Fatigue 2018, Poitiers, France

The Development of Predictive TMF Material Models for Cyclic Plasticity in a Nickel-based Superalloy

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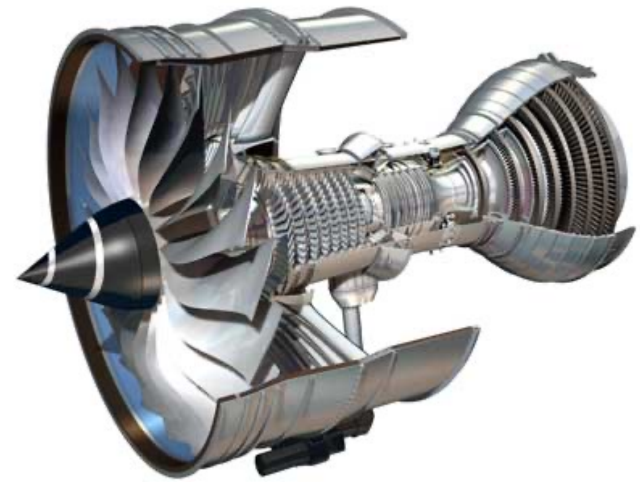
This project has received funding from the *European Union's Horizon 2020 research and innovation programme* and Joint Undertaking Clean Sky 2 under grant agreement No 686600.

Introduction

Motivation

- The European ACARE 2050 strategic agenda sets out ambitious goals to reduce CO2 and NOx emissions and perceived noise (75%, 90%, and 65%, respectively) by the year 2050.
- At present 3 Gtonnes of CO2 are produced every year by air travel. This is completely unsustainable.
- Future jet engine designs are expected to utilise higher core temperatures and lower component weights in order to meet these targets.
- Turbine discs (RR1000) are an area of engine architectures that are expected to require more rigorous lifing assessments as a results of these shifts in design paradigms.



DevTMF

Clean Sky

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DevTMF

Development of Experimental Techniques and Predictive Tools to Characterise Thermo-Mechanical Fatigue Behaviour and Damage Mechanisms (DevTMF)

- **Dev**elopment of Experimental Techniques and Predictive Tools to Characterise **T**hermo-**M**echanical **F**atigue Behaviour and Damage Mechanisms
- An EU (H2020) funded collaborative project between Rolls-Royce, Linkoping University, Swansea University and the University of Nottingham.
- The project aims to increase operational and service life of present and future gas turbine components by enabling more accurate predictions of design life.
- Nottingham contacts for the project are Dr. C. J. Hyde (lead) and Dr. J. P. Rouse (deputy lead).

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Material Model Formulation

Elastic Visco-Plastic Model

- A phenomenological level elastic visco-plastic material model is implemented here for the description of RR1000's cyclic behaviour. A total of 11 temperature dependent material constants are required (with related temperature dependent rates).
- Back stress is decomposed into two Armstrong-Frederick components, allowing for the description of dynamic recovery.
- Drag stress contains both non-linear and linear (pseudo stabilised) components.
- A power law flow rule is used for viscous effect description.

$$\varepsilon_T = \varepsilon_e + \varepsilon_p + \varepsilon_{th}$$

$$\sigma = \lambda Tr\left(\varepsilon_M - \varepsilon_p\right) + 2\mu\left(\varepsilon_M - \varepsilon_p\right) - (3\lambda + 2\mu)\,\alpha\theta \boldsymbol{I}$$

$$\varepsilon_M = \varepsilon_T - \varepsilon_{th} \qquad \theta = T - T_0$$

$$f = J(\sigma - \chi) - R - k \qquad J(\sigma - \chi) = \left[\frac{3}{2}(S - \chi')(S - \chi')\right]^{1/2}$$

$$\sigma_v = Z\dot{p}^{1/n}$$

$$\dot{\chi}_i = \frac{2}{3}C_i\dot{\varepsilon}_p - \gamma_i\chi_i\dot{p} + \frac{1}{C_i}\frac{\delta C_i}{\delta T}\chi_i\dot{T} \qquad \chi = \sum_{i=1}^{N}\chi_i$$

$$\dot{R} = bQ\dot{r}_2 + r_2\left(\frac{\delta b}{\delta T}Q + \frac{\delta Q}{\delta T b}\right)\dot{T} + H\dot{p} + \frac{\delta H}{\delta T}p\dot{T}$$

$$r_2 = \frac{1}{b}\left(1 - e^{-bp}\right)$$

$$d\varepsilon_p = \frac{3}{2}\left\langle\frac{J(\sigma - \chi) - R - k}{Z}\right\rangle^n \frac{S - \chi'}{J(\sigma - \chi)}dt$$

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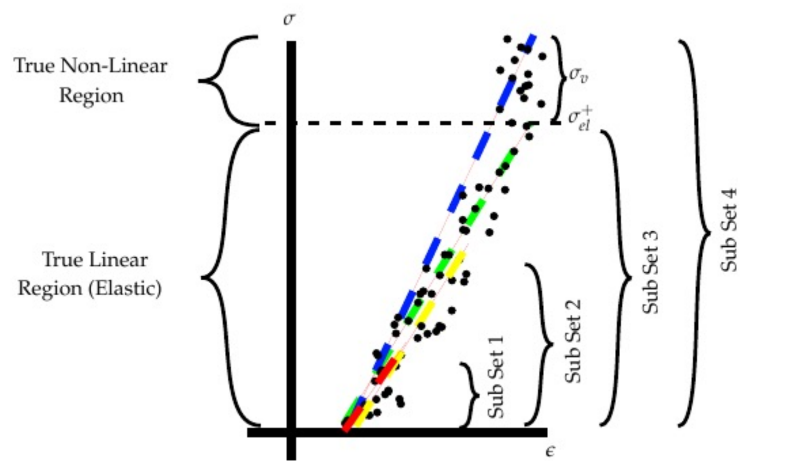
Material Parameter Determination and Optimisation

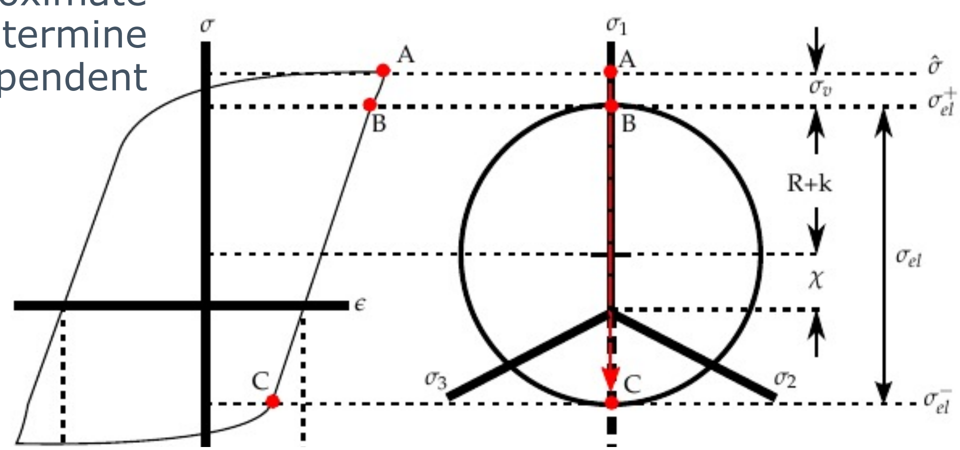
Stress Partitioning and Limits

- A wealth of historical data is available for RR1000. Automated data analysis methods have been developed in order to process the results efficiently.
- Linear regression methods are used to estimate elastic limits in fully reversed experimental hysteresis loops. Cottrell's stress partitioning method is used to approximate dual variable evolution and determine approximate values for material dependent parameters.



$$\sigma_v = \hat{\sigma} - \sigma_{el}^+ \qquad R + k = \frac{\sigma_{el}}{2}$$

$$\chi = \begin{cases} \sigma_{el}^+ - \frac{\sigma_{el}}{2}, & \text{if } \sigma_{el}^+ \geq \sigma_{el}^- \\ 0, & \text{if } \sigma_{el}^+ = \sigma_{el}^- \\ \sigma_{el}^- + \frac{\sigma_{el}}{2}, & \text{if } \sigma_{el}^- \geq \sigma_{el}^+ \end{cases}$$



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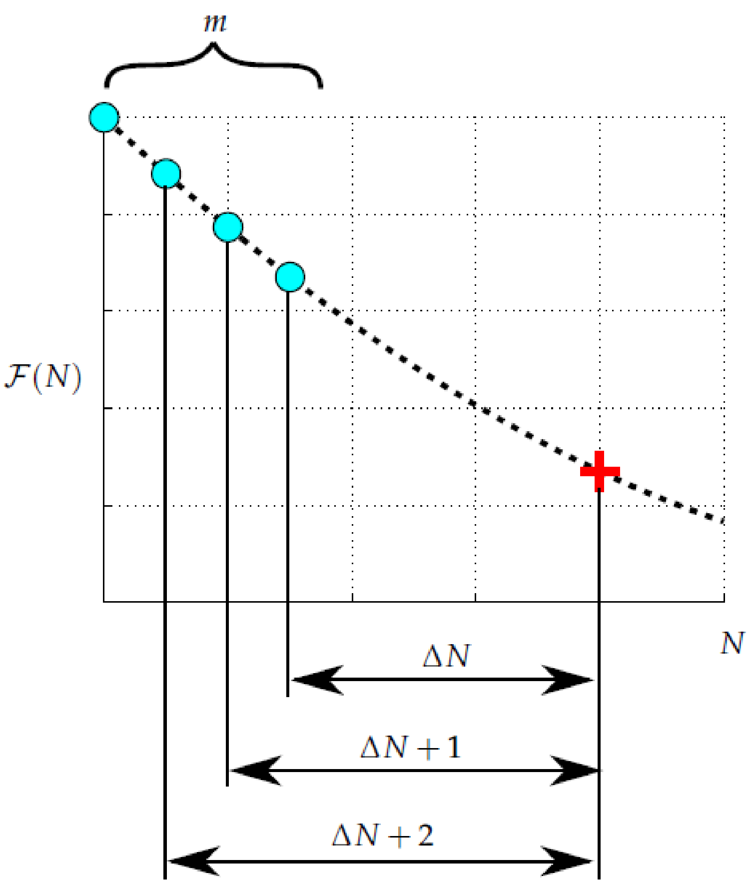
Cycle Jumping Methods

Reducing optimisation effort

- Large numbers of hysteresis loops may be generated in the cyclic testing of RR1000 over an industry relevant temperature range.
- Cycle jumping has been implemented in optimisation algorithms (LSQNONLIN) in order to process this data in a reasonable amount of time.
- A generalised Taylor series approach has been developed and utilised, such that the value "true" (solved for using MATLAB's ODE45 function) values of the dual variables can be maximised in estimating projected values.



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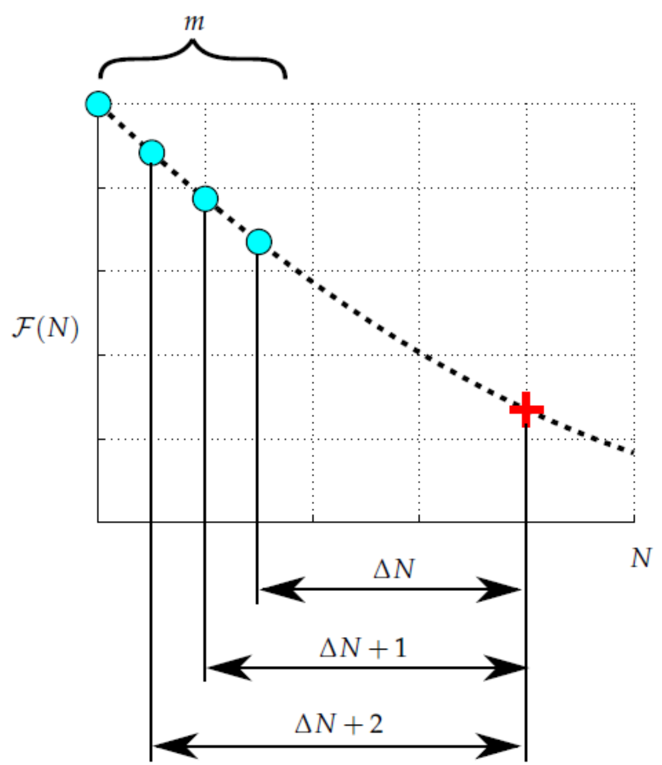
Cycle Jumping Methods

Reducing optimisation effort

$$\begin{bmatrix} \mathcal{F}_{N-(\Delta N)} \\ \mathcal{F}_{N-(\Delta N+1)} \\ \vdots \\ \mathcal{F}_{N-(\Delta N+m-1)} \end{bmatrix} = \begin{bmatrix} 1 & -(\Delta N) & \cdots & g(m-1)\dfrac{(\Delta N)^{m-1}}{(m-1)!} \\ 1 & -(\Delta N+1) & \cdots & g(m-1)\dfrac{(\Delta N+1)^{m-1}}{(m-1)!} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & -(\Delta N+m-1) & \cdots & g(m-1)\dfrac{(\Delta N+m-1)^{m-1}}{(m-1)!} \end{bmatrix} \begin{bmatrix} \mathcal{F}_N \\ \mathcal{F}_N^{(1)} \\ \vdots \\ \mathcal{F}_N^{(m-1)} \end{bmatrix}$$

$$g(\alpha) = \begin{cases} +1 & \text{if } \alpha \bmod (2) = 0 \text{ (Even)} \\ -1 & \text{if } \alpha \bmod (2) = 1 \text{ (Odd)} \end{cases} \qquad x \bmod (y) = x - ny \quad \text{where} \quad n = \lfloor \frac{x}{y} \rfloor$$

$$g(i-1)\frac{(\Delta N+i-1)^{j-1}}{(j-1)!}$$



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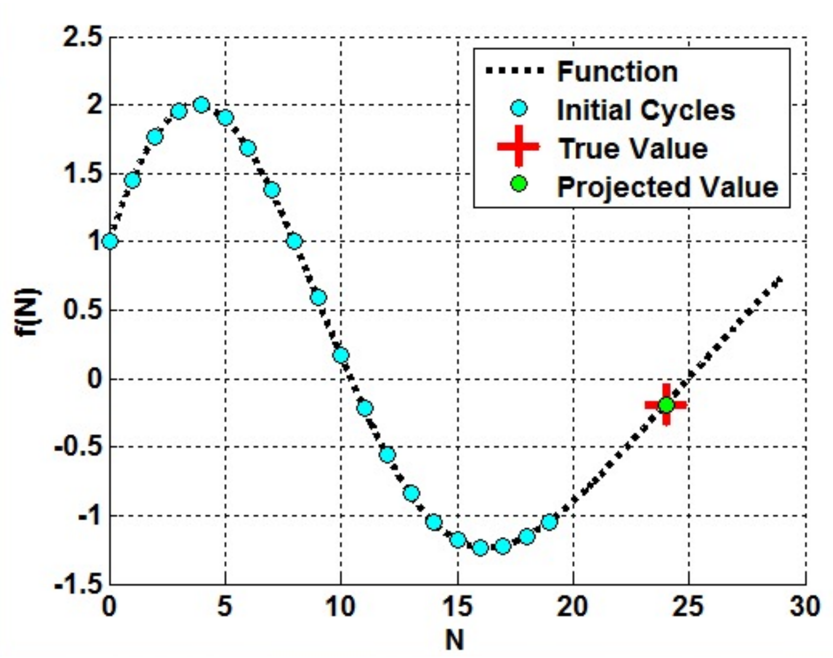

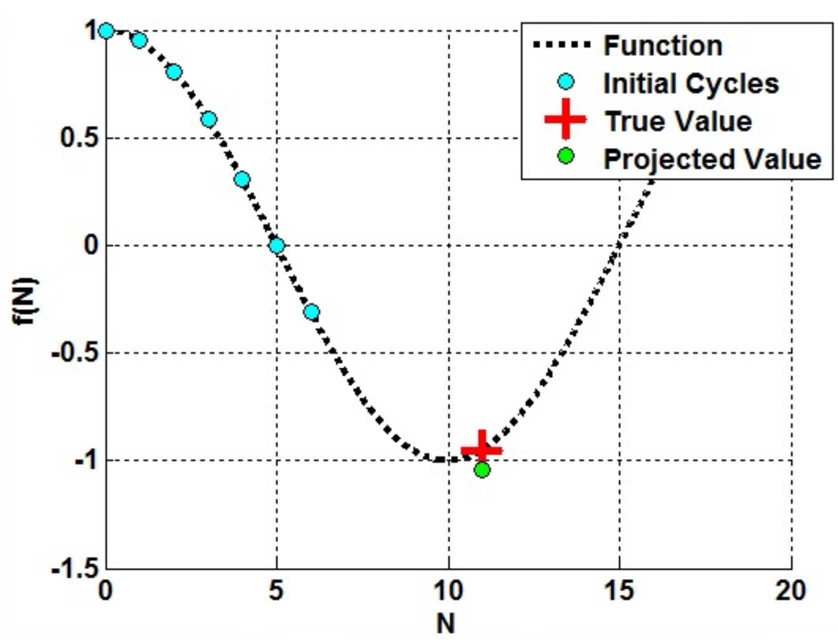

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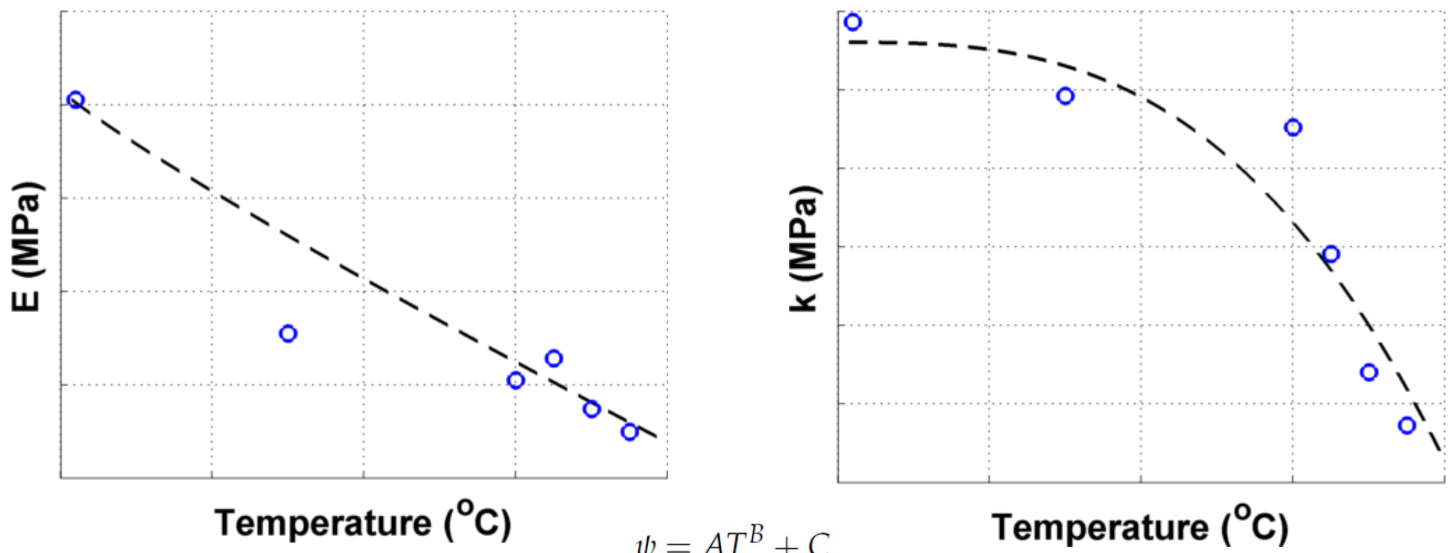
Temperature Dependent Material Parameter Functions

An-isothermal relationships for elastic material parameters



$$\psi = AT^{B} + C$$

$$\psi = A \exp BT + C \exp DT$$

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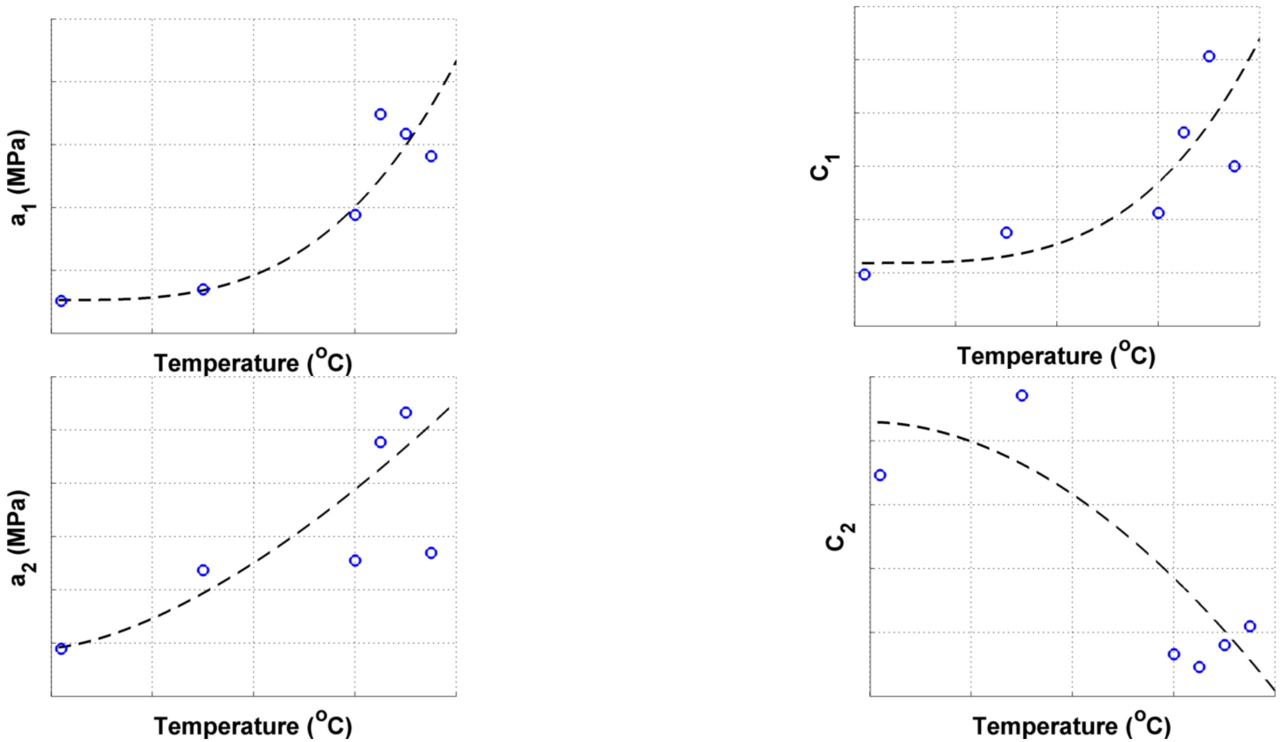

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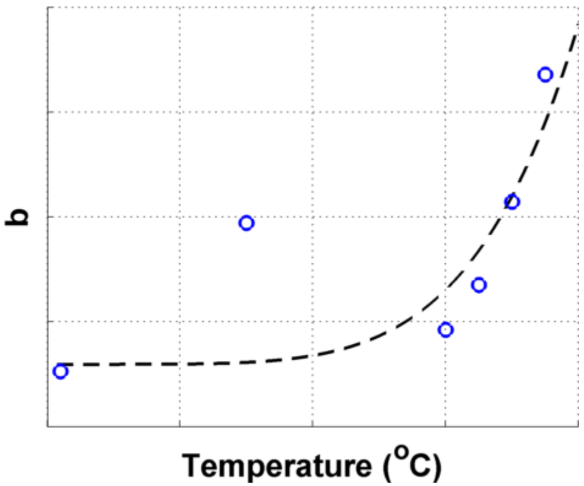

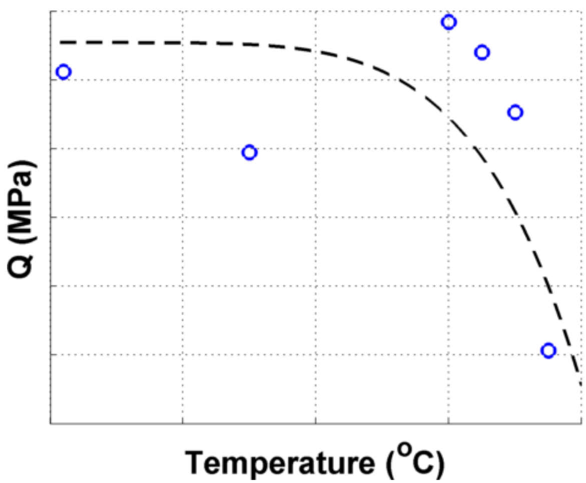

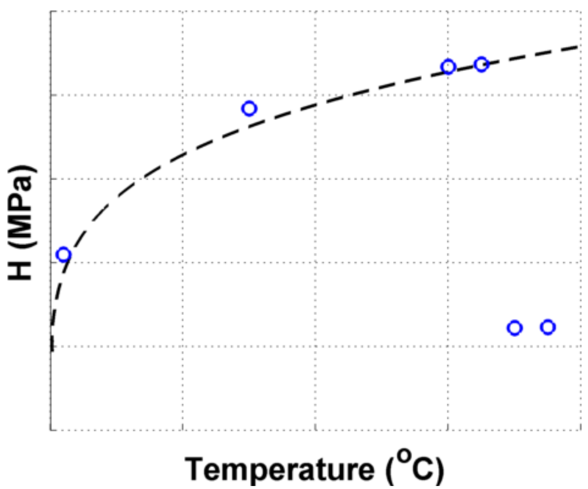

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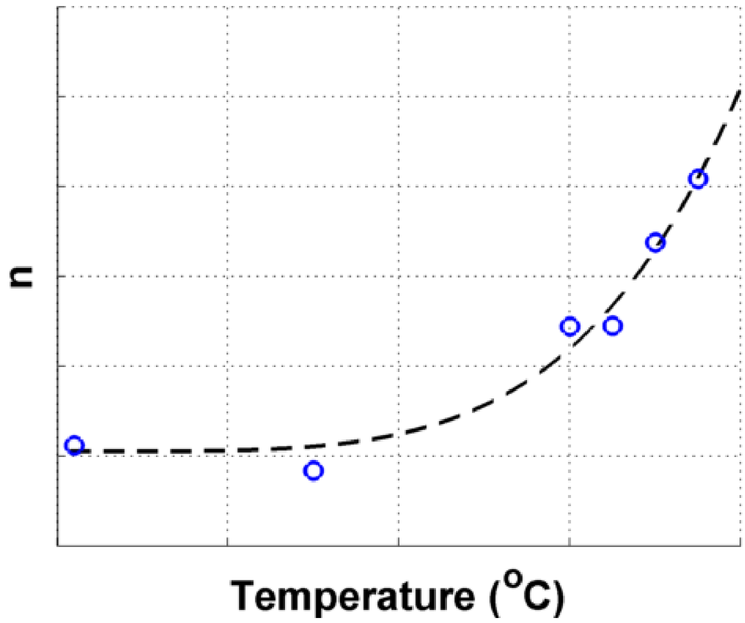

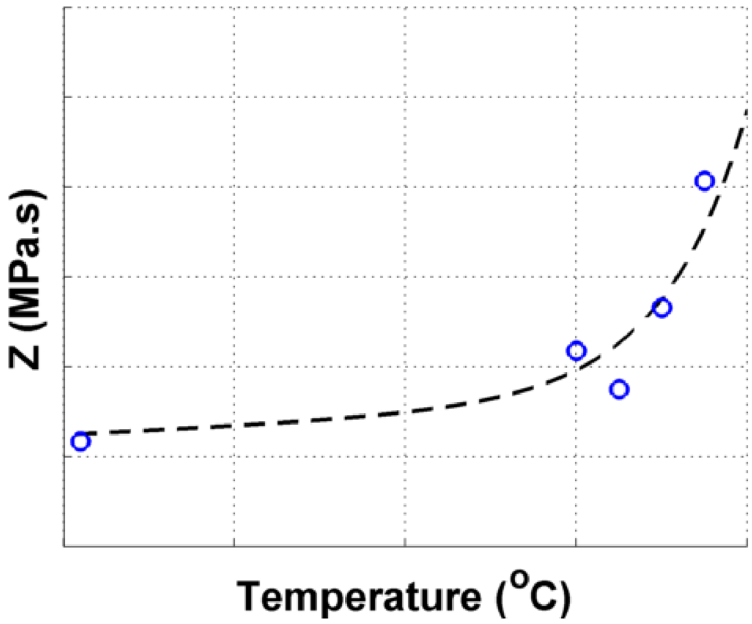

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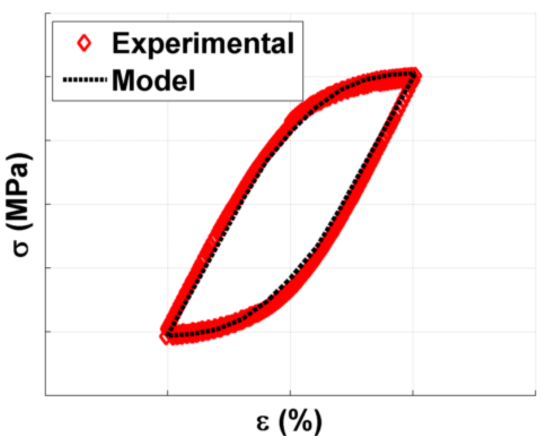
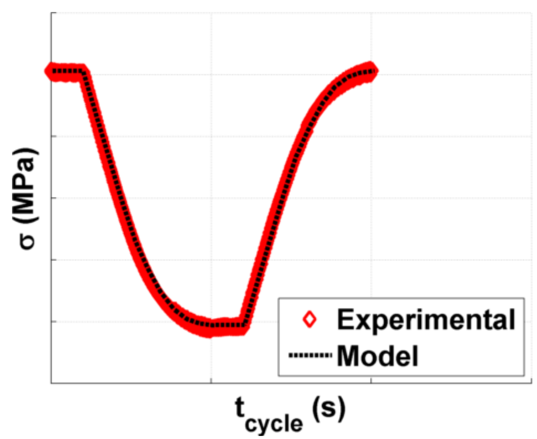
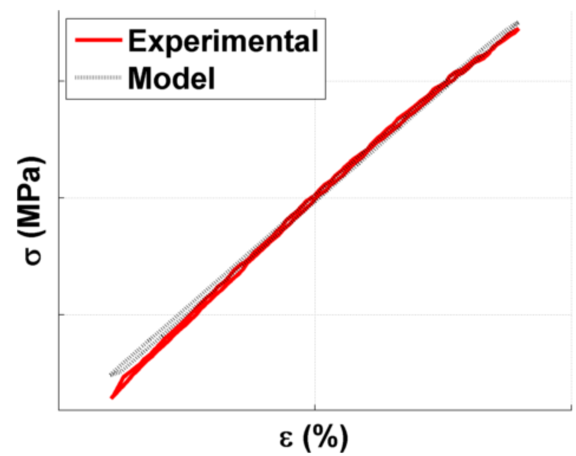
Isothermal Material Parameters

Example RR1000 results

- Due to commercial sensitivity, normalised results only are presented here for RR1000.
- Validation against fully reversed and R≠0 test waveforms has indicated that the model described above is suitable for the description of RR1000 under isothermal conditions.
- A limited number of small strain range an-isothermal waveforms have been considered, however these only validate temperature dependency in E and k. New experimental data (generated in DevTMF) will attempt to extend this.







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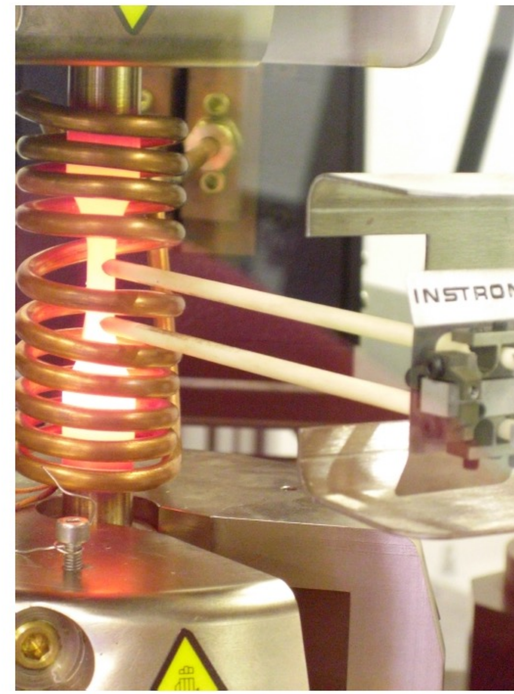
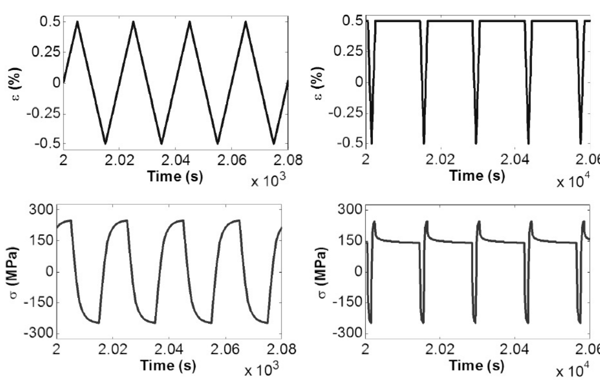
Example Applications (Chromium Steel)

Chromium Steel P91

- In the interest of presenting meaningful data, results for P91 (a chromium alloy used in power plant) are given here.
- An identical model formulation has been used, with material model parameters determined for 400°C, 500°C, and 600°C isothermal conditions. Experimental data used a loading rate of 0.1%/s and strain limits of +/-0.5%. 2 minute hold periods were used in certain isothermal tests. Good agreement with in phase and out of phase an-isothermal results can be observed.





$$F(x) = \sum_{i=1}^{N_{cyc}} \sum_{j=1}^{N_{sample}} \left(\sigma_{ij}^{exp}\right)^2 - \left(\sigma_{ij}^{pred}\right)^2$$

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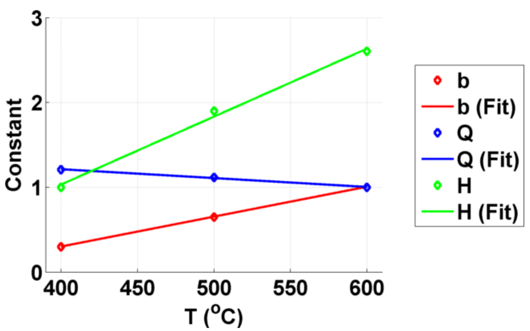
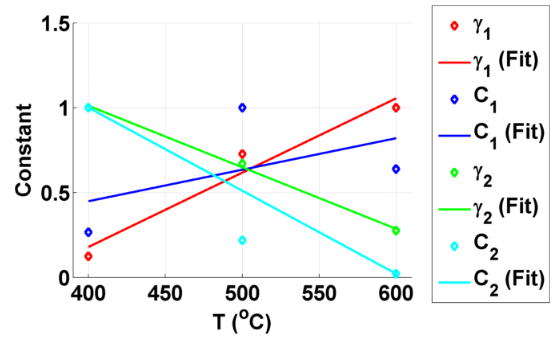
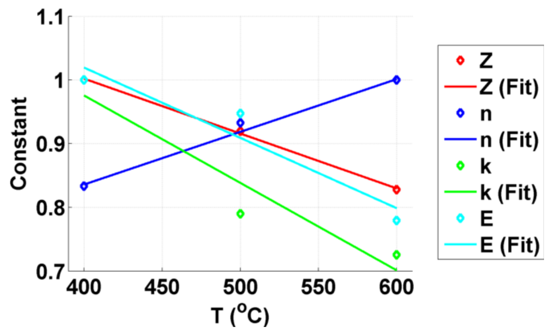
Example Applications (Chromium Steel)

Chromium Steel P91







$$\gamma_1(MPa) = 2.5449T - 913.59$$
$$C_1 = 62.047T - 9805.6$$
$$\gamma_2(MPa) = -3.7521T + 2547.2$$
$$C_2 = -707.95T + 427833$$
$$Z(MPa.s^{1/n}) = -2.6524T + 4146.2$$
$$n = 0.0018T + 1.099$$
$$b = 0.0071T - 2.2322$$
$$Q(MPa) = 0.0458T - 71.447$$
$$k(MPa) = -0.2818T + 313.08$$
$$E(GPa) = -0.188T + 248.85$$
$$H(MPa) = -0.0125T + 3.3847$$

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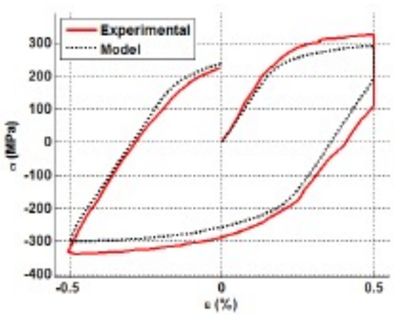
Example Applications (Chromium Steel)

600°C Isothermal



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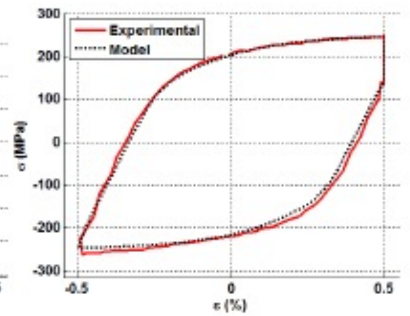

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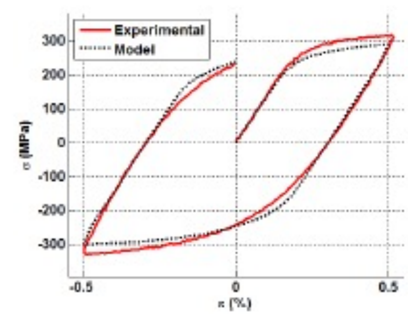

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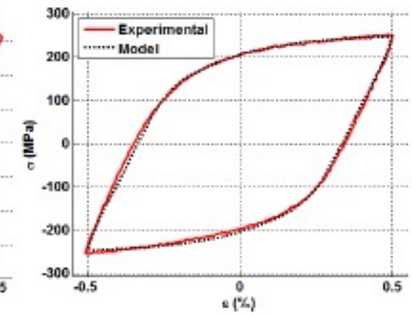

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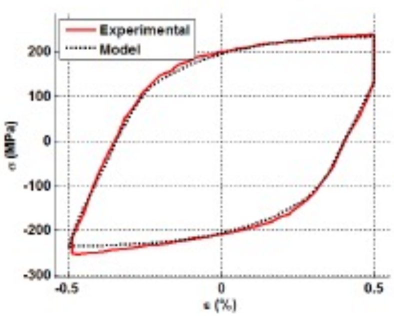

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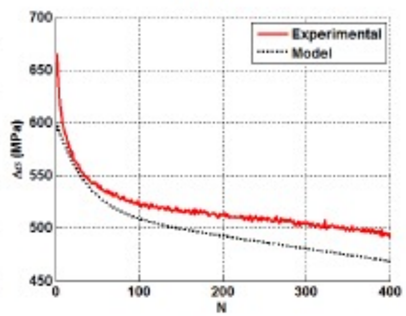

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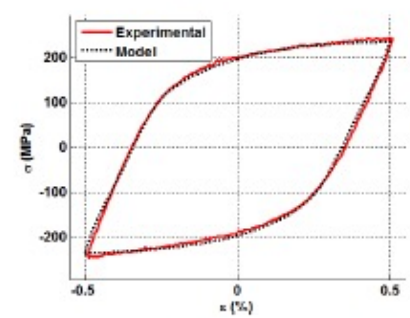

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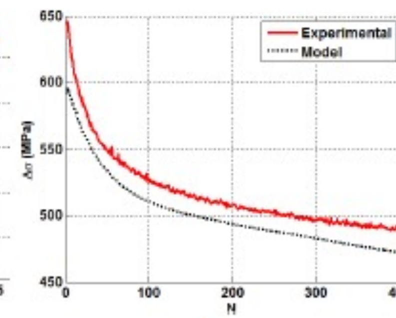

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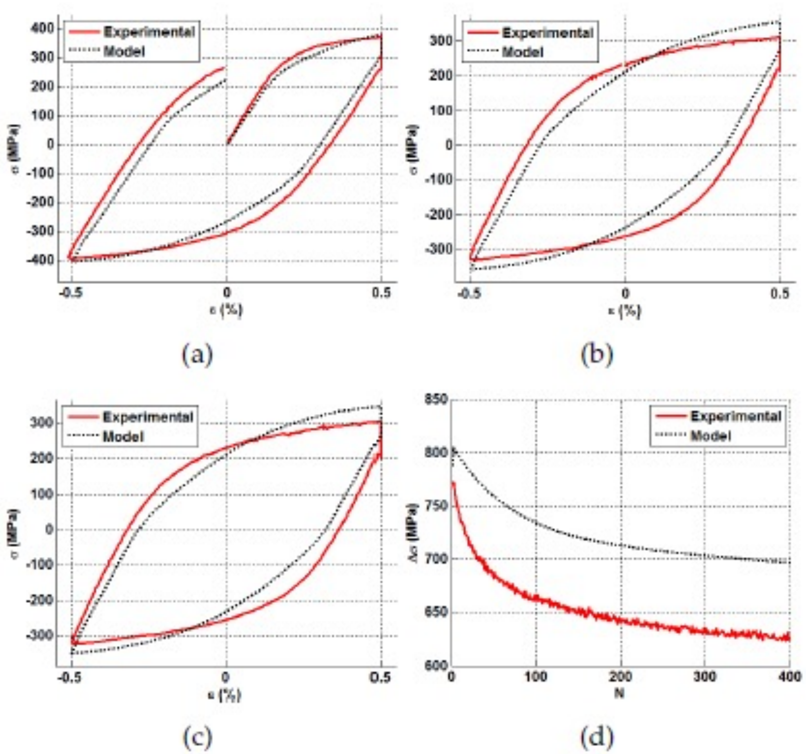
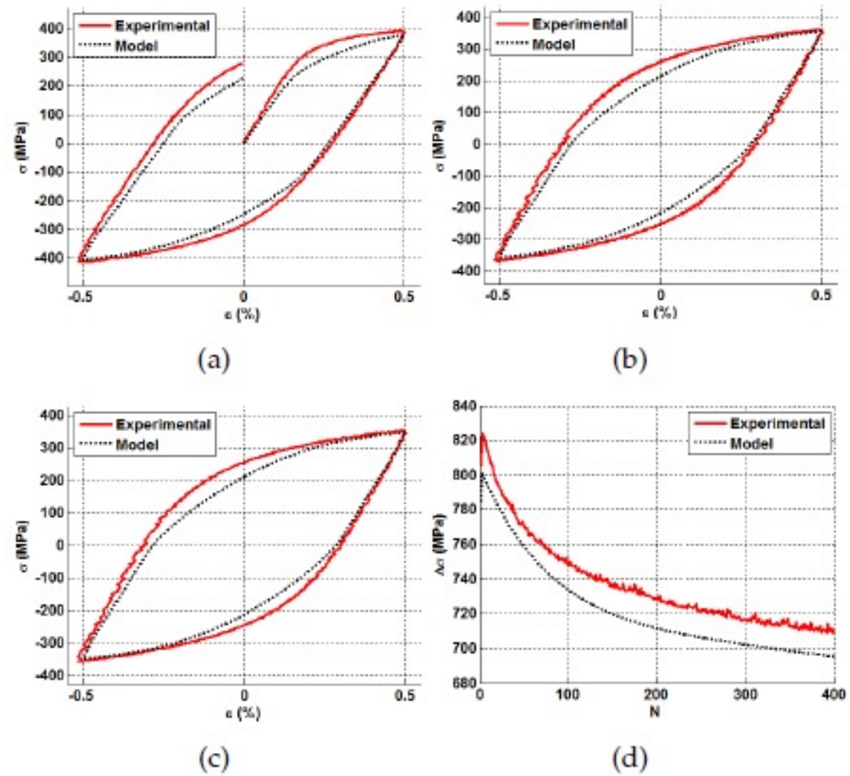
Example Applications (Chromium Steel)

500°C Isothermal





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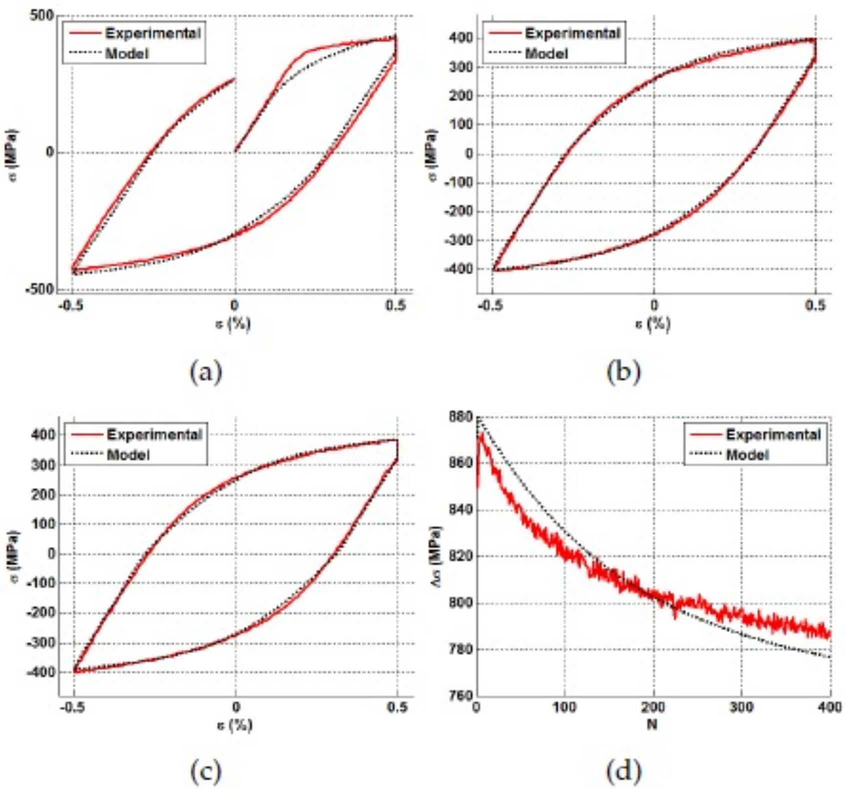
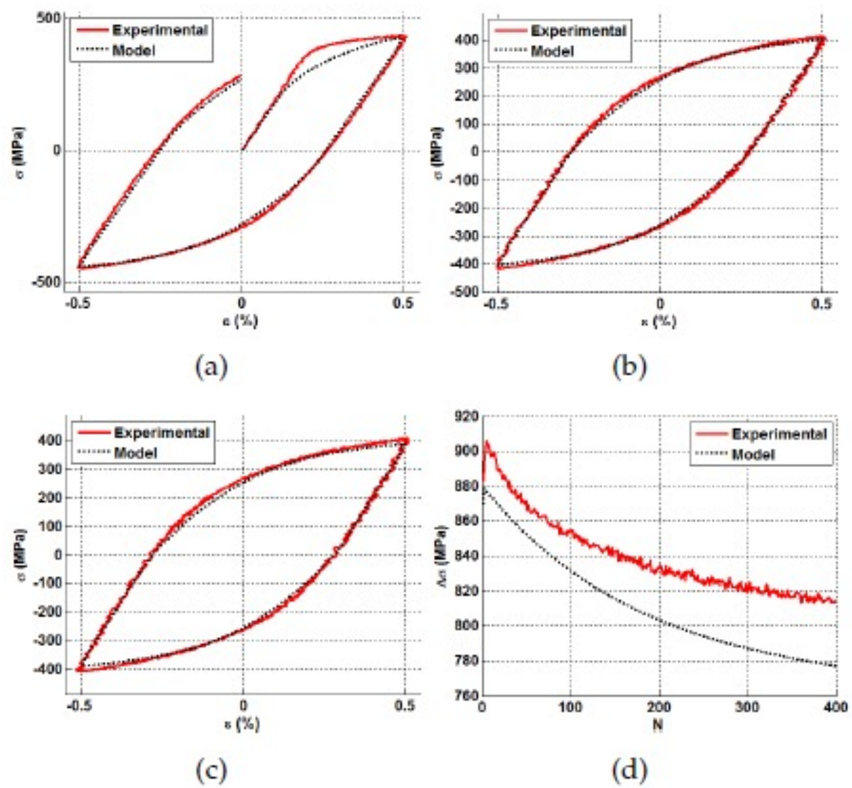
Example Applications (Chromium Steel)

400°C Isothermal





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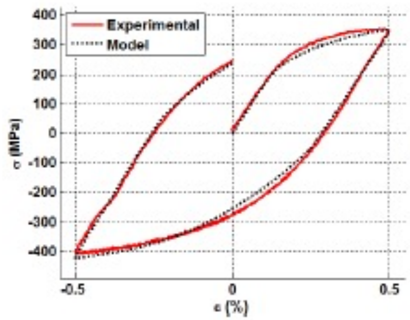
Example Applications (Chromium Steel)

An-isothermal In Phase



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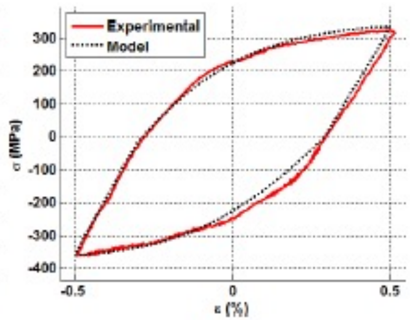

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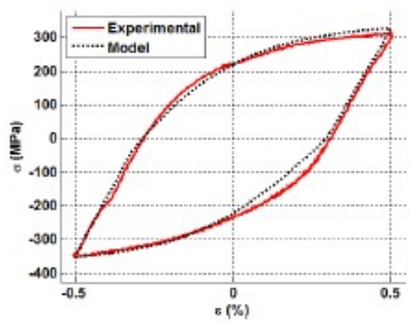

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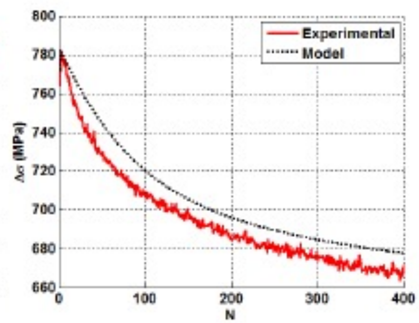

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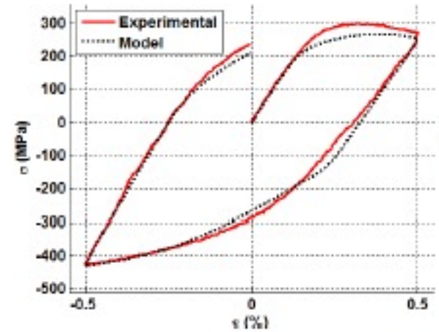

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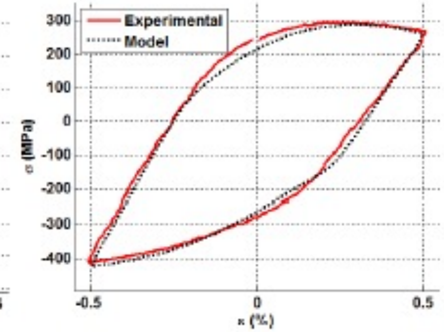

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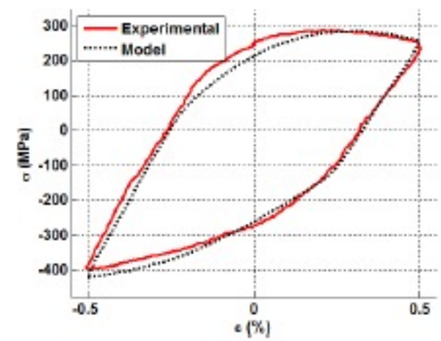

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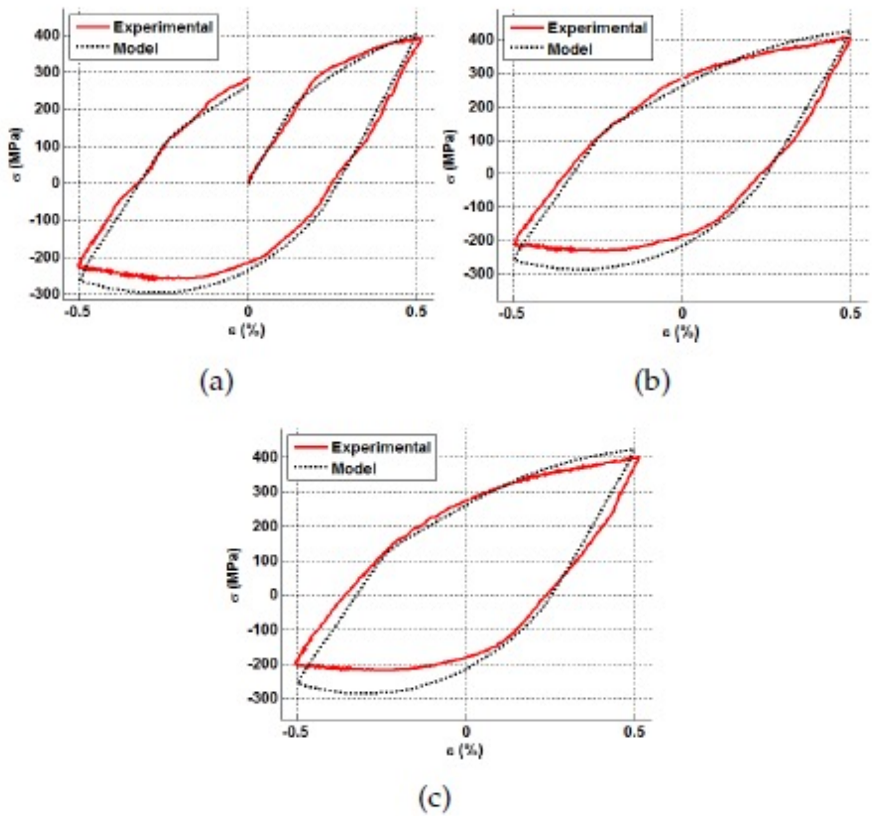
Example Applications (Chromium Steel)

An-isothermal Out of Phase



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International Journal of Fatigue

Volume 113, August 2018, Pages 137-148

A case study investigation into the effects of spatially dependent convection coefficients on the fatigue response of a power plant header component

J.P. Rouse [a], P. Zacharzewski [a], C.J. Hyde [a], R. Jefferson-Loveday [a], A. Morris [b], S.T. Kyaw [c]

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https://doi.org/10.1016/j.ijfatigue.2018.03.032

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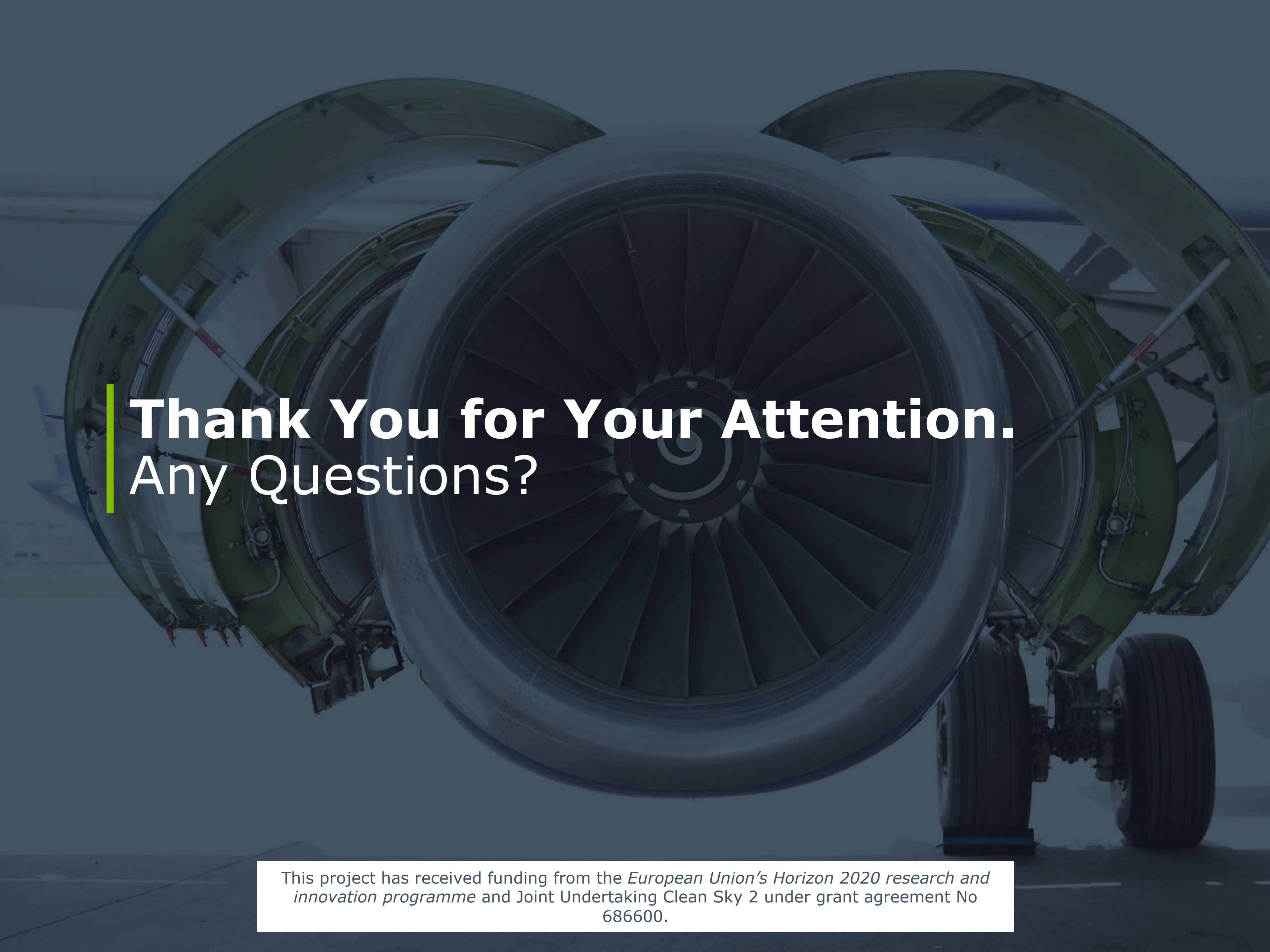
Conclusions

Future Work

- A unified (elastic visco-plastic) material has been used for the description of cyclic plasticity in RR1000 over a temperature range which makes the model useful for advanced component lifing. Initial results suggest a good level of agreement may be achieved under isothermal and an-isothermal conditions, however additional experimental results will bear this out (to be generated by Swansea University as part of DevTMF).
- A Taylor series based cycle jumping method may be used to reduce the amount of computational effort required solve for model variable on a cycle by cycle basis. This in turn may be used in optimisation procedures when large numbers of experimental hysteresis loops (all of which should be considered in objective functions) are available. Future work will look to fine tune cycle jumping parameters for material model optimisation problems.
- Stabilised hysteresis loops generated by the model may be used in Jiang's memory surface concept to estimate the number of cycles to failure (see the presentation by D. Leidermark, Thursday 31st May, 10:50, Room D).

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* and Joint Undertaking Clean Sky 2 under grant agreement No 686600.



Thank You for Your Attention.
Any Questions?

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