Modelling Creep in Steel Structures Exposed to Fire

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WHY MODEL CREEP:

- Initial motivation:- Safety concerns regarding exposure of steel tendons in Unbonded Post Tensioned (UPT) slabs to fire.

WHY IS CREEP IN STEEL OFTEN OVERLOOKED?

- Creep in steel is thermally activated.
- Typically concrete cover and fire coating are sufficient to protect the steel from reaching a high enough temperature for a long enough time.

EXTREME CASES:

- What if concrete spalls?
- Relaxation of tension in bolted connections

AIMS OF THIS WORK:

- To provide a overview of creep theories, constitutive relations and modelling techniques useable by structural engineers.
- To model creep in commercial Finite Element Method (FEM) packages for incorporation in larger structural models (UPT concrete slabs for instance).

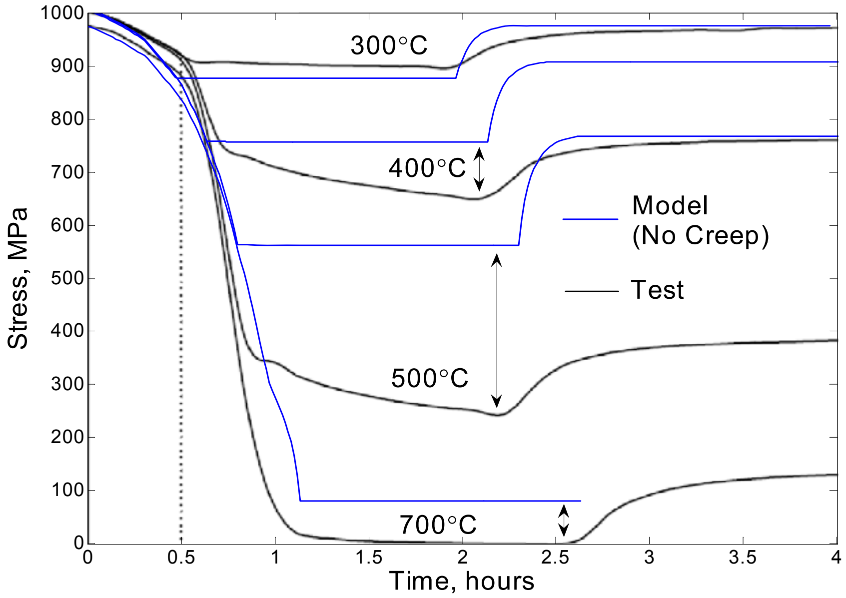


Fig. 1. Stress Relaxation in Prestressed Steel Tendons at Elevated Temperature. Modelled Without Explicit Accountability of Creep.

Creep Deformation Mechanisms:- An Overview

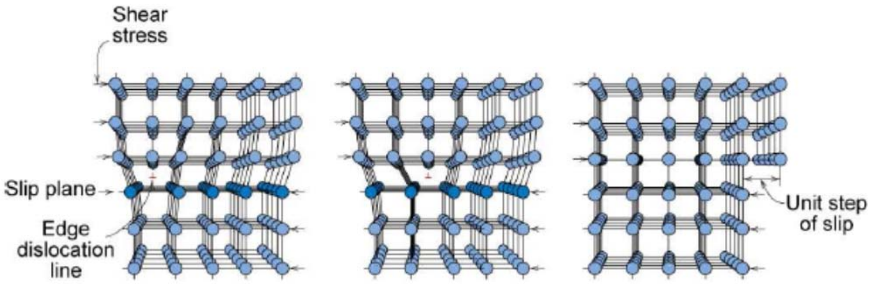
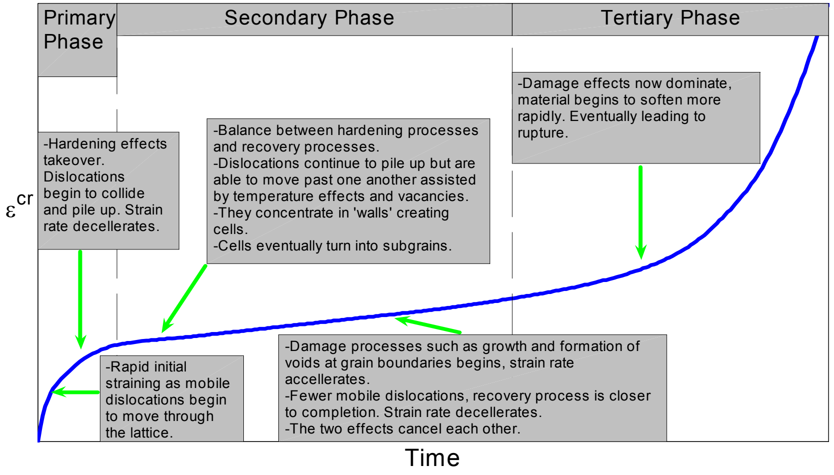


Fig. 2. Plastic Deformation by Dislocation Movement (Callister, 2006)

- Plastic and viscoplastic (creep) strains occur through the dislocation glide along a slip plane (Fig. 2).
- Continuous glide or creep is activated thermally through the diffusion of vacancies allowing dislocations to ‘climb’ obstacles.
- The dislocation climb mechanism dictates the rate of straining at moderate stresses through the time taken to overcome obstacles.
- At very high stresses the rate becomes increasingly glide dependent due to the speed of release of stored strain energy during the hardening or primary creep phase.



-Hardening effects takeover. Dislocations begin to collide and pile up. Strain rate decellerates.

-Balance between hardening processes and recovery processes.
-Dislocations continue to pile up but are able to move past one another assisted by temperature effects and vacancies.
-They concentrate in 'walls' creating cells.
-Cells eventually turn into subgrains.

-Damage effects now dominate, material begins to soften more rapidly. Eventually leading to rupture.

-Rapid initial straining as mobile dislocations begin to move through the lattice.

-Damage processes such as growth and formation of voids at grain boundaries begins, strain rate accellerates.
-Fewer mobile dislocations, recovery process is closer to completion. Strain rate decellerates.
-The two effects cancel each other.

Fig. 3. Creep Strain Phases over Time at Constant Stress and Temperature

Viscoplastic Constitutive Theory

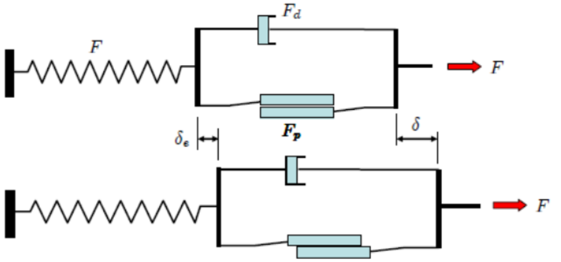


Fig. 4. 1D Elasto-Viscoplastic Material Model (Pankaj)

- A common 1D elasto-viscoplastic material model:- The spring, friction slider, damper model (Fig. 4).
- The damper allows stress states to be reached outside the yield surface! How much outside (overstress) dictates the strength of the flow.
- In time equilibrium is reached, the yield surface meets the stress state.

$\sigma_{vis} = f = \sigma_{vm} - Y$	Viscous or Overstress in terms of the Von Mises stress and the yield surface.
$\dot{\varepsilon}^{cr} = \dot{\varepsilon}_0 \left\langle \frac{f}{D} \right\rangle^n$	The power law dependance of the uniaxial plastic strain rate (flow potential).
$\dot{\varepsilon}^{cr} = \dot{\varepsilon}_0 \left\langle \exp\left(\frac{f}{D}\right) \right\rangle$	Power law breakdown flow potential algorithm.
$\dot{\varepsilon}^{cr}_{ij} = \dot{\varepsilon}^{cr} n_{ij}$	Multiaxial creep strain.
$n_{ij} = \frac{\partial f}{\partial \sigma_{ij}} = \frac{3}{2}\frac{s_{ij}}{f}$	Flow direction tensor in terms of the stress deviator tensor.

Numerical Creep Modelling:- Stress Relaxation in Prestressed Steel Tendons at Elevated Temperatures.

TENDON TESTS AND MODELLING

- Stress relaxation in prestressed steel tendons was modelled in ABAQUS and compared to experimental relaxation curves from Maclean (2007).
- Tests were performed on tendons prestressed to tensions of around 1000MPa.
- Approximately 11% of the tendon length (5390mm) was heated about its centre in a tube furnace at a rate of 10˚C/min towards designated 90 minute soak temperatures.
- Soak temperatures of 300˚C, 400˚C, 500˚C and 700˚C were tested.
- Tendons were allowed to cool naturally after soaking.
- Stress was measured at the restraints.
- Half tendons were modelled using C3D8T continuum elements (Fig. 5).

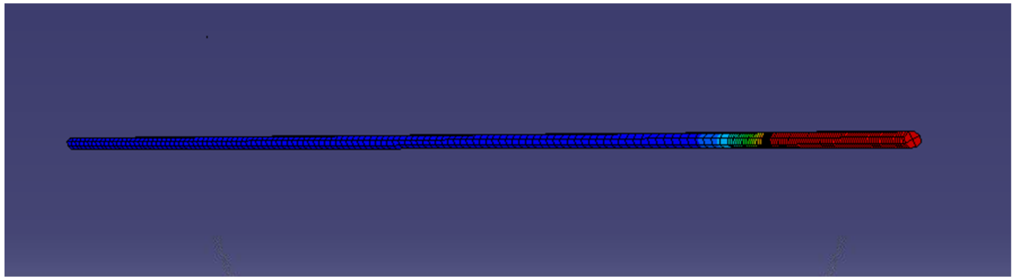


Fig. 5. FEM Tendon Mesh and Heated Region

MODELLING CREEP IN ABAQUS:

- ABAQUS offers 3 in-built models.
  - ☐ 2 Power law models (one including time hardening, one including strain hardening) and a hyperbolic sine model suitable for modelling the exponential stress relation of creep strain rate at high stresses.
  - ☐ User has to define constants.
  - ☐ Constants can be tabulated with temperature or other field variables.
- Or a creep user defined subroutine option.
  - ☐ User can codes their own uniaxial creep strain algorithm.
  - ☐ Written in Fortran.
  - ☐ User is also asked to code the derivative of the uniaxial strain rate with respect to the deviatoric stress (Von Mises or Hills) to allow implicit integration where the strain rate becomes more transient.
- ABAQUS computes flow direction tensor itself.

SPECIFIC CONSIDERATIONS:

- High stresses!
  - ☐ Transition stress between power law and power law breakdown taken as 1/1000th of the shear modulus, *μ*, (Frost and Ashby, 1982).

$$\mu = \mu_0\left[1 - 1.09\left(\frac{T - 300}{T_M}\right)\right]$$

  - ☐ The shear modulus of steel at 300K, μ_0, is 81GPa.
  - ☐ Stresses are well above the transition stress until temperatures approach 700˚C.
  - ☐ Therefore use a subroutine coded power law breakdown model or a in-built hyperbolic sine model!
- Temperature ramp phase.
  - ☐ The creep strain rate is rapid during the temperature ramp phases. The temperature ramp assists the recovery process against strain hardening at all points through this phase.
  - ☐ The increase in temperature decreases the shear modulus and can be coded as a softening effect. The resistive effect of the strain hardening has been assumed negligable due to the above points.

CONCLUSIONS:

- Constants should be determined from experimental data if at all possible!
- Convergence can be an issue when strain rates are highly transient. If possible try and smooth these regions.

Fig. 6a. Power law breakdown model:

$$\dot{\varepsilon}^{cr} = 10^{13}\exp\left(\frac{\sigma_{dev}}{\sigma_0}\right)\exp\left(\frac{-Q_c}{RT}\right)$$

Note:- σ_0 is the transition stress between power law and power law breakdown creep, taken as 0.001μ. Q_c is the creep activation energy (taken as 254 KJm^{-1} (Gales, 2008)). *R* is the universal gas constant.

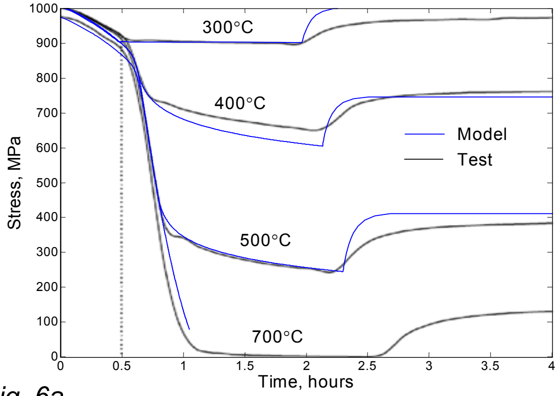


Fig. 6a.

Fig. 6b. Harmathy (1967) model:

$$\dot{\varepsilon}^{cr} = \frac{\varepsilon^{cr,0}}{\ln 2}\cosh^{-1}\left(2^{Z\theta/\varepsilon^{cr,0}}\right)$$

$$Z = 8.21\times10^{13}\exp(0.0145\sigma)$$

$$\varepsilon_{cr,0} = 9.262\times10^{-5}\sigma^{0.67}$$

$$\theta = \int_0^t \exp\left(\frac{-Q_c}{RT}\right)dt$$

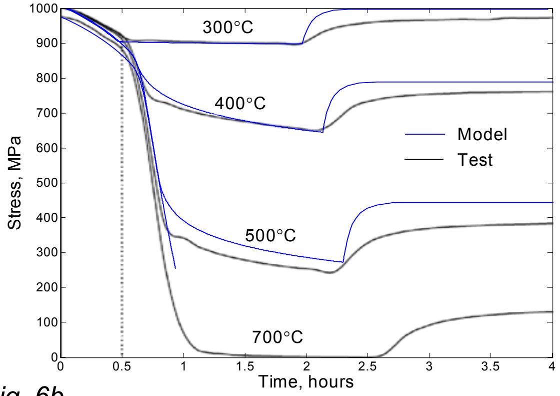


Fig. 6b.

Fig. 6c. Hyperbolic sine model (in-built):

$$\dot{\varepsilon}^{cr} = 2\times10^{13}\sinh\left(\frac{\sigma_{vm}}{\sigma_0}\right)\exp\left(\frac{-Q_c}{RT}\right)$$

Note: To use the model in ABAQUS as stated the transition stress was tabulated as its inverse against temperature as a field variable. This required the use of a User Defined Field (USDFLD) subroutine.

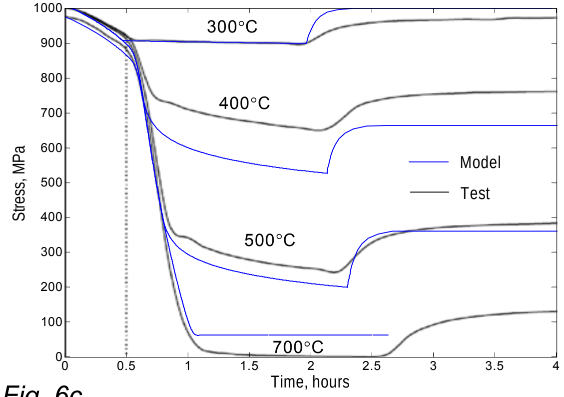


Fig. 6c.