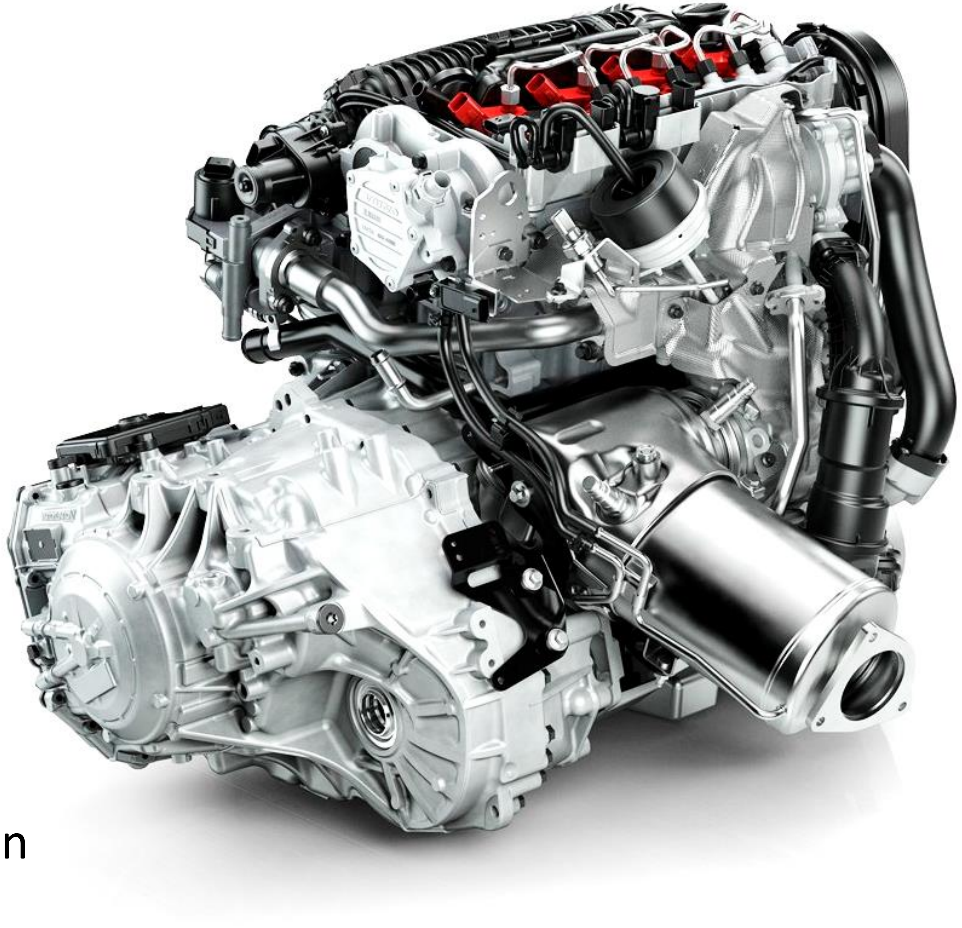
Challenges in Computational Prediction of TMF



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A Summary of our Experiences & Experiments with Cylinder Head Materials

Cast Aluminium A356-T7 + 0.5% Cu Alloy

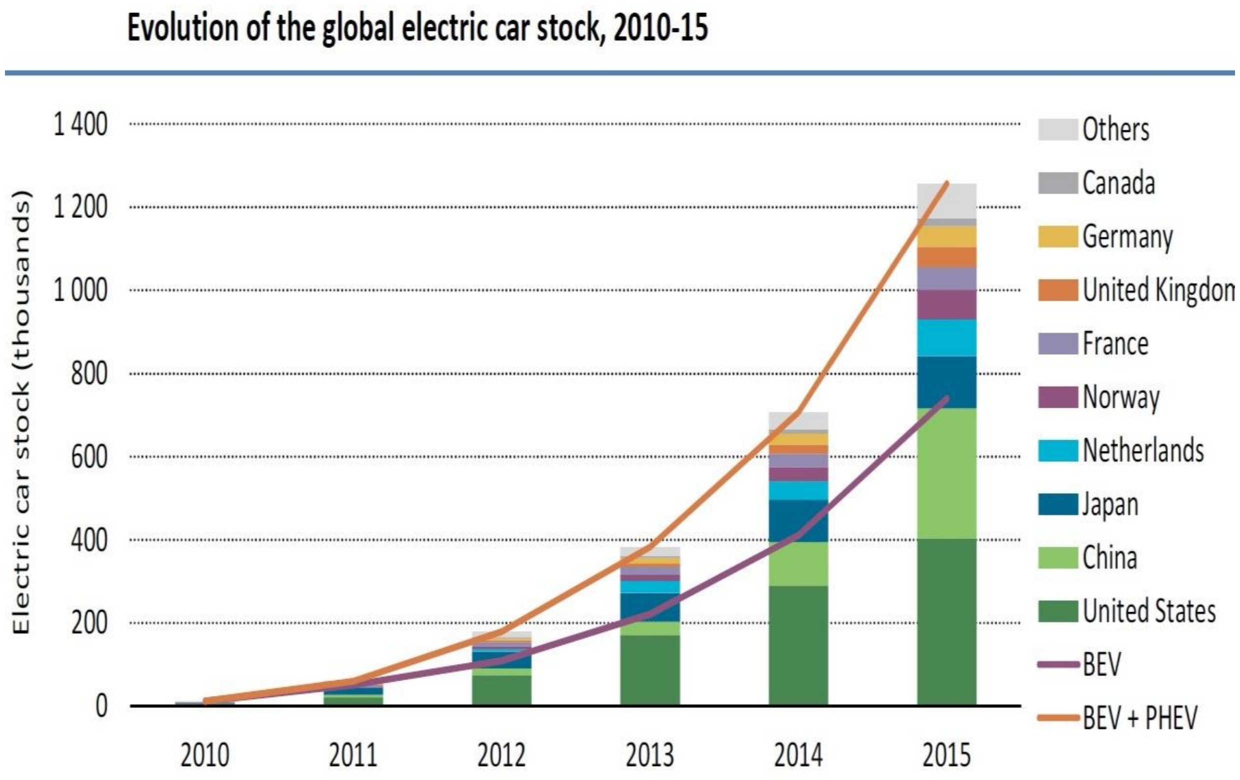
Project Introduction

Methodology

Results & Reflections

Current Automotive Landscape

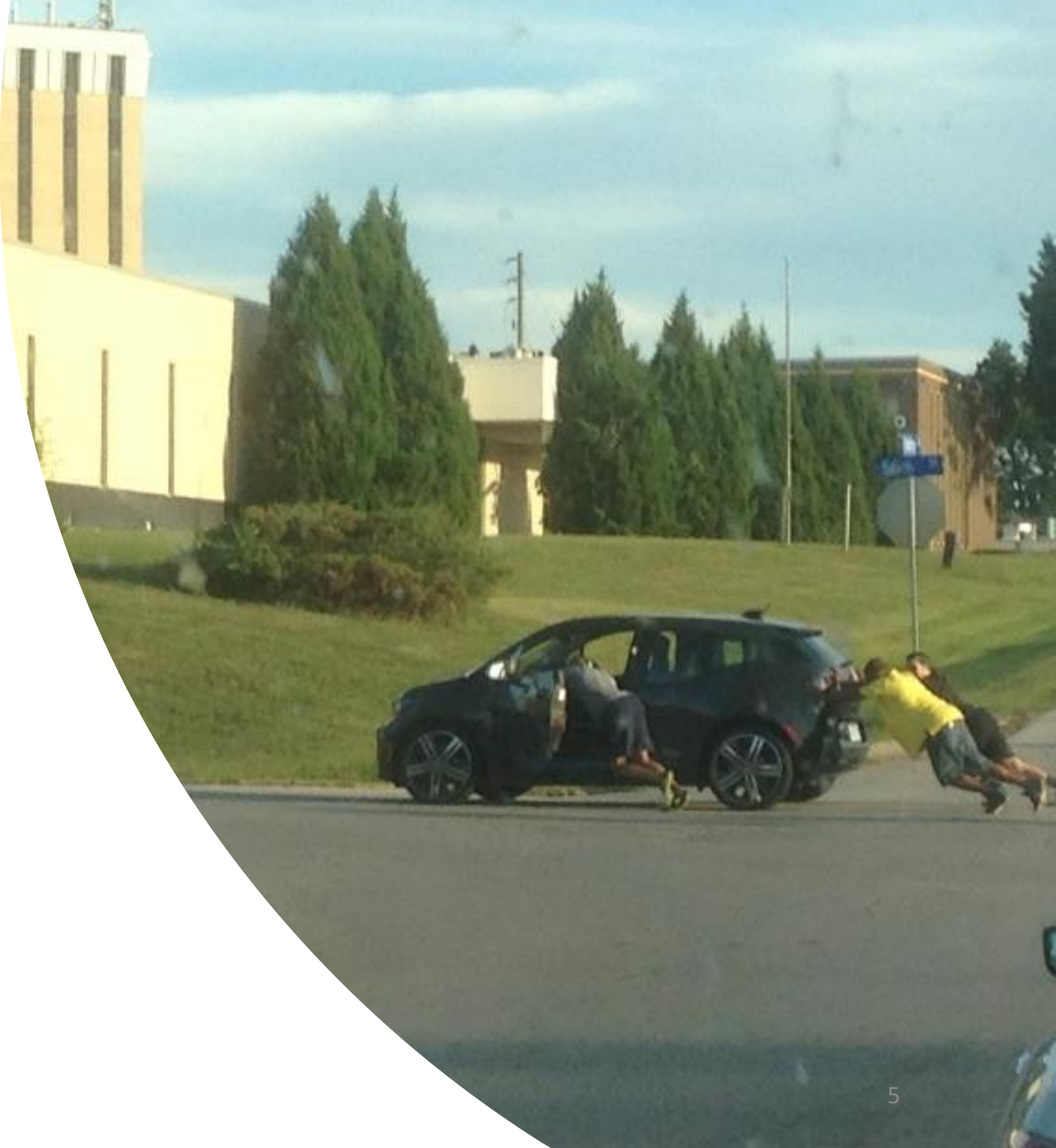
- Regulations to
  - Increase fuel economy
  - Decrease CO_2 emissions
- Rise of the electric cars
  - Green
  - High performance



Source: IEA

Electric Cars – The Unsolved Issues

- Range anxiety
- Cost (Rare earth minerals for battery)
- Charging time
- Vampire drain
- Power Source
- Range vs Performance



Transition Technology

- Hybrids & Range extended EVs
- Engine downsizing - reduced frictional losses & lighter engines
  - Reduces fuel consumption
  - Reduces CO_2 emissions
  - Fuel efficient vehicles without compromising engine performance through forced induction

Challenges with Powertrain Electrification

- Higher thermal loads on engine materials
  - 2 Types of fatigue: LCF/TMF, HCF
- Hybrids
  - Quick starts & rapid approach to maximum power
  - Increased start-stop cycles

Volvo Cars & Powertrain Electrification

<u>Thermomechanical Fatigue Life Prediction of High Specific Power IC Engine Cylinder Heads</u>

- Formulate efficient material/fracture models for description of thermo-mechanical deformation and fracture behaviour of cast aluminum alloys.
- Thermo-mechanical fatigue testing and materials characterization.

The Cylinder Head in a Combustion Engine

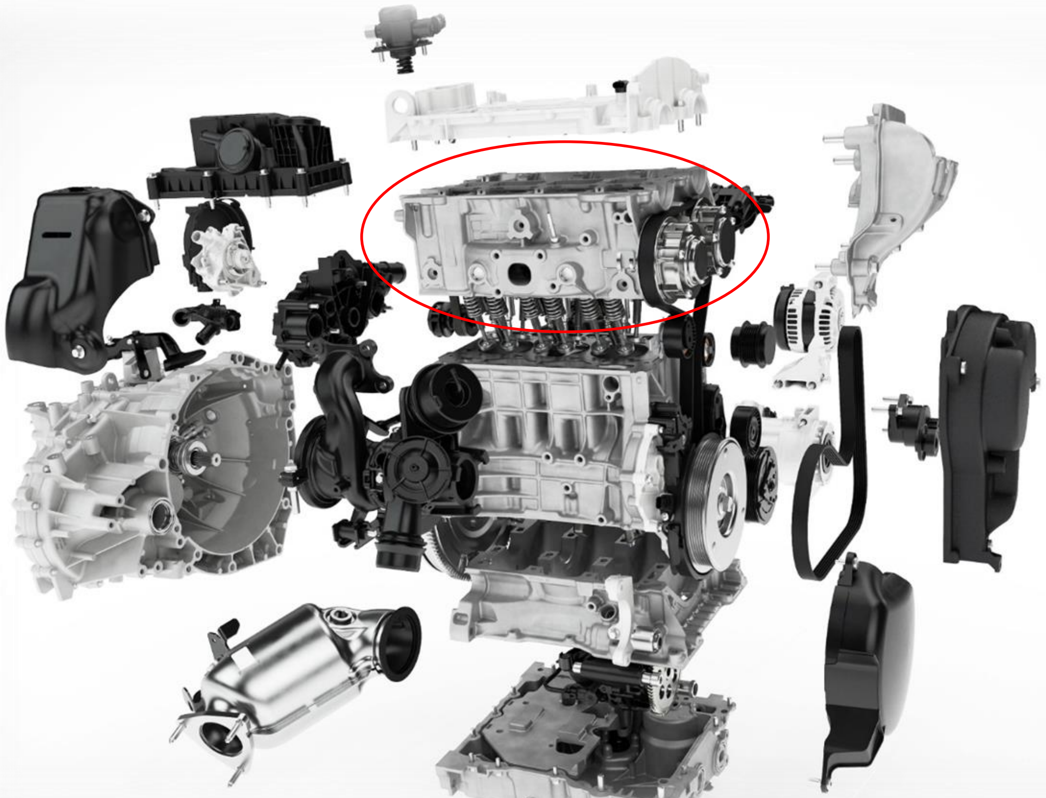


Image Source: Volvo Cars

TMF in Cylinder Heads

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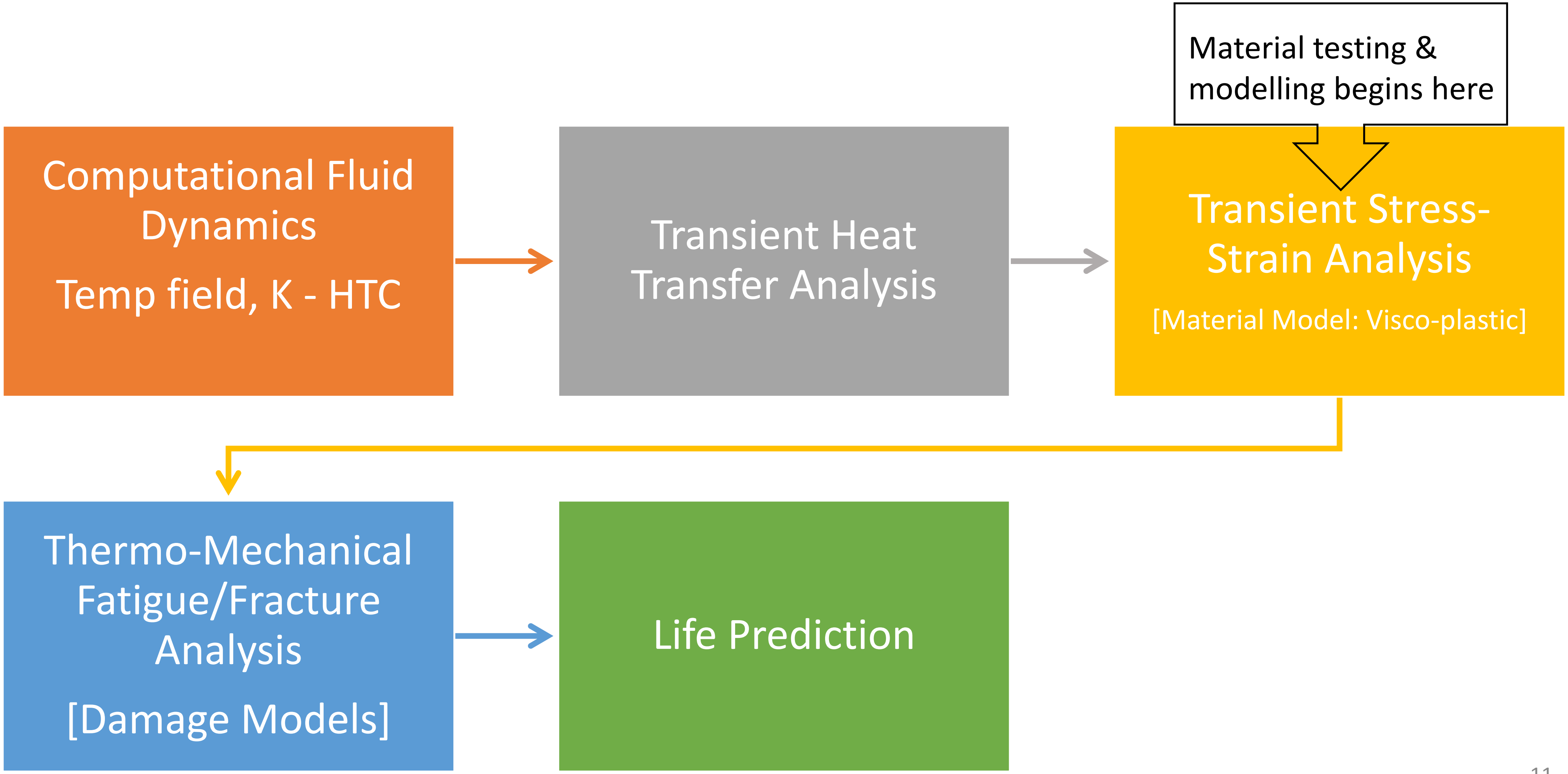
Modelling Steps – CAE Procedure



Modelling Steps – CAE Procedure

1. Continuum deformation modelling

   - to obtain the load-response time history

2. Fracture modelling

   - to predict the life of the component using the obtained load-response history

Sample Extraction: Volvo VEP-4 Gasoline Engines

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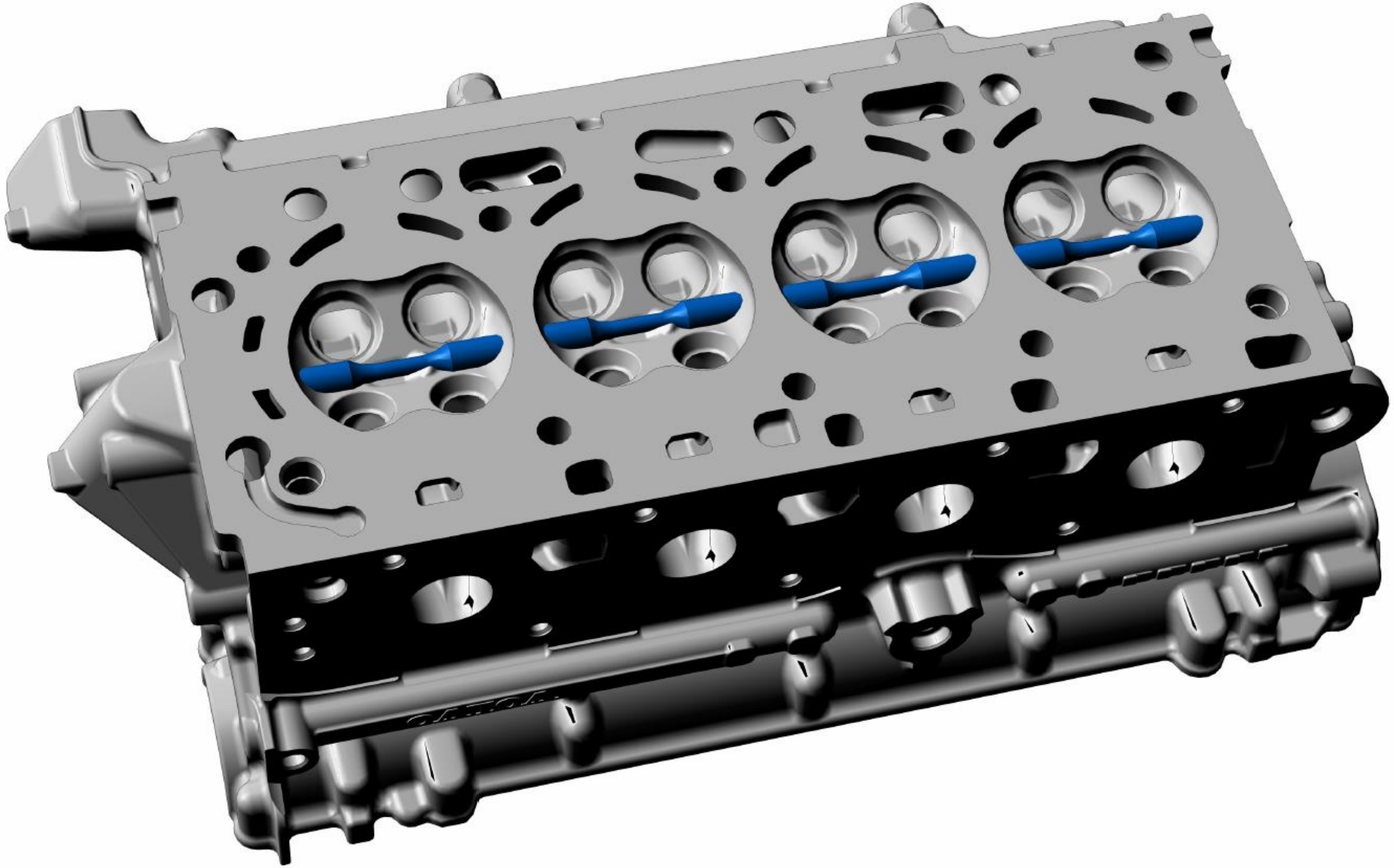


Phenomena & Testing

1. Elasticity
2. Cyclic Plasticity
   - Isotropic Hardening
   - Kinematic Hardening
   - Mean Stress Relaxation
3. Coefficient of thermal expansion
4. Relaxation
5. Ageing

- Tensile Tests
- Cyclic Strain Controlled Tests
- Dilatometry
- Strain Controlled Tests
- Hardness & Fatigue Tests

Temperature dependence

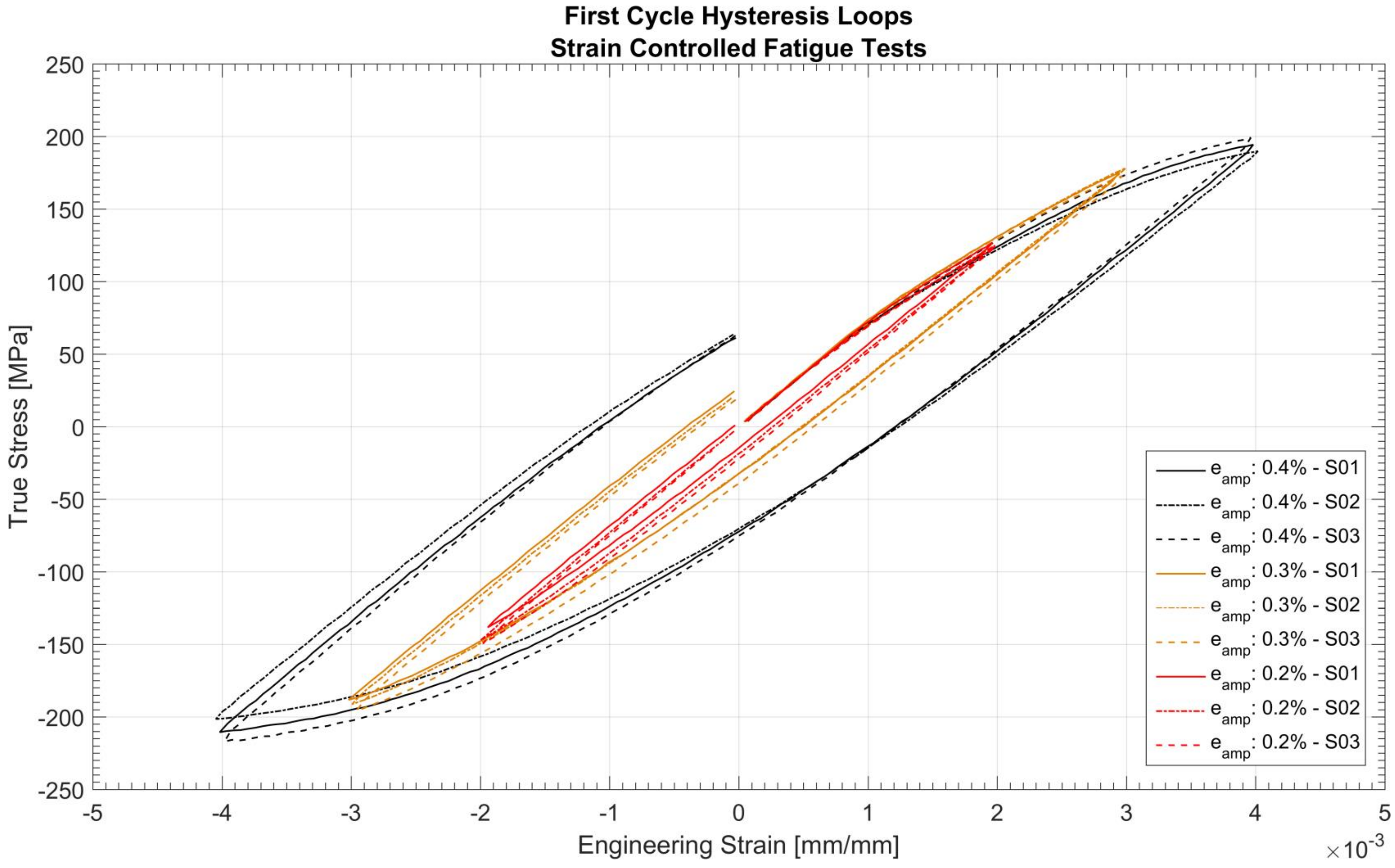
Modelling Continuum Plasticity

Test Plan – Cyclic Plasticity

Base line tests: run at 1 % sec^{-1}, 2-3 replicas

- Four temperatures: RT, 150, 200, 250 °C
- Three total strain amplitudes: 0.2, 0.3 and 0.4 % (R_{ε} = - 1)
- Without hold time: Time independent plasticity modelling

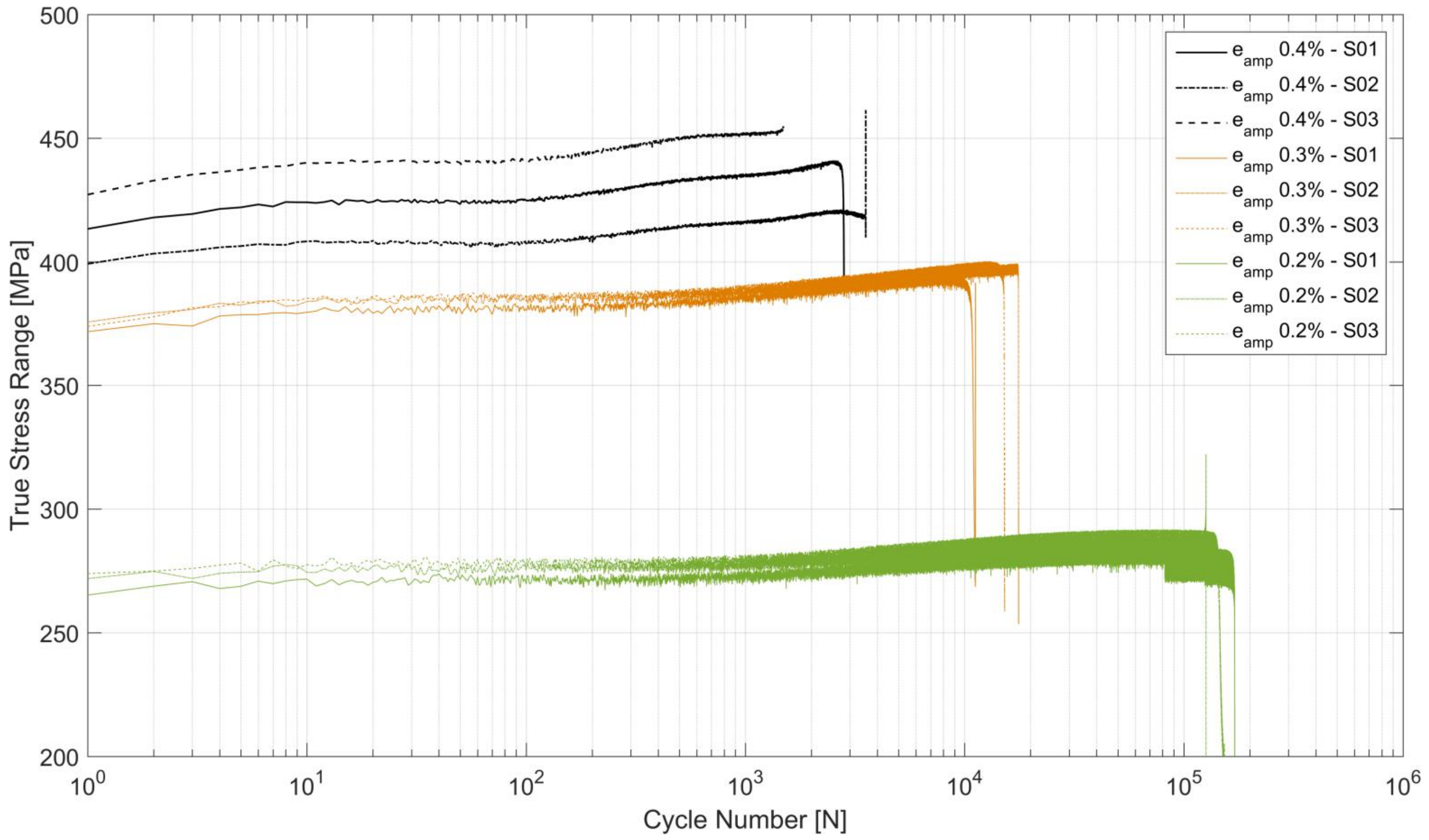
Results – Strain Controlled Deformation



Inference:

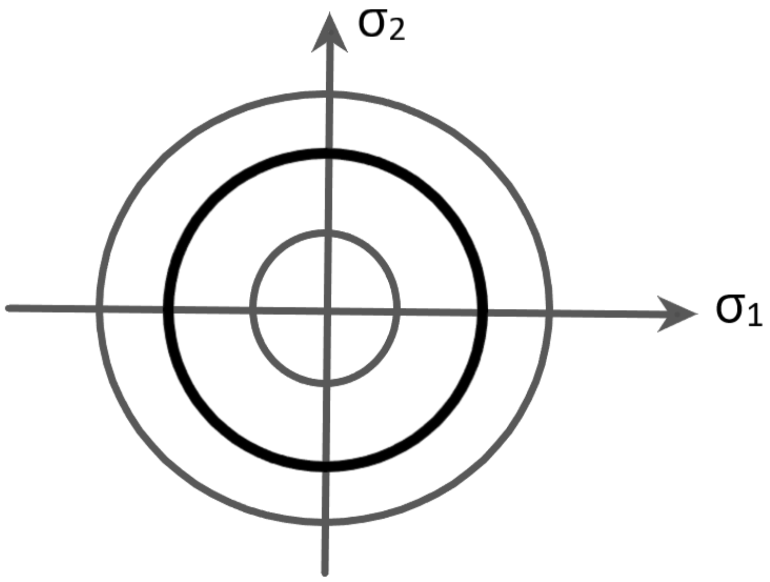
- Asymmetric Stress Development
- Scatter between replicas with identical loading

Stress Evolution – Room Temperature

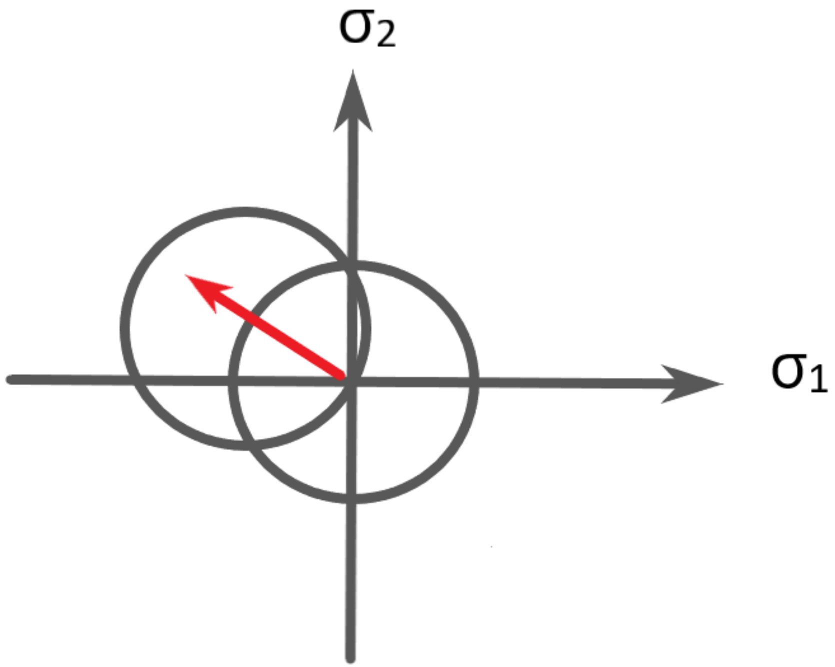


Cyclic Plasticity: Characteristics

Isotropic Hardening



Kinematic Hardening



Other Factors Affecting Continuum Plasticity

Difference in Yield

[Redacted]

Differing Loading/Unloading Stiffness

[Redacted]

Reduced Scatter at Elevated Temperatures

[Redacted]

Constitutive Modelling – An Overview

- Mathematical simplifications of complex physical behaviour
- Links the state of stress & strain
- Factors that affect the model:
  - Nature of the material
  - Temperature
  - Loading Rate, etc.,
- Problems with too much parameters in a model
- Complexity of a model depends on:
  - Purpose
  - Required precision

Combined Hardening Model: Abaqus

Yield Surface:

$$F = f(\sigma - \alpha) - \sigma^0 = 0$$

Non linear kinematic hardening model ($\sigma_0 = \sigma|_{\text{o}}$)

Evolution Equation: $\dot{\alpha}_k = C_k \frac{1}{\sigma^0}(\sigma - \alpha)\dot{\bar{\varepsilon}}^{pl} - \gamma_k \alpha_k \dot{\bar{\varepsilon}}^{pl}$

Overall backstress: $\alpha = \sum_{k=1}^{N} \alpha_k$

$\mathbf{C_k, \gamma_k}$ – Material parameters that are calibrated from cyclic data

Combined Hardening Model: Abaqus

Yield Surface:

$$F = f(\sigma - \alpha) - \sigma^0 = 0$$

Isotropic hardening model

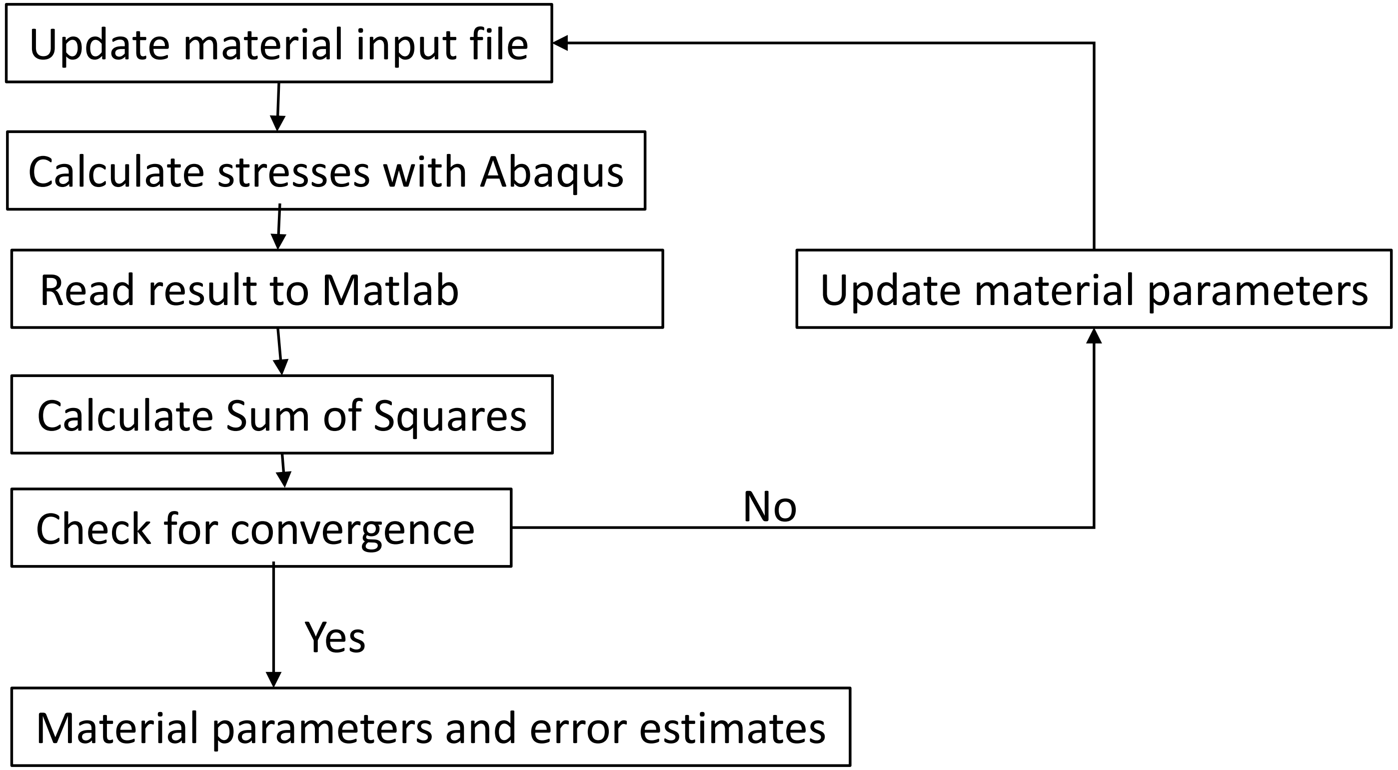
Exponential Law: $\sigma^0 = \sigma|_0 + Q_\infty \left(1 - e^{-b\bar{\varepsilon}^{pl}}\right)$

$\boldsymbol{\sigma|_0, Q_\infty, b}$ *– **Material parameters that are calibrated from cyclic data***

$\sigma|_0$ – Yield at zero plastic strain, Q_∞ – Maximum change in the size of the yield surface

b – Rate at which the size of the yield surface changes as plastic straining develops

Material Model Calibration & Potential Issues



Can we accurately predict TMF?

Ageing in the Material & Kinetics

[Redacted]

Kinetics of Ageing

[Redacted]

Effect on Stress Evolution

[Redacted]

Effect on Yield Surface Evolution

[Redacted]

Effect on Tension vs Compression Yield Evolution

[Redacted]

Effect on Fatigue Curves

[Redacted]

Energy Methods – Total / Per Cycle Dissipated Energy

[Redacted]

Summary

- Trade-offs are needed and should be thought-out in order to balance the complexity of the model and the accuracy desired.
- When high temperatures are involved, ageing affects more than just the yield strength of the material.
- The kinetics of ageing could be affected by deformation.
- The transient nature of the fatigue life curves should be studied when ageing is involved to avoid over-estimating the life of the component.
- Energy criteria to predict TMF should be handled with care especially when the loads aren't completely reversed.

End of Presentation

Questions?