BRE Centre *for* Fire Safety Engineering

Modelling Creep in Steel Structures Exposed to Fire

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INTRODUCTION

Motivation:

- Lack of attention to the affects of creep in prestressed steel tendons within Unbonded Post Tensioned (UPT) concrete slabs if exposed to fire.
- There seems a general lack of understanding and consideration of creep in general within steel structures. There is often an assumption Eurocode plastic stress strain curve data will implicitly account for creep (Fig. 1).

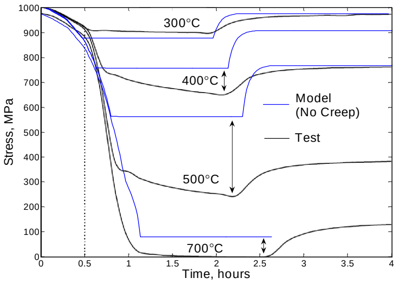


Fig. 1. Relaxation of Stress in Prestressed Steel Tendons at Elevated Temperature versus a FEM Relaxation Model using Eurocode Plastic Stress Strain Data For Prestressing Steel (No Creep).

CREEP DEFORMATION MECHANISMS - AN OVERVIEW:

DISLOCATION GLIDE:- Responsible for the magnitude of the deformation.

- The movement of dislocations along a slip plane under applied stress.

DISLOCATION CLIMB:- Responsible for the rate of deformation (in power law creep).

- The ability of dislocations to 'climb' obstacles in their path such as other dislocations.
- Thermally activated! Diffusion of vacancies (missing atom within a otherwise locally regular crystal) to dislocation lines. Creep in metals is thus thermally activated!

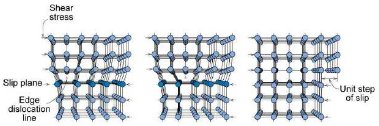


Fig. 2. Plastic Deformation by Dislocation Movement (Callister, 2006)

HARDENING:- Resistance to deformation through the collision and 'pile up' of dislocations (Fig. 3a).

RECOVERY:- A resulting decrease in lattice defects such as dislocations facilitated through dislocation climb and other thermal effects allowing 'pile ups' to clear.

- Dislocations concentrate in walls creating cells (Fig. 3b).
- Cells gradually clear of mobile dislocations creating regular crystal subgrains (Fig. 3c).
- Dislocations of opposite polarity annihalate within walls, subgrains grow into grains (Fig. 3d).

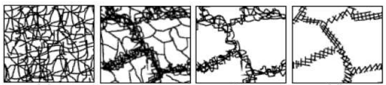
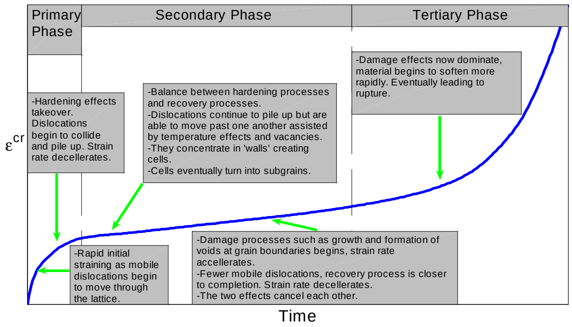


Fig. 3. Recovery Process (Humphrey and Hatherly, 2004)

CREEP PHASES:- Dictated by hardening, recovery and material damage processes (Fig. 4).



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

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

-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 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.

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

Fig. 4. Phases of Creep Strain Behaviour with Time under Constant Stress and Temperature

ELASTO-VISCOPLASTIC CONSTITUTIVE RELATIONS

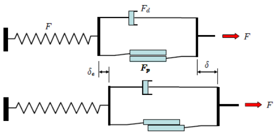


Fig. 5. 1D Material Elasto-Viscoplastic Model (Pankaj)

SPRING, FRICTION SLIDER, DAMPER 1D MATERIAL MODEL:

- Yield is defined herein by Von Mises Criterion.
- Spring represents elastic deformations.
- Friction slider only becomes active the instant elastic yield is surpassed. Friction prevents non elastic strains being recovered on unloading.
- The dashpot represents the initial build up and slow release of stored strain energy under applied stress. With time an equilibrium state is achieved under the applied stress.
- The dashpot allows a stress state to exist outside the yield surface!

SOME KEY EQUATIONS OF VISCOPLASTIC CONSTITUTIVE THEORY:

$$\sigma_{vis} = f = \sigma_v - Y$$

The viscous or overstress in terms of the yield surface, Y and the Von Mises stress, σ_{vm}.

$$\dot{\varepsilon}^{cr} = \dot{\varepsilon}_0 \left\langle \frac{\sigma_{vis}}{D} \right\rangle^n$$

$$\dot{\varepsilon}^{cr} = \dot{\varepsilon}_0 \left\langle \exp\left(\frac{\sigma_{vis}}{D} \right) \right\rangle$$

Power law and power law breakdown (exponential) relations (stress dependent) between overstress and uniaxial plastic strain rate (flow potential). D represents a drag or resistive stress which can include strain hardening and other evolving hardening and softening effects.

$$\dot{\varepsilon}^{cr}_{ij} = \dot{\varepsilon}^{cr} n_{ij}$$

Computation of the multiaxial creep strain rate in terms of the flow potential and flow direction.

$$n_{ij} = \frac{\partial f}{\partial \sigma_{ij}} = \frac{3}{2}\frac{s_{ij}}{f}$$

Flow direction tensor in terms of the yield criteria, f, stress tensor, σ_{ij}, and the stress deviator tensor, s_{ij}.

NUMERICAL CREEP MODELLING:- PRESTRESSED STEEL TENDONS AT ELEVATED TEMPERATURES

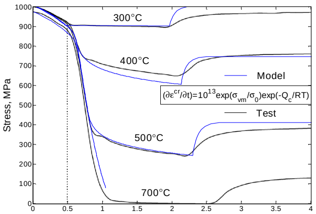


Fig. 6a.

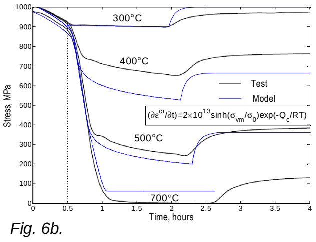


Fig. 6b.

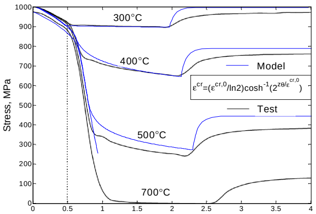


Fig. 6c.

TENDON MODELS (ABAQUS):

- Stress relaxation in prestressed steel tendons has been modelled using C3D8T continuum elements including creep and compared to tests by Maclean (2007).
- 11% of the tendon length was heated at a rate of 10℃ per minute to 300℃, 400℃, 500℃ and 700℃.
- Strain hardening has not been included. The combination of high stress and increasing temperatures strongly aid the recovery process. Thus a temperature dependent drag stress has been used in Figs. 6a and 6b.
- Drag stresses determined from Macleans tests at a range of temperatures closely matched the temperature dependant transition stress between power law and power law breakdown behaviour, σ_0. The transition stress is taken as 1/1000th of the temperature dependant shear modulus, μ (Frost and Ashby, 1982).

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

- Typically the Von Mises stress is used as opposed to overstress for simplicity. Constants can be determined from experimental data by equating creep strain rate to the Von Mises stress.

Fig. 6a. Power Law Breakdown Model; b. Hyperbolic Sine Model (In Built within ABAQUS); c. Harmathy (1967) Model

CONCLUSIONS

- The user defined subroutine options within various commercial FEM packages offer a versatile means of using a variety of creep models. Only uniaxial models need to be coded, multiaxial computation is performed by the package.
- Reasonable accuracy in the constants used is essential for meaningful results. These must be based around experimental data or previous research.
- Numerical methods by nature struggle to handle highly transient systems. Where creep strains show a high degree of transience convergence during implicit integration can be hard to achieve as shown in 700˚C models. Issues may also occur when the state of the system is transient, such as fluctuating or sudden temperature changes and cyclic loading.
- Generally creep is a steady state process and in many structural cases modelling as such will suffice, removing most issues with convergence.