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Advanced Charge Structural Modelling for Solid Rocket Motor Systems

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IMEMTS 2015
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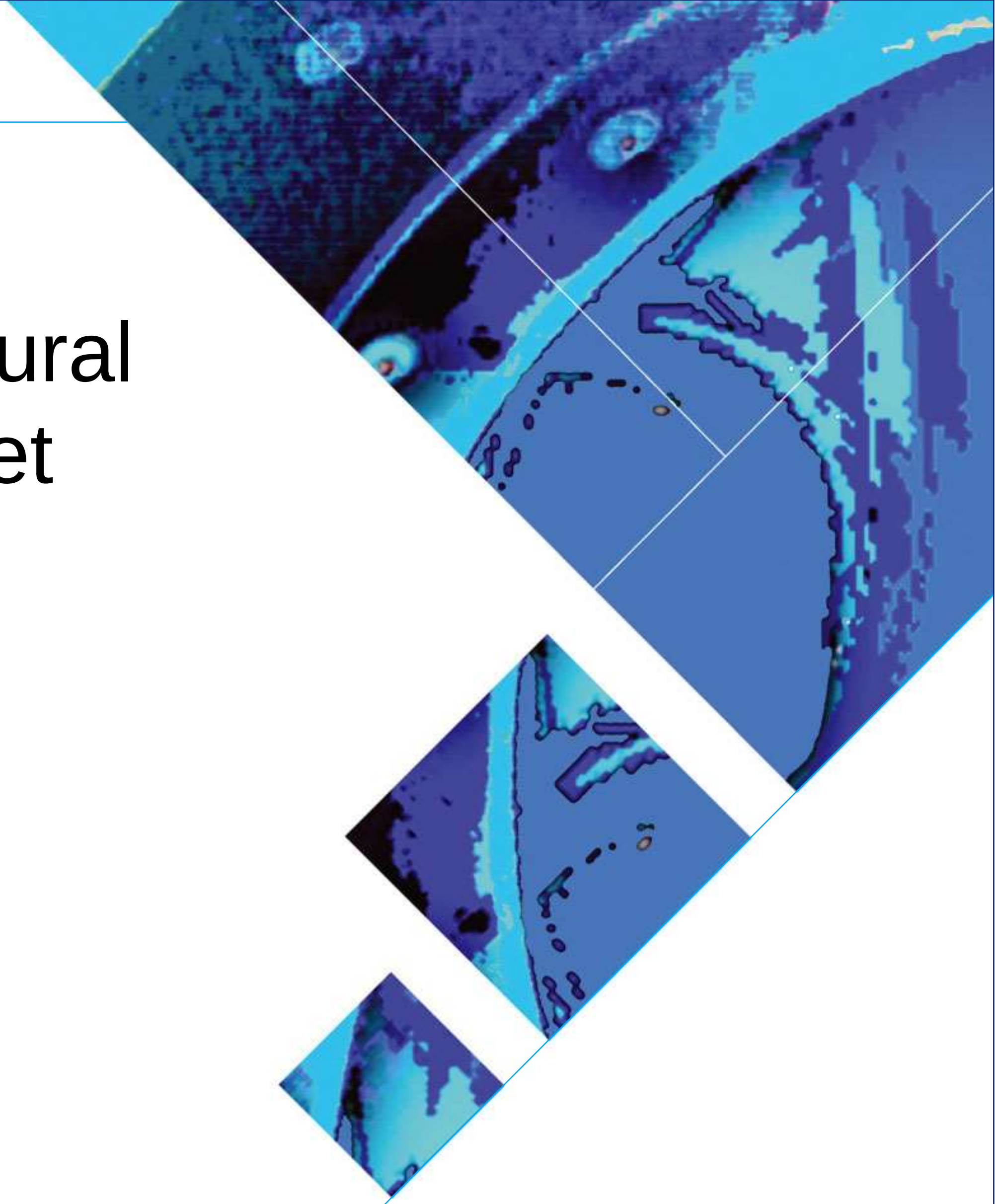

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Introduction

- Roxel the motor supplier for MBDA's IM Brimstone Missile
  - Currently for UK MoD Tornado GR4
- Problems discovered during development
  - Required improved charge structural modelling
  - Discussed further in *"Development of IM Brimstone Rocket Motor; An IM, Minimum Smoke, Air-Launched System,"* A. Strickland (IMEMTS 2015)
- Presentation will discuss:
  - Developments in material models and validation
  - Improvements in experimental testing
  - Improvements in failure criteria and validation

Tornado GR4

IM Brimstone Rocket Motor

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Rocket Motor Required Loads

- Solid rocket motors have a propellant charge which is required to survive extreme thermal and mechanical loads

- In a typical example a rocket motor would be expected to be:-
  - Wide operating temperature extremes
  - Exposed to thermal loads; hot, cold, rapid changes in temperature…
  - Undergo in-flight sorties or manoeuvres
  - Ignition with rapid pressurisation
  - Robust throughout its service life

- Other loads include thermal shock cycling and vibration induced damage

- Predicting their response to this highly dynamic environment is no easy task
  - Various rates, temperatures, pressures and loading history

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Viscoelastic Material Models

- Linear viscoelasticity with linear elastic models is defined by the hereditary integral split into two parts:

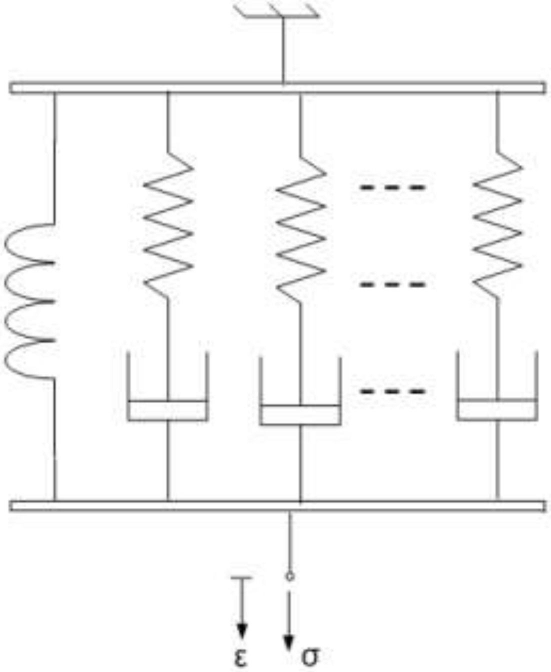
$$\tau(t) = G_0\left(\gamma - \int_0^t \dot{g}_R(s)\gamma(t-s)ds\right)$$

- This form can be generalised for nonlinear models by $\tau_0 = \tau_0(\gamma)$ defined by a hyperelastic function:

$$\tau(t) = \tau_0(t) + \int_0^t \dot{g}_R(s)\tau_0(t-s)ds$$

- The non-dimensional shear relaxation modulus can be given in terms a Prony series:

$$g_R(t) = 1 - \sum_{i=1}^{N} \bar{g}_i{}^P\left(1 - e^{-\frac{t}{\tau_i{}^G}}\right)$$



Phenomenological representation of Maxwell-Wiechert Model

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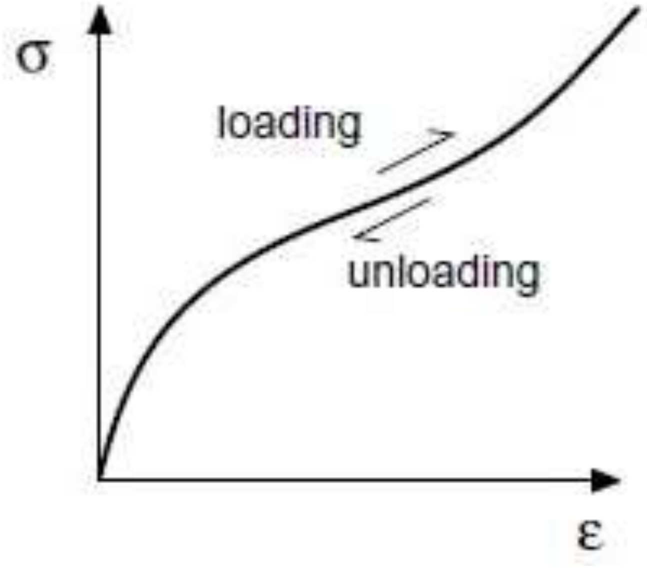
Hyperelastic Models

- Hyperelastic models can be defined in terms of principal invariants I_1, I_2 and J

- One such expression is the Mooney Rivlin model where the strain energy potential is given by:

$$U = C_1(\bar{I}_1 - 3) + C_2(\bar{I}_2 - 3) + \frac{1}{D_1}(J-1)^2$$



Load-Unload Behaviour of Hyperelasticity

- Where the C_1, C_2 and D_1 are model parameters

- With flexibility of Finite Element software users can define their own materials

- This has been part of ongoing research to develop models to do this

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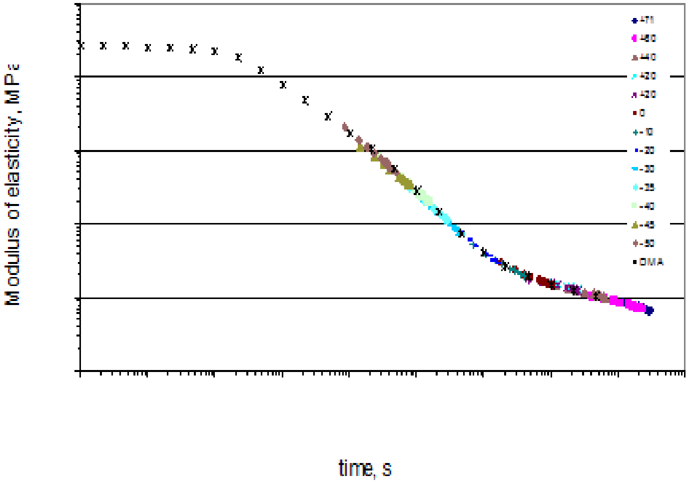
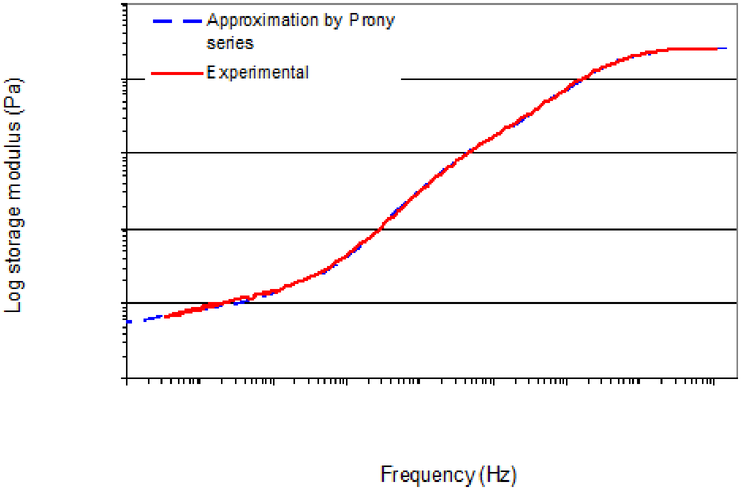
Propellant Constitutive Response

- It is known the propellant response is based on time, temperature and pressure
- Rate of relaxation not dependent on pre-strain level
- Model can be fitted with relaxation data or Dynamic Mechanical Thermal Analysis (DMTA) data
- Good fit to Prony series with around 25 parameters
- Slightly difficult to fit with large numbers of parameters



Relaxation Modulus Data



Storage Modulus with Fit

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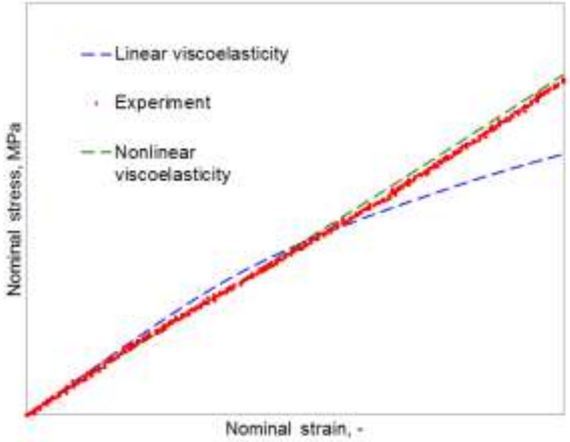
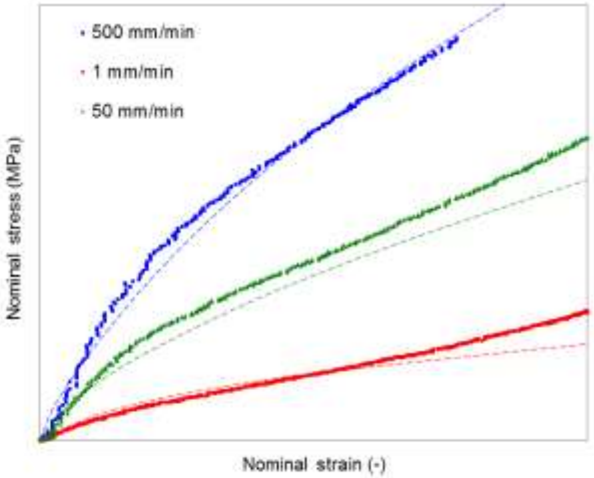
Isothermal Model Validation

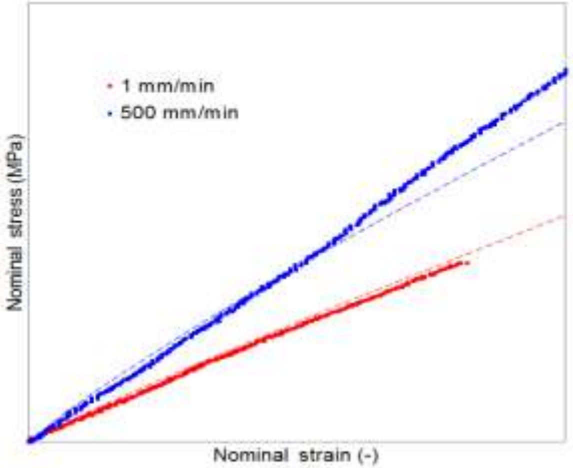
- Significant improvement in response of nonlinear elasticity compared to linear elasticity models
- Good fit for a wide range of temperatures and rates
- Further improvements are still required
  - For higher strains (albeit above typical levels)
  - Improved cold response



Linear vs Nonlinear elasticity



Cold Analysis of Experiment vs Nonlinear Model



Hot Analysis of Experiment vs Nonlinear Model

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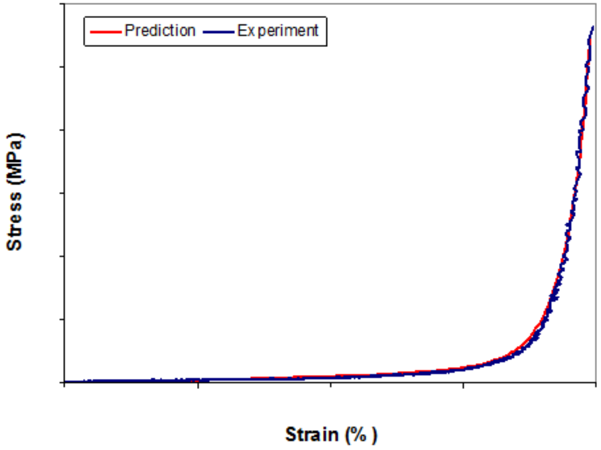
Non-Isothermal Model Validation

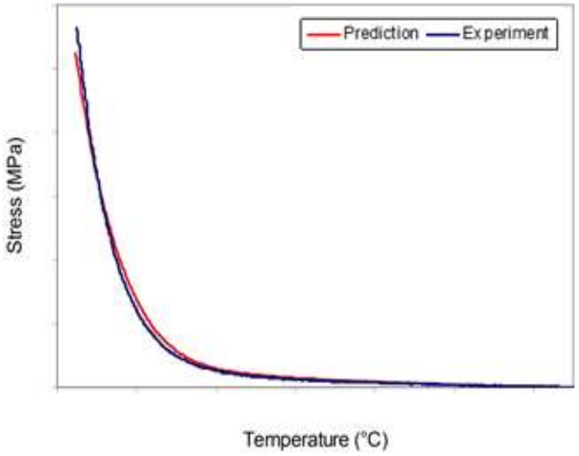
- Simultaneous straining & cooling tensile testing of propellant
    - Advanced technique mastered at Roxel
    - Closely replicates actual motor cooldown load response
    - Coupled thermal-mechanical load
    - Includes effect of CTE, rate, material nonlinearity
    - Provides excellent data to validate model

- However, is a very challenging method to perfect

Tensile Specimen Modelled - (von Mises Stress)



Stress vs Strain



Stress vs Temperature

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Damage Modelling

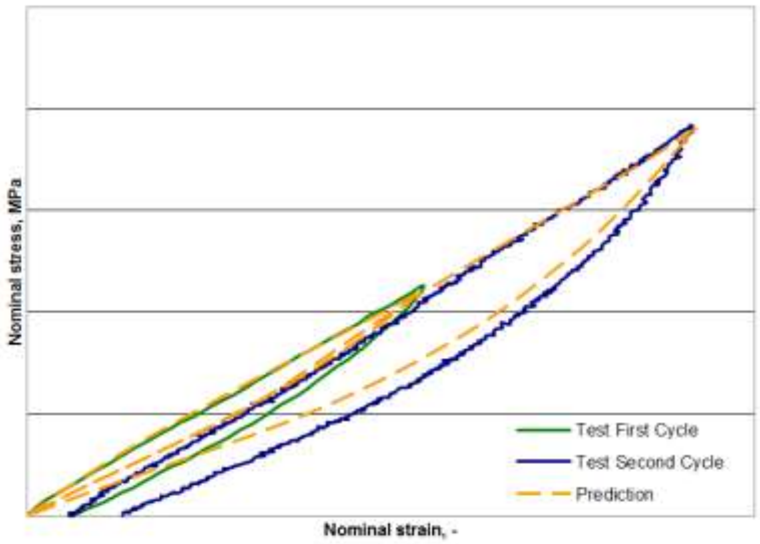
- Damage modelling is useful to assess the charge design robustness
  - Over the service life and cumulative environmental exposure

- Stress softening or Mullins effect is found in elastomers

- Gradual breakdown of micro-structure

- Observed as corresponding reduction in stiffness with loading and unloading

- Stiffness stabilises after certain number of cycles



Stress Softening or Mullins Effect Modelling vs Experiment Results

- Nonlinear model found to closely match Mullins damage effect

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Failure Modelling

- Many failure criteria exist for elastomers and propellants

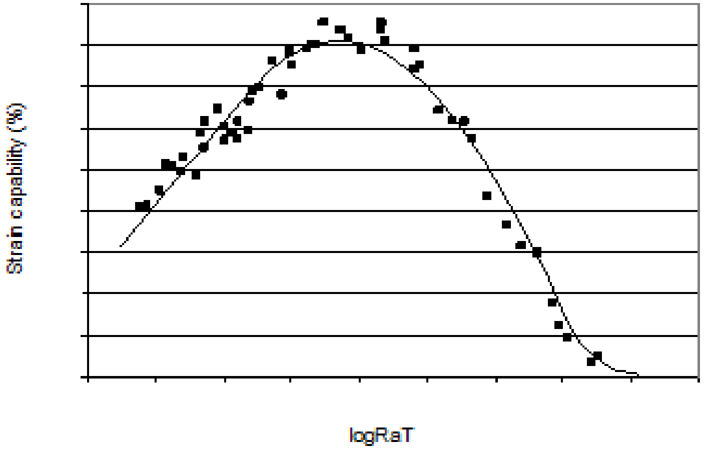
- Stress, Strain or Strain energy density (SED) are commonly used

- Capability needs to be defined using reduced rate:

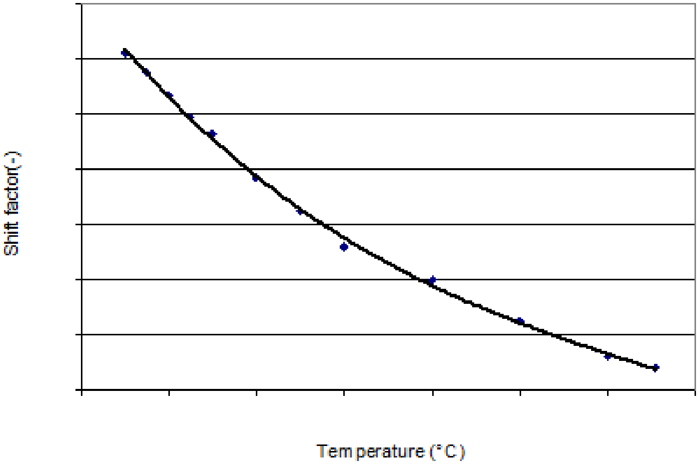
$$logRa_T = logR + loga_T(T)$$

- Safety factor (SF) is given by:

$$SF = \frac{SED_{capability}(logRa_T)}{SED_{load}(logRa_T)}$$



Example Strain Capability Curve



Example Shift Factor Curve

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Improved Failure Criteria

- Previous failure criteria took into account rate and temperature effects but not effects due to pressure

- Stassi stress is a criterion which takes hydrostatic pressure effects into account
  - Good criteria for motor pressurisation load case

$$\sigma_{Stassi} = \frac{\sqrt{9(k-1)^2\sigma_m^2 + 4k\sigma_{eq}^2 - 3(k-1)\sigma}_{m}}{2k}$$

- Where the equivalent stress σ_{eq} is given by:

$$\sigma_{eq} = \sqrt{\frac{1}{2}\left((\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right)}$$

- The mean stress is given by:

$$\sigma_m = -\frac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33})$$

- Parameter *k* depends on ratio between compressive and tensile strength

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Failure Predictions and Results

Method	Failure Temperature
Stress based	-68°C
Strain based	-47°C
SED based	-65°C
Stassi Stress	-60°C
Actual cracking temperature	-62°C to -64°C

- Failure predictions found for cooldown load case show only few criteria are valid
  - Strain is very conservative as found in practice
  - Stress is slightly optimistic
  - SED is most accurate
  - Stassi stress is also a good criteria

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Bondline Modelling and Knockdown Factors

- Bondline strength Is determined by:

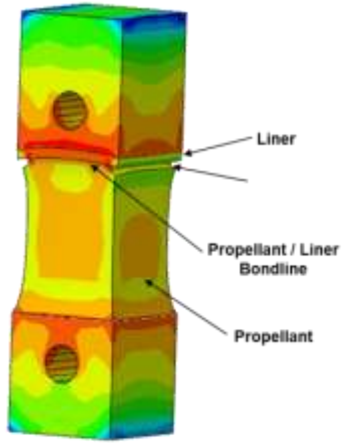
$$SF_{bond} = \frac{Bond\ line\ Capability\ (logRa_T)}{Bond\ line\ tensile\ normal\ stress\ (logRa_T)}$$

- Can be introduced into FE model by using contact elements to determine propellant to insulation bond SF

- Knockdown factors (KDF) can be calculated to account for variability, ageing and thermal shock cycling

$$KDF = \frac{Residual\ (damaged)\ propellant\ capability}{Undamaged\ propellant\ capability}$$

- The variability knockdown factor accounts for charge casting process, property distribution, specimen preparation and test variability
  - Predict cumulative damage SF for propellant charge



Tensile Bond Test Sample Modelled (Von Mises Stress Presented)

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Knockdown Factors

- Thermal Shock Cycling KDF
  - Based on a power law fatigue damage model
  - Fatigue testing was carried out at various load ratios
  - Then damage is determined at a single load ratio by measuring residual properties post the fatigue damage cycling

$$KDF = \frac{Residual\ capability\ after\ n\ shock\ cycles}{undamaged\ capability}$$

- Cold Storage Strain Endurance KDF
  - Rocket motors are typically required to survive long periods of cold storage
  - In order to evaluate this small scale testing was carried out
  - Tensile specimens were stored at cold temperature under strain and then residual properties determined
  - Power law damage model used to derive knockdown factor due to cold storage strain endurance:

$$KDF = \frac{Residual\ capability\ after\ n\ days\ cold\ storage}{undamaged\ capability}$$

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Thermal Shock Cycling Results

- Model successfully predicts a valid number of thermal shocks to failure
  - Compared to actual motor tests it appears to be conservative

Predicted Number of Thermal Shock Cycles to Failure		Motor Test Result
Average Number	30	>40**
Minimum Number*	17	
Maximum Number*	47	

* Includes coefficient of variation
** Test stopped

- This is a significant step forward in predicting propellant life

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Conclusions

A number of conclusions can be drawn from the improvements into the propellant structural analysis methodology:-

- The improved nonlinear hyper-viscoelastic model provides good constitutive response
- Model closely predicts propellant response to thermal-mechanical loads
- Predictions for charge cracking temperatures are very close to the experimental observations
- Stassi stress is a valid criteria for pressurisation and cooldown
- The predicted number of thermal shock cycles is good but is conservative

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