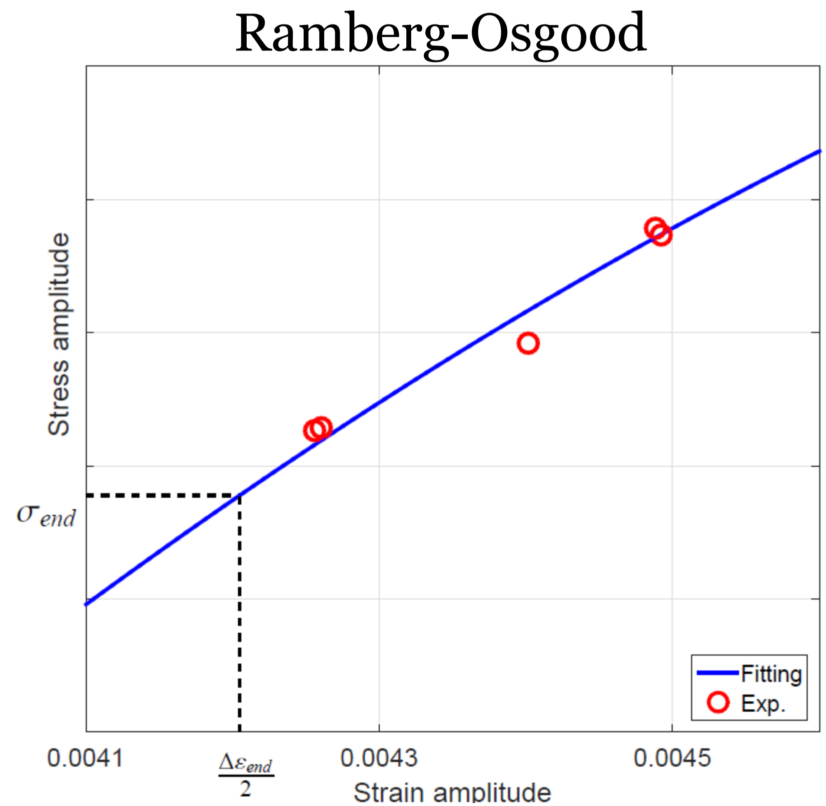
- Analogous to yield surface in plasticity
- Expands with the stress state
- Constant amplitude loading -> $\beta = 0$: no contraction
- Initially $\sigma_{mem} = \sigma_{end}$

Expansion *Contraction* *Stabilisation*



Fatigue endurance limit





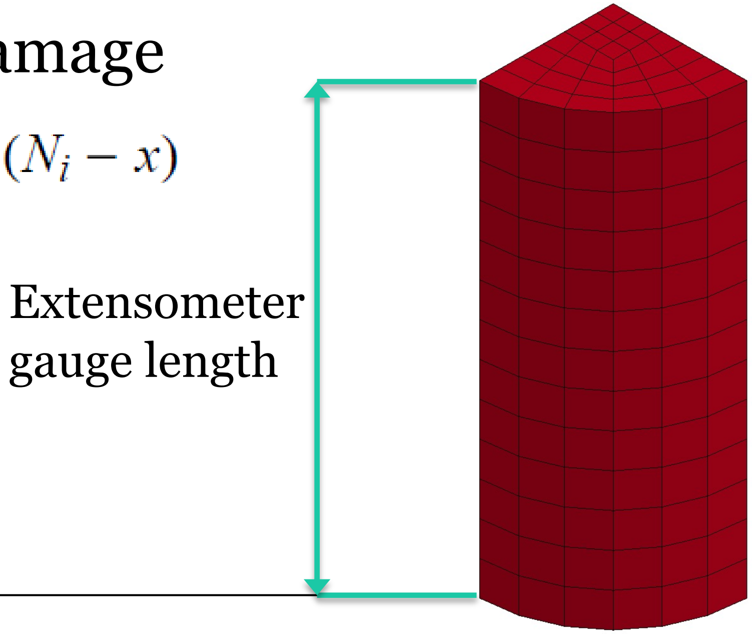
$$(\Delta\varepsilon_{mech} - \Delta\varepsilon_{end})^d N_i = e$$

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K}\right)^{1/n}$$

Specific for the used load cycle

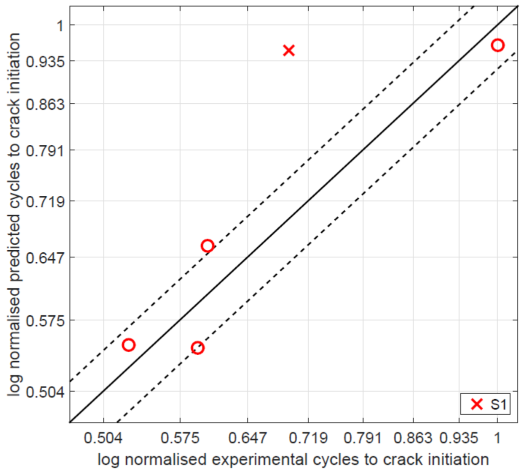
FE-Simulation

- LS-DYNA – implicit solver
- Quarter model
- Stable state:
  - 5% difference in fatigue damage
  - $\omega_c = \Delta\omega_1 + \ldots + \Delta\omega_x + \Delta\omega_{stable}(N_i - x)$
  - ”Cycle jumping”



Results & Discussion

- Uncertainties – material batches
- Endurance limit coupled to load cycle
- Misguiding due to S1 and S3
- Critical-plane?
- Cycle jumping procedure?



Specimen	Normalised predicted N_i	Factor	Experiment Normalised N_i	
$S1$	0.9528	1.3707	0.695	Verification
$S2$	0.5490	1.0440	0.526	Calibration
$S3$	0.9622	0.9622	1.000	Calibration
$S4$	0.5459	0.9200	0.593	Calibration
$S5$	0.6610	1.0952	0.604	Calibration

Conclusions

- The constitutive model gave satisfactory response. Difference due to material batches
- Predicts TMF crack initiation within a factor of 1.37 compared to experiments
- Fatigue damage model accounts for load-sequence effects and eliminates cycle-counting methods
- Reduce uncertainties by including more experiments, only four specimens for calibration and one to verify

Thank you!

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