Validation and Usage of Digital Image Correlation for High Temperature Deformation Measurement in Modern Prestressing Steel

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What is Prestressing Steel (PS)?

Conventional steel rebar

'Unbonded' PS steel

- **Advantages of post-tensioning concrete with PS steel**

- Rapid construction
- Shallow floors (high ceilings)
- Increased span lengths
- Reduces building materials

Highly Optimized

UPT Building Optimization

- **Current guidance is dated and has not kept up with modern optimization trends**

" ***Today's flat-slab post-tensioned buildings, for example, with columns spaced (12 m) on center and span-depth ratios of 40 are more complex and require more engineering attention than typical flat-slab buildings of 40 years ago, with columns spaced at (6 m) on center and span-depth ratios of 20.*** " *-Randall Poston (chair ACI 318)*

Real UPT Slab Behaviour in Fire is **Unknown**

- **UPT optimization increases susceptibility to fire:**

- *Prestressing steel **more sensitive to high temperature** than mild steel*
- ***Spalling** of concrete cover (HS concrete, precompression can contribute to this)*
- *Tendons **run continuous**, local **damage effects the entire floor***

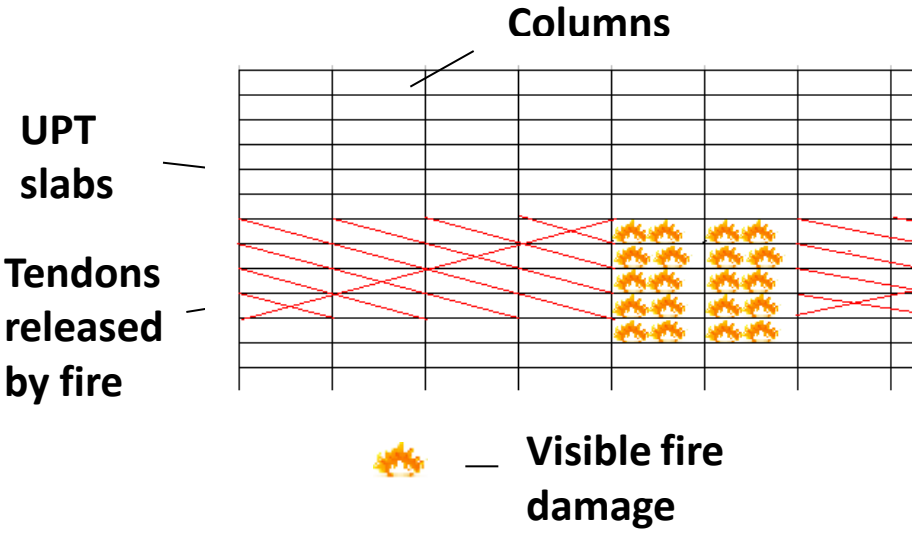
- **Only standard furnace tests of simple span slabs are available:**

  - modern construction?, building materials?, real fires?

2008 standard fire test (Kelly and Purkiss)

Can standard fire tests predict true fire behaviour of these UPT buildings?

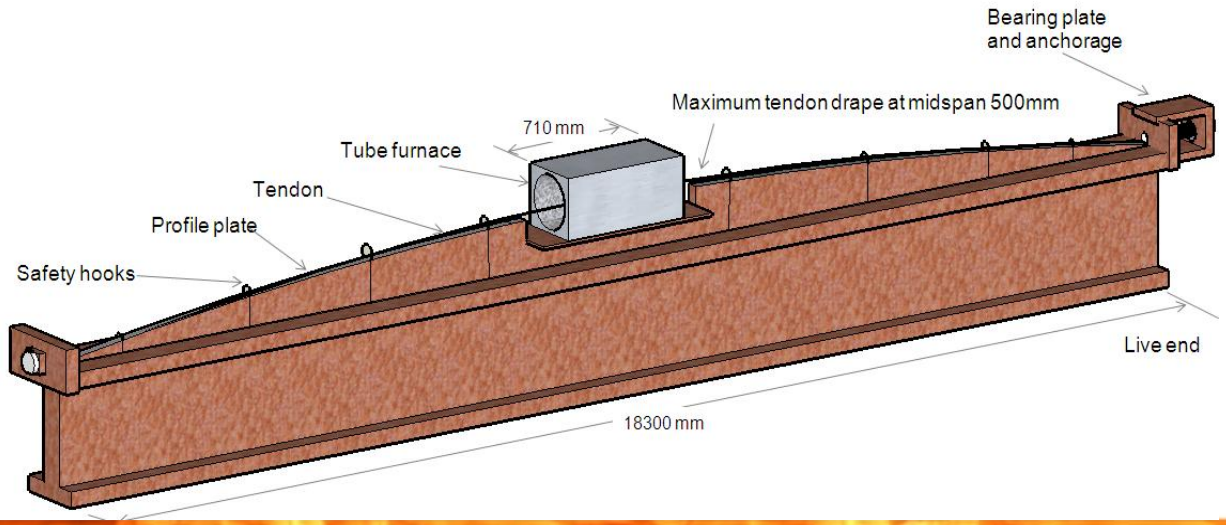
- **Key Biscayne, USA, 2000:**
  - UPT tendons **continuous across 7 interior bays** (> 50m)
  - **Localized fire** on 2nd floor spread vertically to 7th floor over 2 bays
  - **"triggered progressive failure of the UPT slab well beyond the zone of visible damage"**



Post and Korman, Engineering News Record June 12th 2000

Localized Fire Damage

- **Localized fires may be due to *spalling, travelling, ceiling jets…***
- **Queens university tests in 2009 showed that tendon rupture is more probable under localized heating**
- **Complex stress relaxation / strength interaction - influenced by a permanent time dependent damage called, creep**



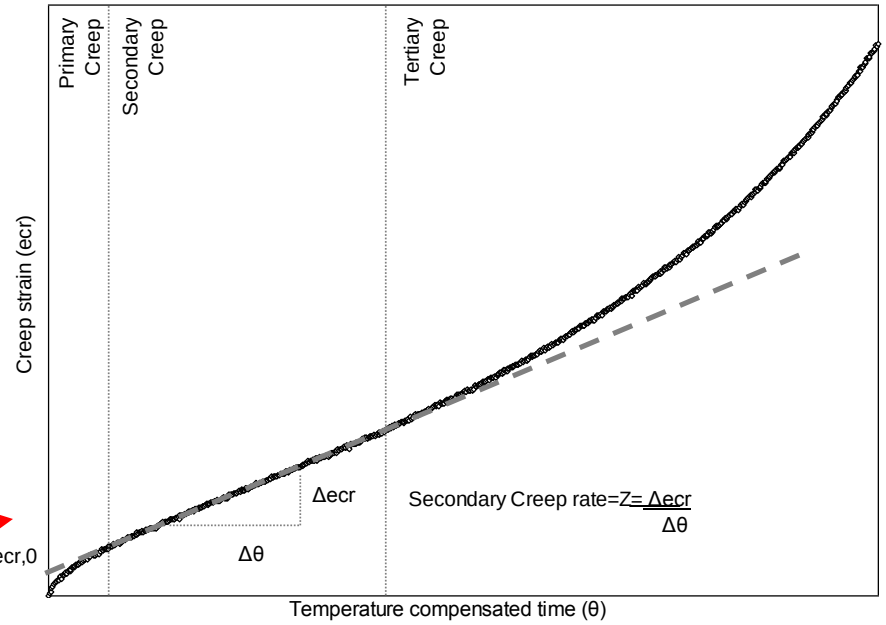
*Localized UPT tendon tests (**strong back tests**) conducted at Queens university in Canada*

High Temperature Creep

- Creep is a time, temperature and load dependent deformation

- Possible to express creep through combined temperature time variable in a heated tensile test at constant load

'Dorn-Harmathy creep model'



- Creep parameters for PS steel are from dated (1970) and different material compositions than modern counterparts- *Errors in creep modelling?*

Temperature Compensated Time

$$\theta = \int_0^t e^{-\Delta H / RT} dt$$

Creep in Prestressing Steel

$$e_{cr} = \frac{e_{cr_0}}{\ln 2} \cosh^{-}(2^{\frac{Z\theta}{e_{cr,0}}})$$

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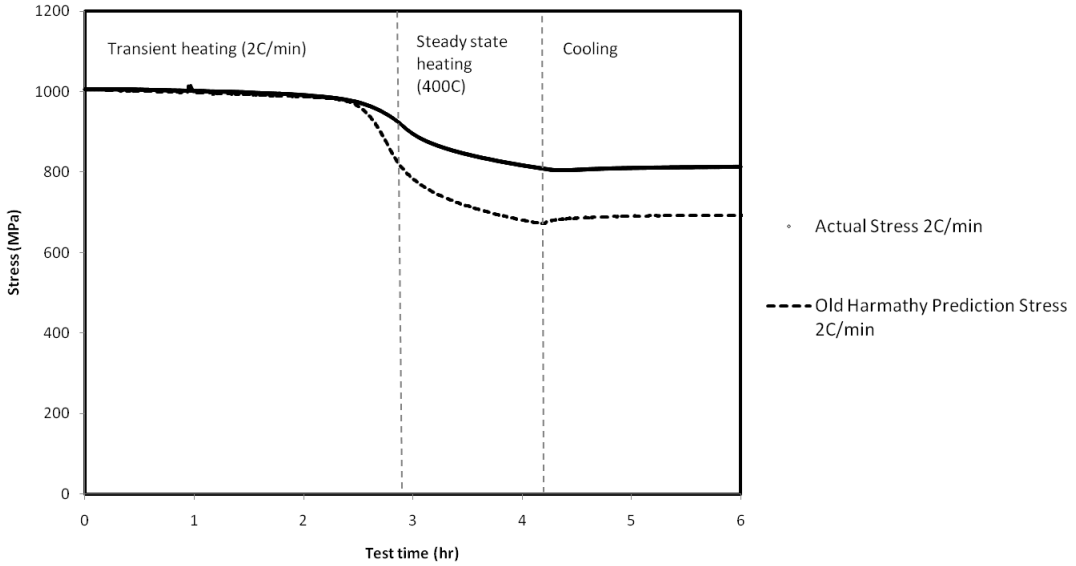
Predicting Creep for Stress Relaxation?

- **Typical Queens university high temperature stress relaxation test**

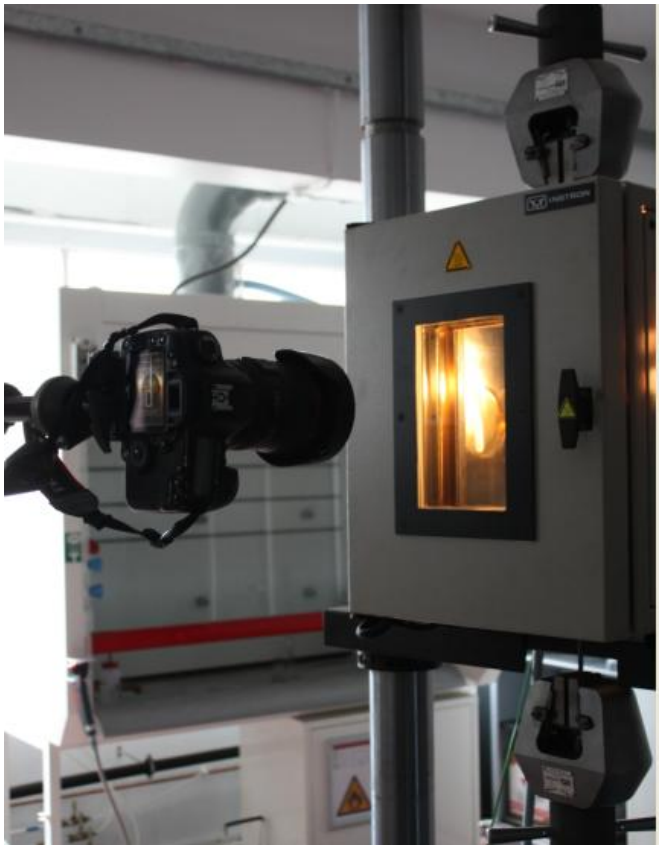


Regimes

- Transient heating
- Steady state hold
- Cooling

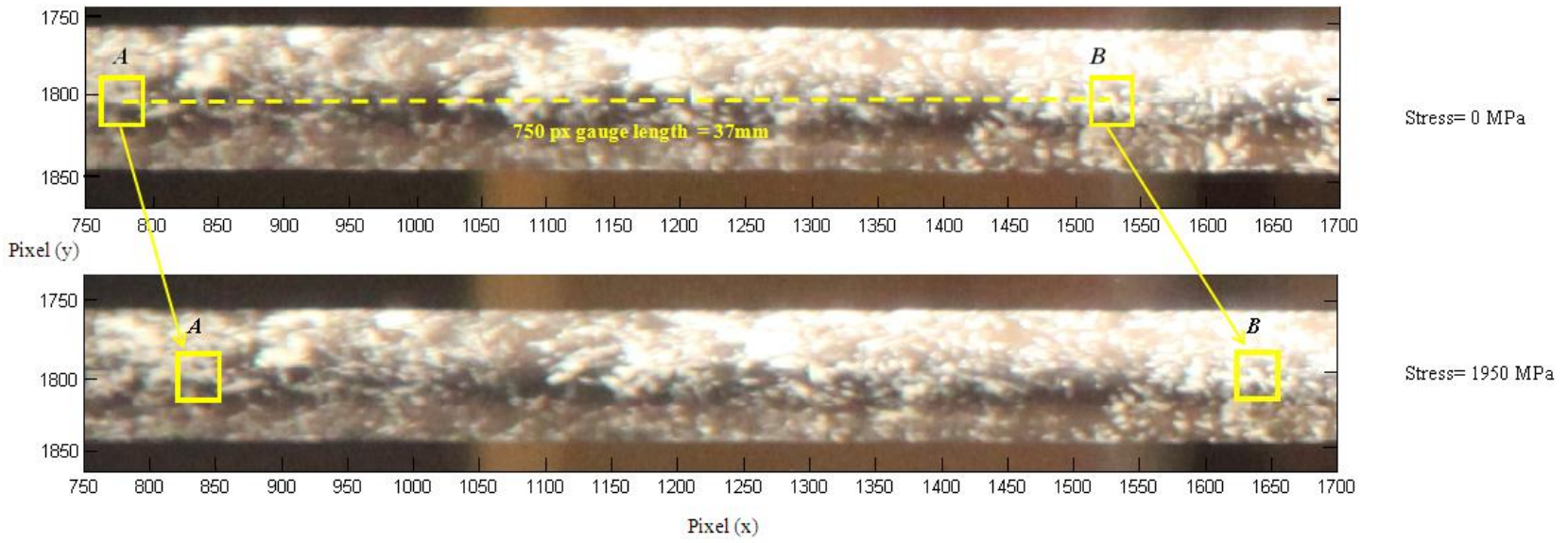
- **Over estimation of (creep)**
- **May be due to parameter extrapolation, older steel derivations, inaccuracies in derivation**

How Can We Derive Modern Creep Parameters?:



Digital Image Correlation (DIC) in *transient* and *steady* state uniaxial tensile tests to measure deformation

What is Digital Image Correlation?



Two photos showing deformation from a uniaxial ambient strength test

Previously validated Image correlation algorithm *(by Dr Andy Take, Queens)* are used to measure virtual deformation (strain) through a series of sequenced test photos

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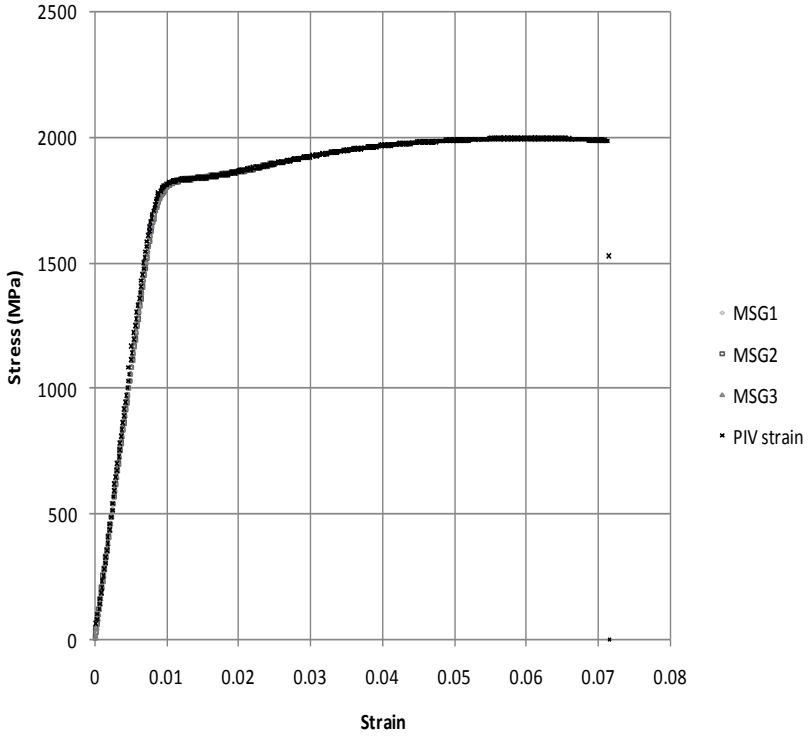
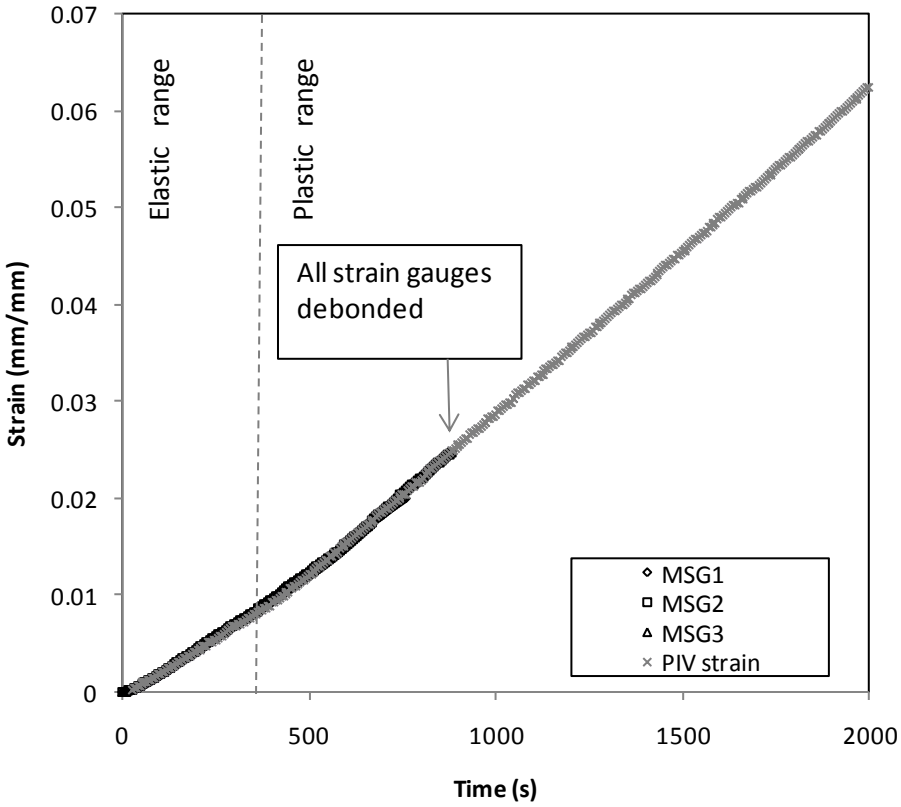
DIC Validation (1 of 2)

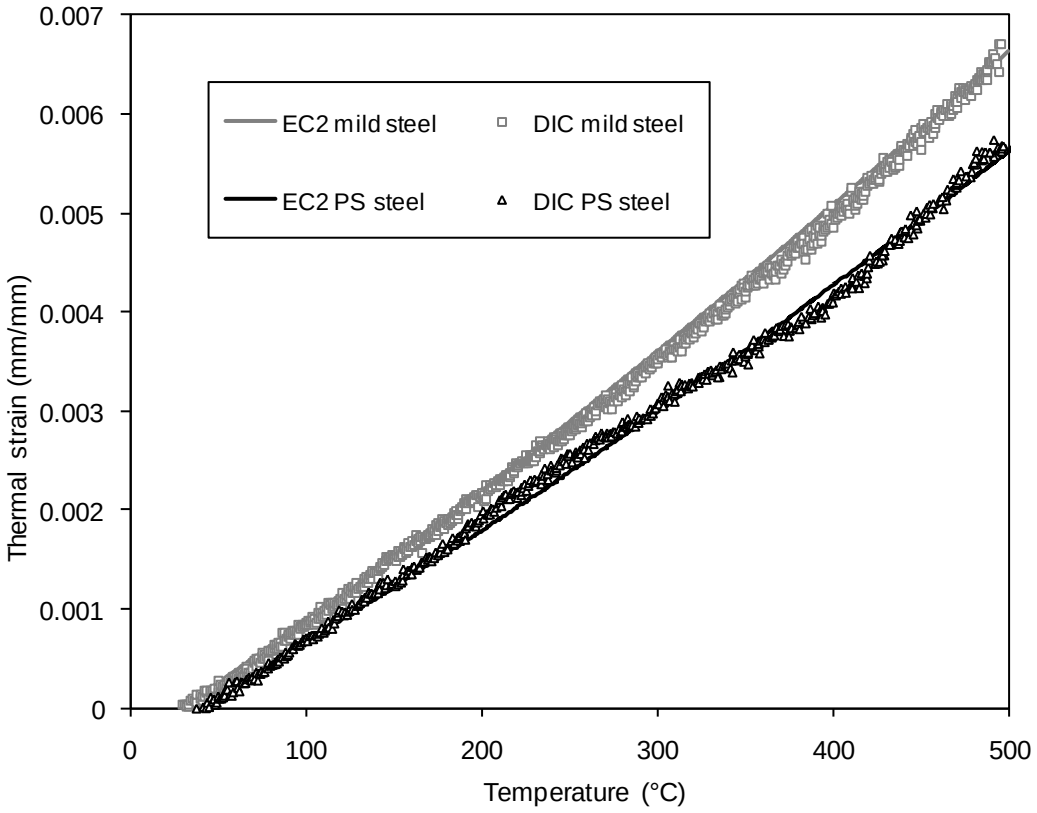
- **Uniaxial *ambient strength test* with comparison of DIC and bonded foil strain gauges**





DIC Validation (2 of 2)

- **Uniaxial *transient thermal expansion test* (unloaded) with comparison of DIC to theoretical calculation(EC2)**

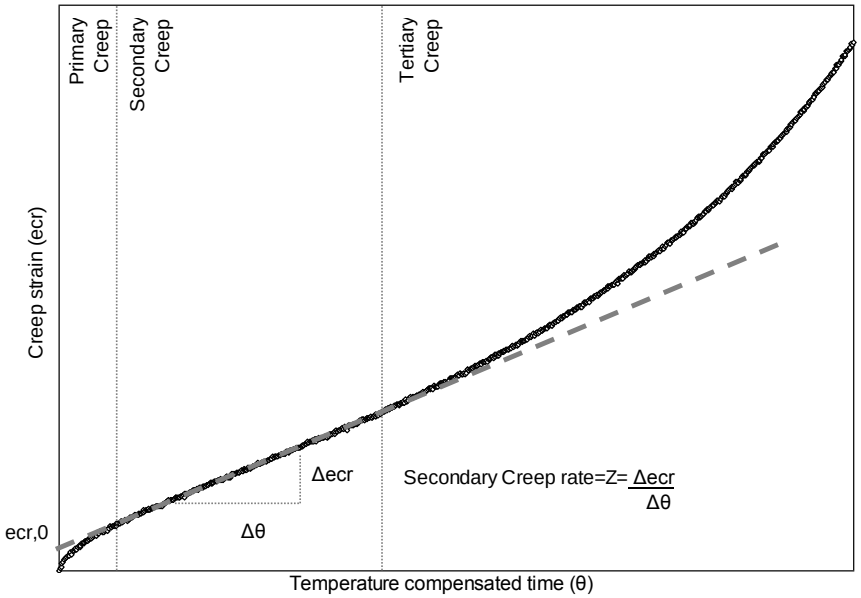


Steady and Transient State Creep Tests

- **Steady and transient state testing are suppose to be equivalent in the *'Harmathy Dorn creep model'* based on activation energy**

Is this really valid and to what extent?

Harmathy-Dorn Creep Model



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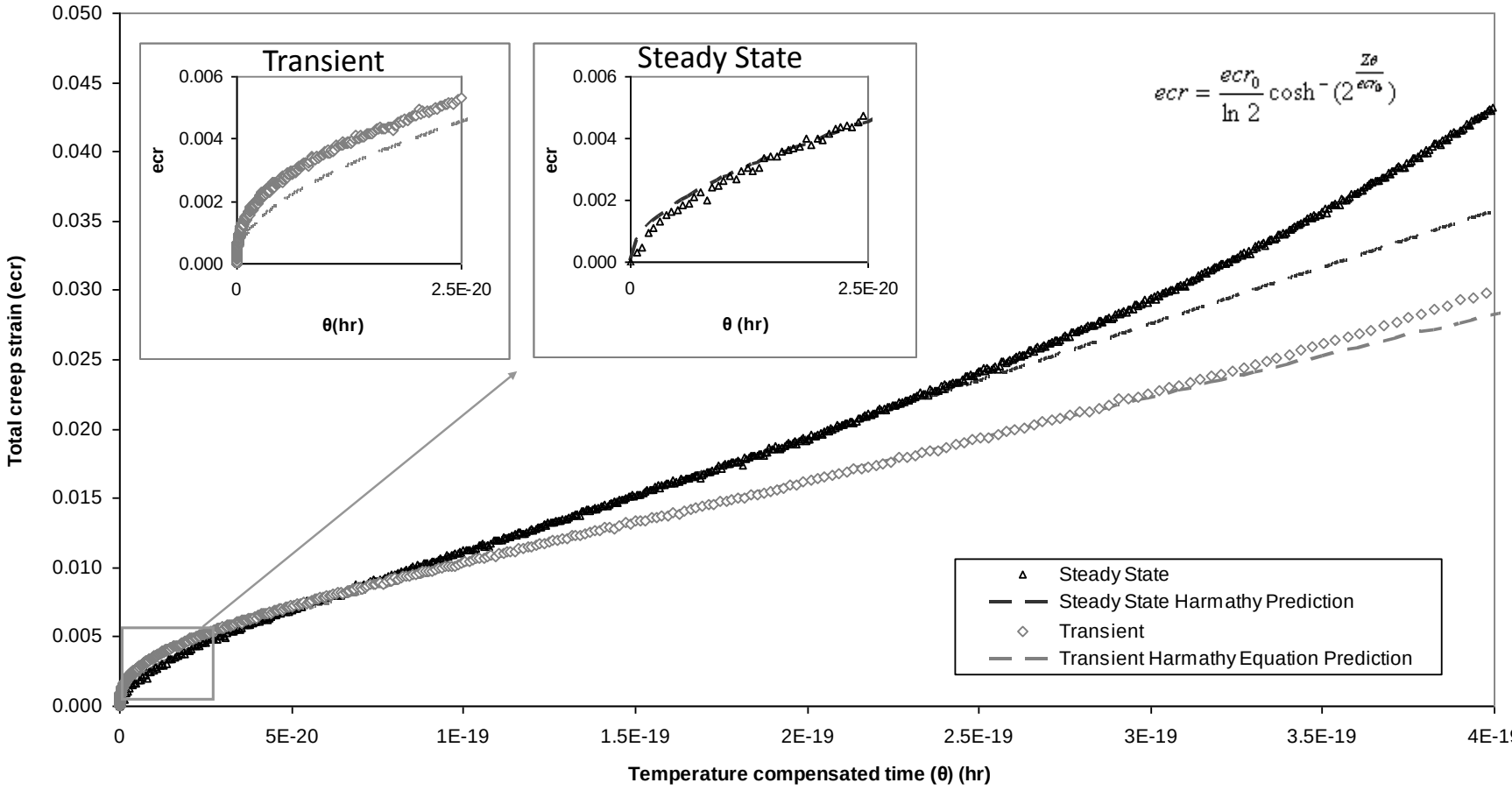
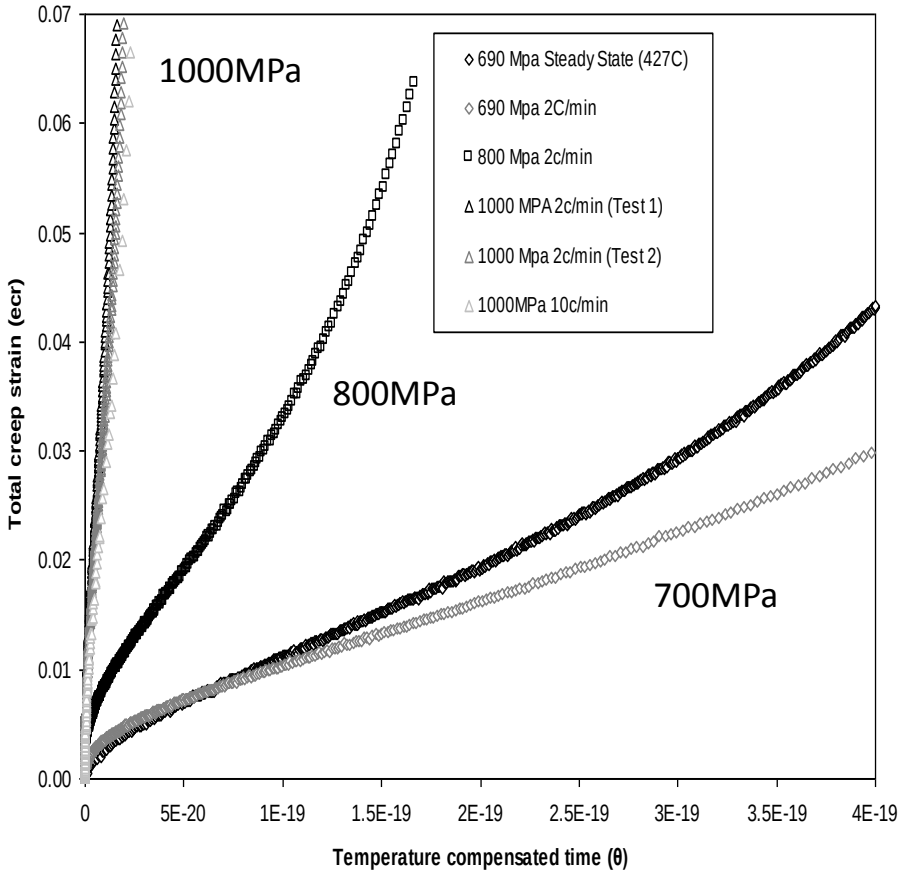
Creep Test Equivalency

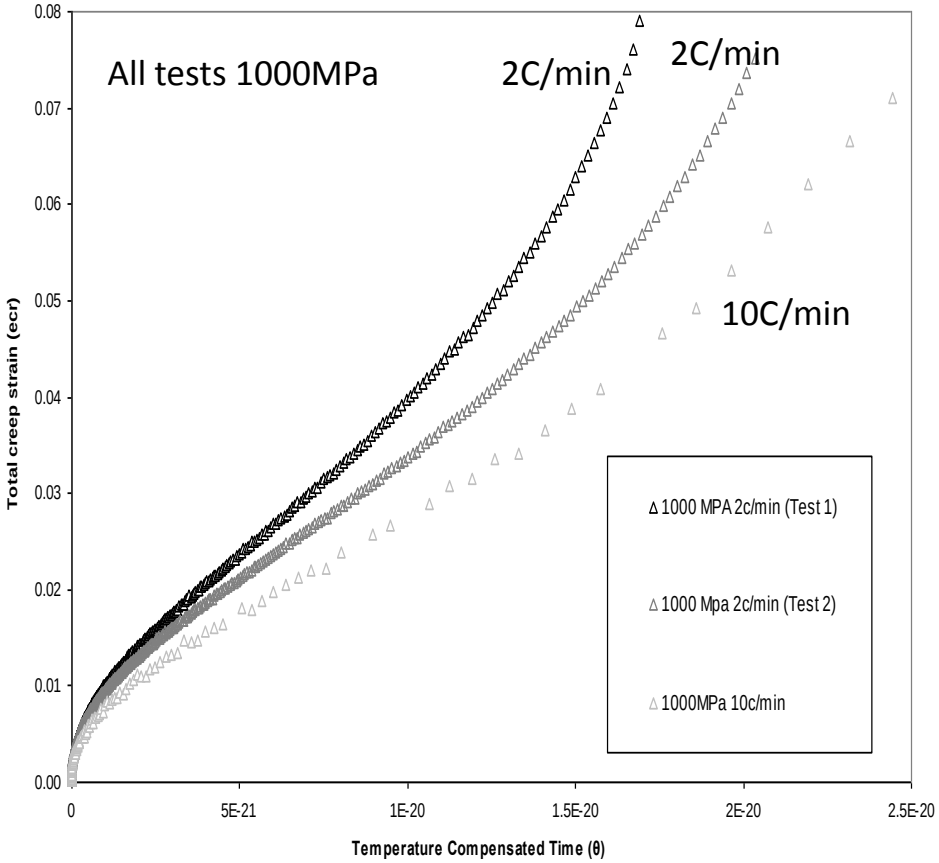
- **Steady state and transient state test at 700 MPa**



Varying Stress and Repeatability



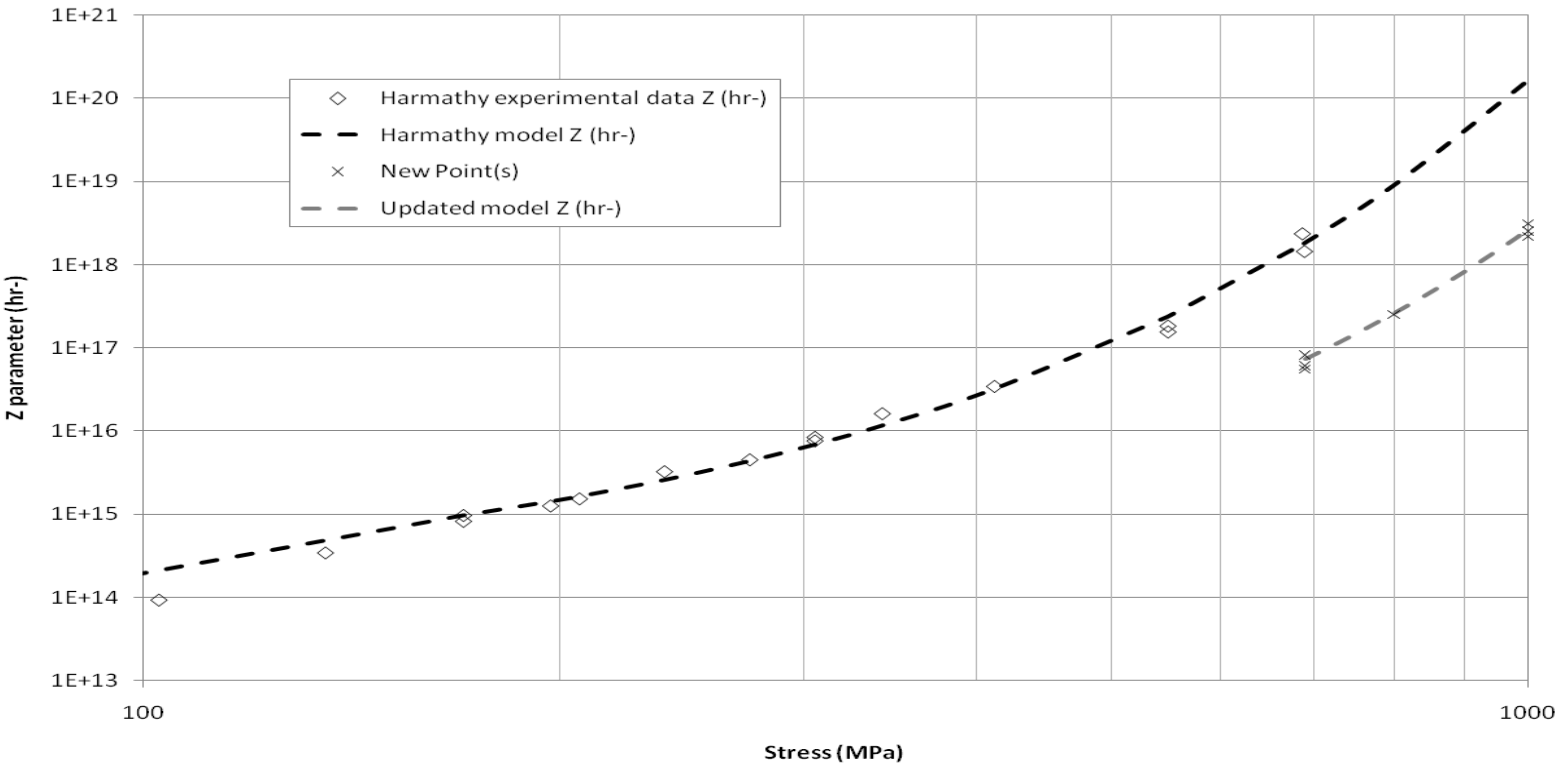
Varied stress levels



Repeatability

Parameter Updates

- **Secondary creep parameter updates (old vs new)**



- **New creep parameters do not match old, suggest less creep deformation in modern PS steel**

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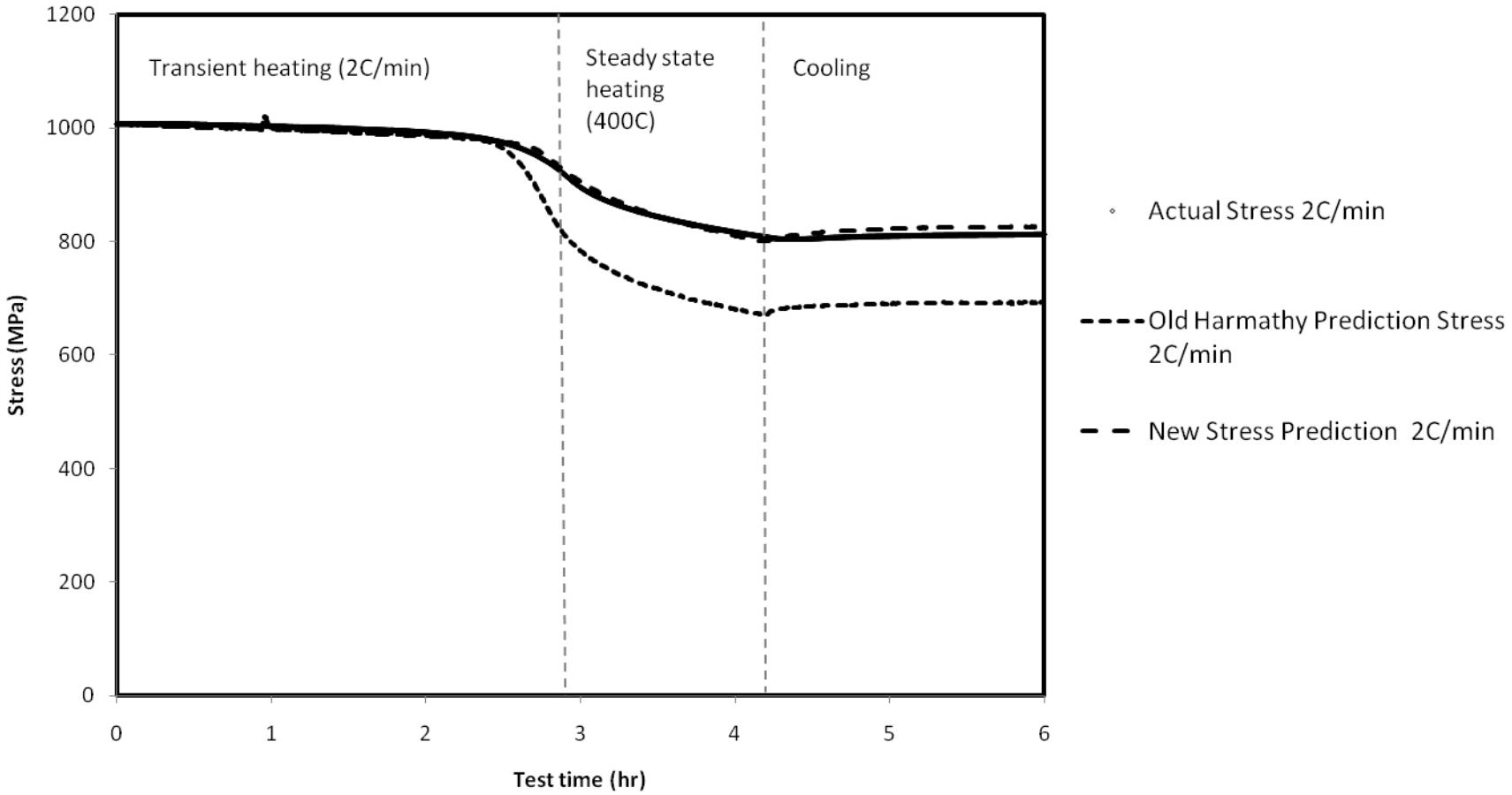
Preliminary Modelling with New Parameters



- **New creep parameters are conservative end**

Key Insights:

- **DIC deformation measurement is adequate when shown with traditional strain prediction and instrumentation**
- **Less limitations for usage *(SGs fall off, extensometers can break in the tertiary phase of creep)***
- **New creep model params. more accurate for high temperature PS stress relaxation *(creep)* predictions**
- **More repeat testing needed at both transient and steady state in order to truly understand and quantify variability and validation using the Dorn-Harmathy creep model for prestressing steel**

Impacts of Research

- **Modern UPT concrete techniques continue to promote innovation in construction; <u>however....</u>**

- *These innovations **potentially sacrifice safety** using out of date prescriptive testing and guidance*

- *Research being conducted will allow us to **rationally design for real fires in real buildings***

One Museum Park

Thank you

The Ove Arup Foundation

The Royal Academy of Engineering

NSERC CRSNG

For additional information

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