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MECHANICAL BEHAVIOR AND FATIGUE STUDIES OF RUBBER COMPONENTS IN ARMY TRACKED VEHICLES

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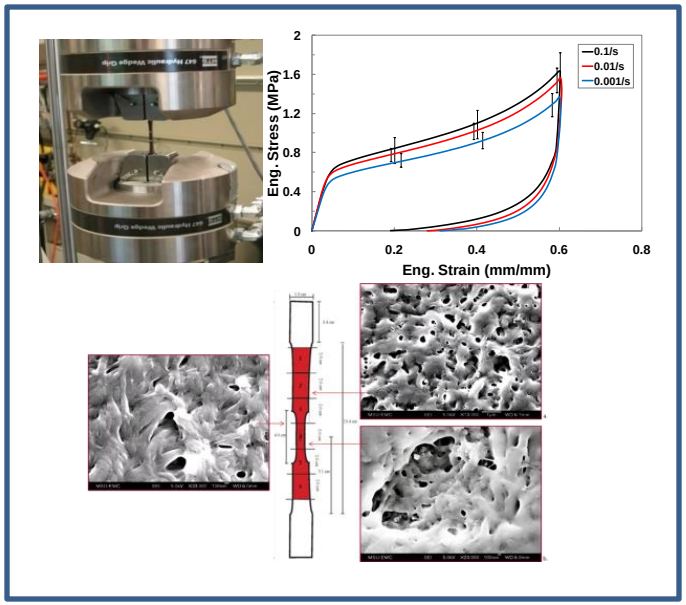
Introduction

- Monotonic approach
  - Internal state variable (ISV) model for metals
  - ISV modeling strategy moved to glassy polymers (Bouvard et al., 2010)
  - Current efforts to apply ISV modeling strategy to elastomers
- Fatigue approach
  - Researchers have historically separated fatigue crack initiation and propagation
  - (McDowell et al., 2003) refined the earlier crack stages into incubation and microstructurally and physically small crack growth, greatly increasing accuracy
  - Microstructure has been incorporated into the multistage modeling for metals at CAVS
  - Researchers have typically only investigated long crack for elastomers (Mars and Fatemi, 2003; Busfield et al., 2002; Chou et al., 2007)
  - Current efforts are to add MSC/PSC, INC to fatigue modeling of elastomers and incorporate microstructure

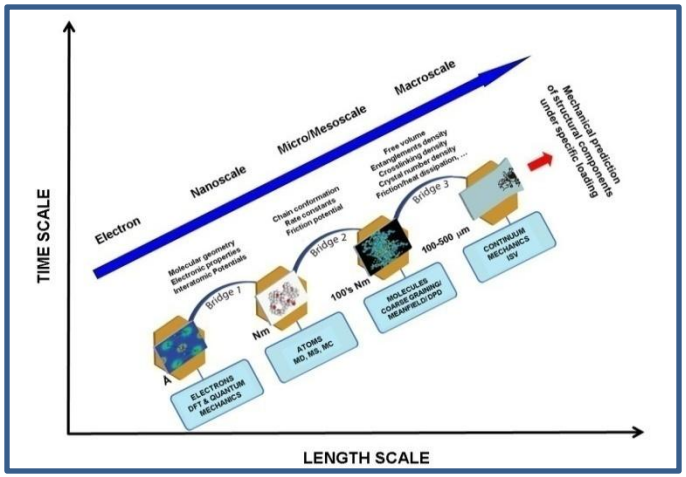
Overview

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

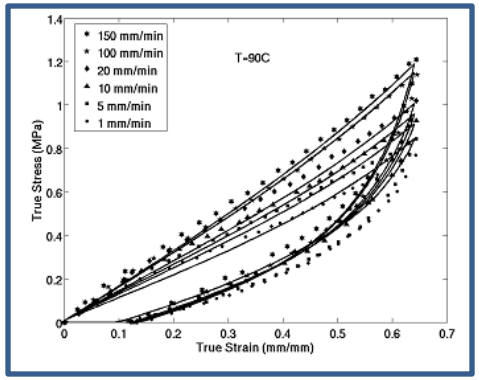
Experiments and Stereology to Capture Structure–Property Relationships



Multi-Scale Internal State Variable Modeling

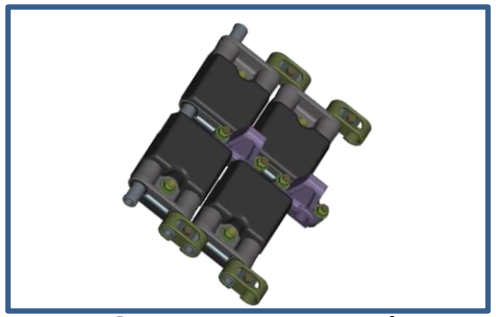


Material Database and FEA Material Model Development for Polymer Materials



Model Verification at Material Level

System Level Modeling

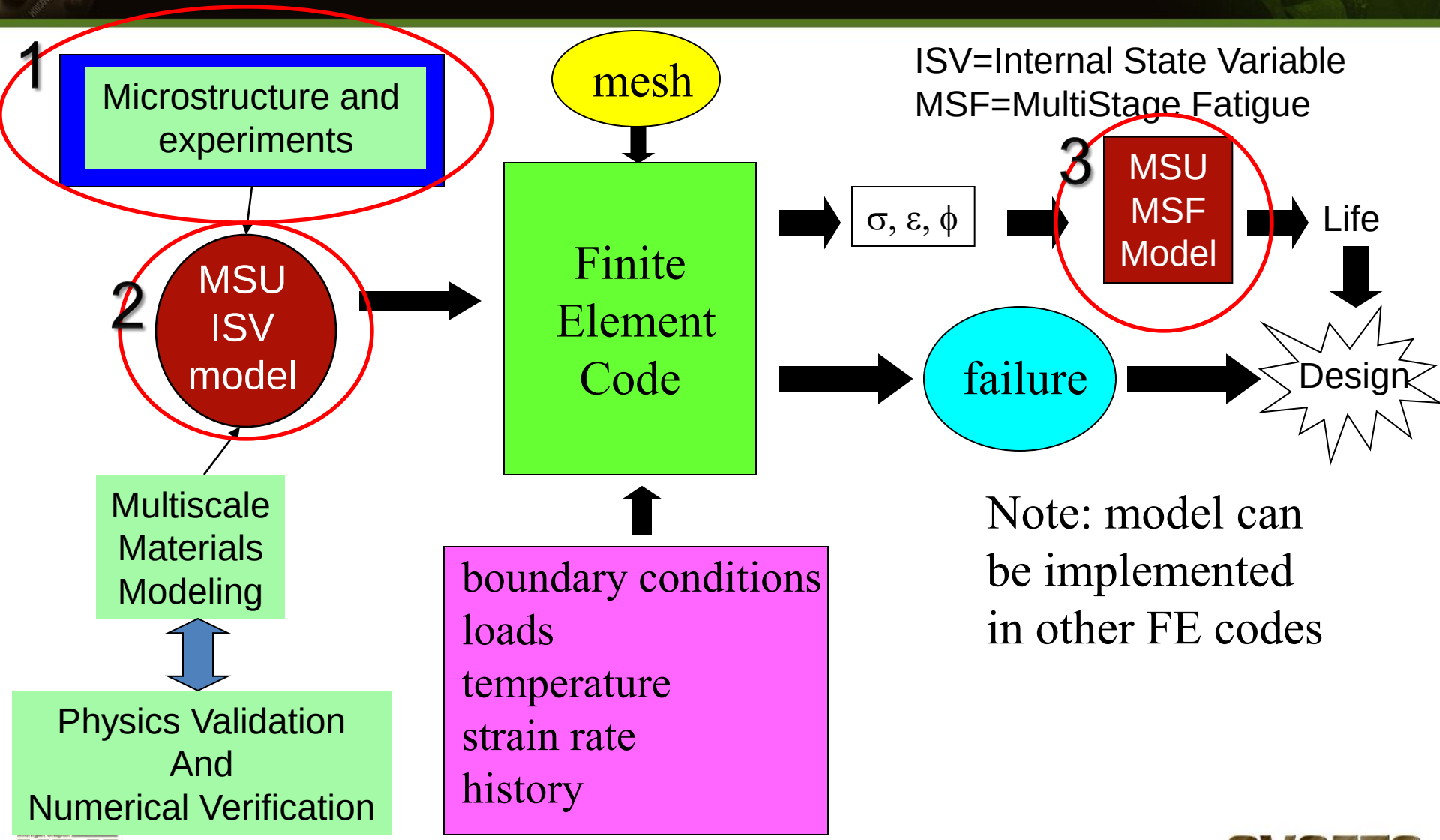


Component Level Validation

Motivation

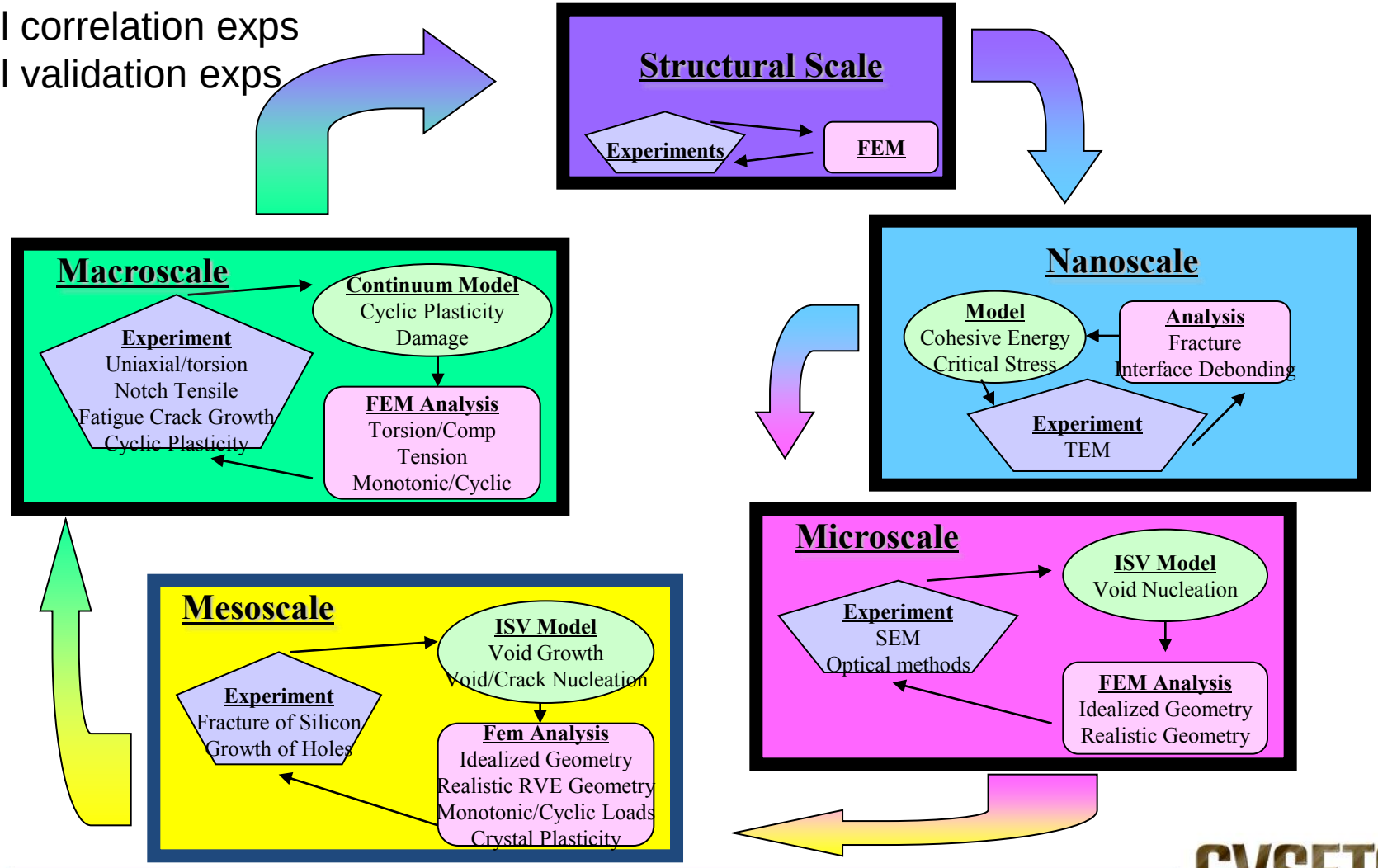
- Components of focus on tank track
  - Bushings
  - Road wheels
  - Suspension
  - Backer pads
- Extreme Loading conditions
  - High temperature
  - High friction
  - Complex loading
- Road wheel backer pad failure at one-half of the design target mileage

Macroscale MSU ISV/MSF Models Implementation and Use



Multiscale Experiments

1. Exploratory exps
2. Model correlation exps
3. Model validation exps

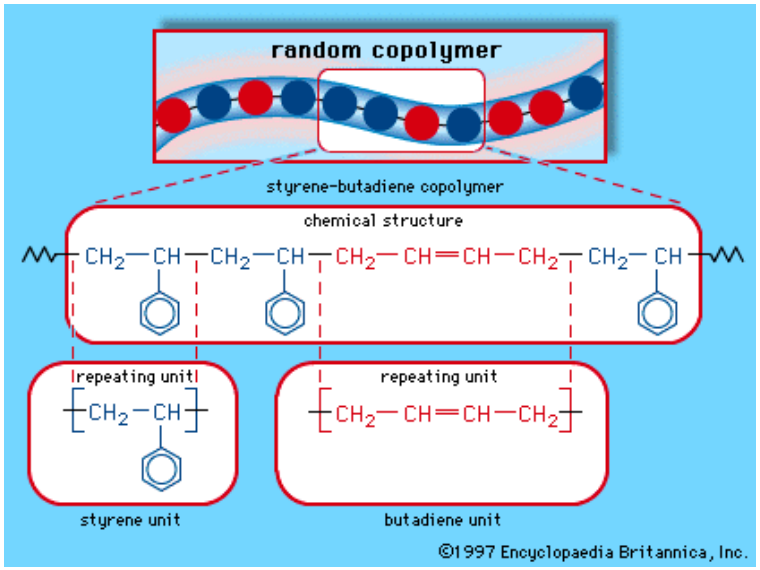


Material: Styrene Butadiene Rubber

- Random copolymer – styrene and butadiene are randomly distributed throughout the polymer chain
- 3:1 butadiene to styrene by weight
- Commercially used in a wide range of projects

General properties of SBR

Property	Value	Units
Glass Transition temperature	-40	° C
Temperature range	-28 to 76	° C
Tensile strength	4.8	MPa
Stretch Limit	150	%
Density	91.5	Lbs/cu ft



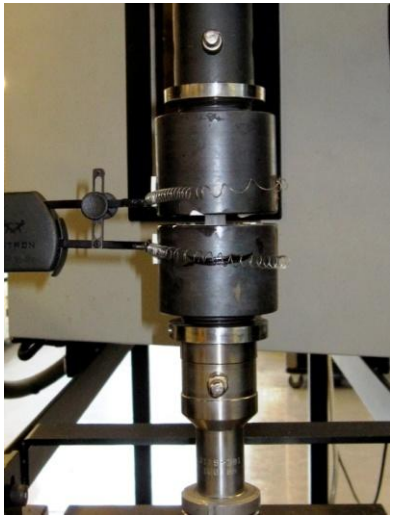
Experimental Methods: DMA

- Dynamic mechanical analysis
  - TA Instrument Q900 Dynamic Mechanical Analyzer
  - Rectangular 1.5 in x 0.135 in x 0.06 in specimen with DMA tensile clamps (ASTM D4065-01)
  - Oscillated at 1 Hz for a range of temperatures to include temperature transitions
  - Tg measured using midpoint method

Experimental Methods: Set-up

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

Compression Test

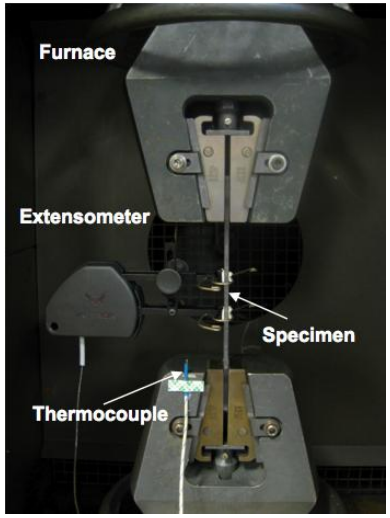


Low strain rates
(10^{-4} s^{-1} to 10^{-1} s^{-1})

Hopkinson Bar

High strain rates
(1200 s^{-1} to 3000 s^{-1})

Tension Test

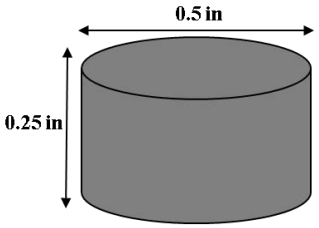


Low strain rates
(10^{-4} s^{-1} to 10^{-1} s^{-1})

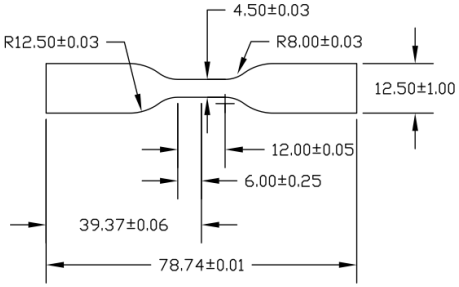
Fatigue Test

Low frequency
(2Hz)

Specimen Geometry



Geometry of 0.5 L/D ratio



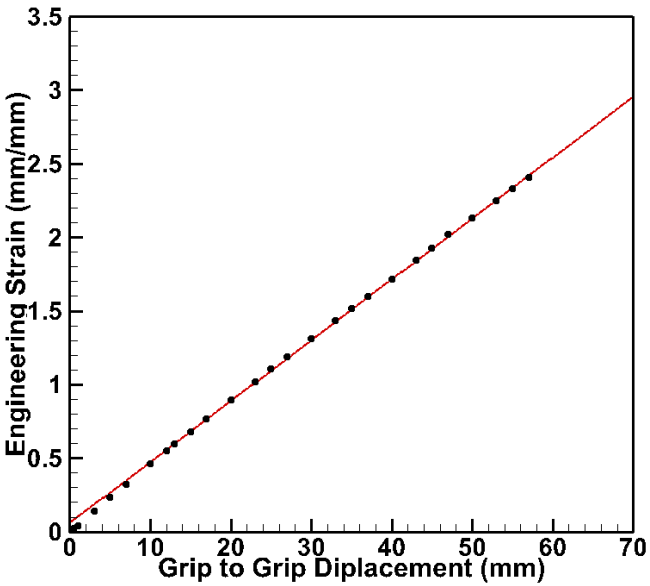
Scaled from ASTM D412

Experimental Methods: Monotonic Loading

- Stress state dependence
  - Tension
    - Strain controlled from extension to get local strain rate
    - Strain in the gage measured by laser extensometer
  - Compression
    - Extensometer mounted on platens to remove compliance
    - Strain controlled from extensometer
- Rate dependence
  - Strain rates of 0.001, 0.01, 0.1, 1200, 2000, 2600, 3000 /s
- Temperature dependence
  - -5C, 23C and 50C

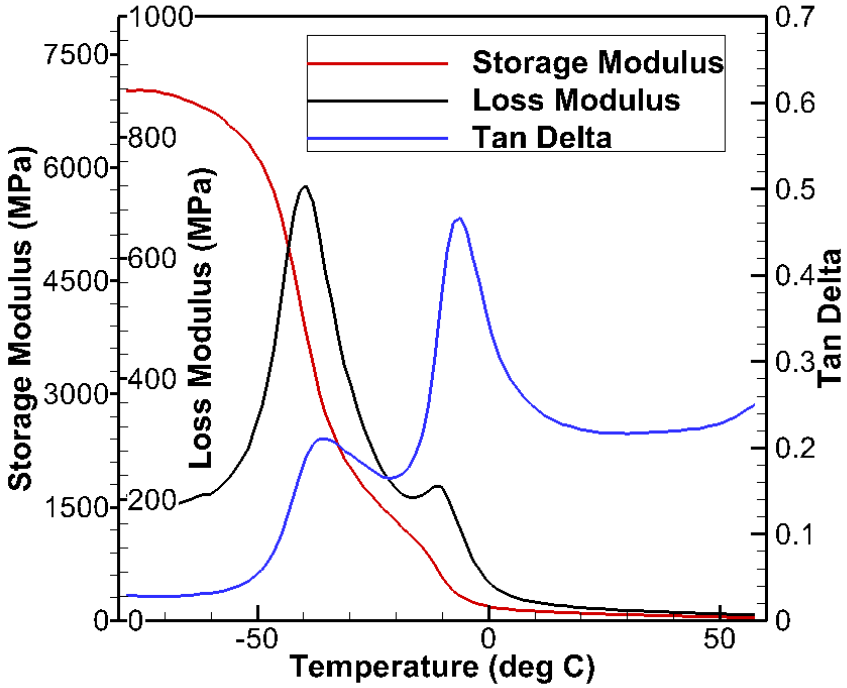
Experimental Methods: Fatigue Loading

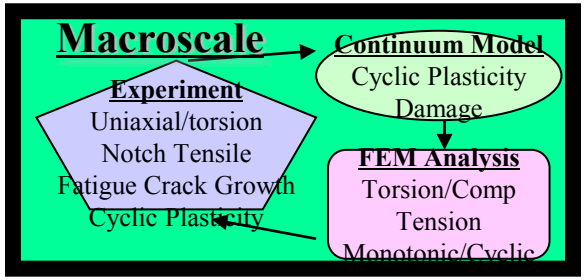
- Uniaxial tension
- Servo-hydraulic load frame
- R = 0.5, freq = 2 Hz
- Δε/2 = 20.3, 22.3, 28.1, 31.9 and 36.3%
- Displacement control
- Displacement-strain correlation made using laser extensometer



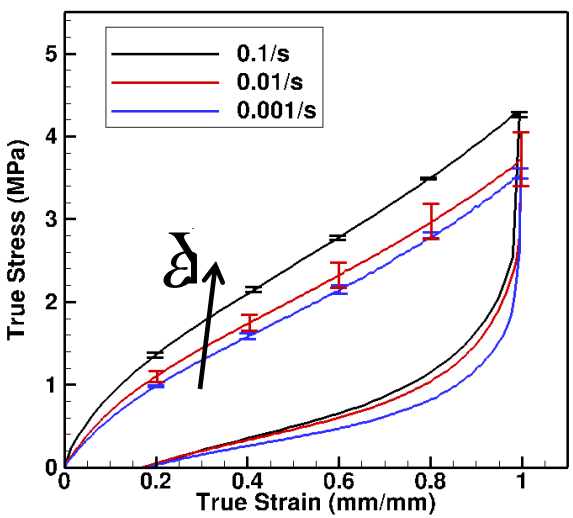
Results: DMA

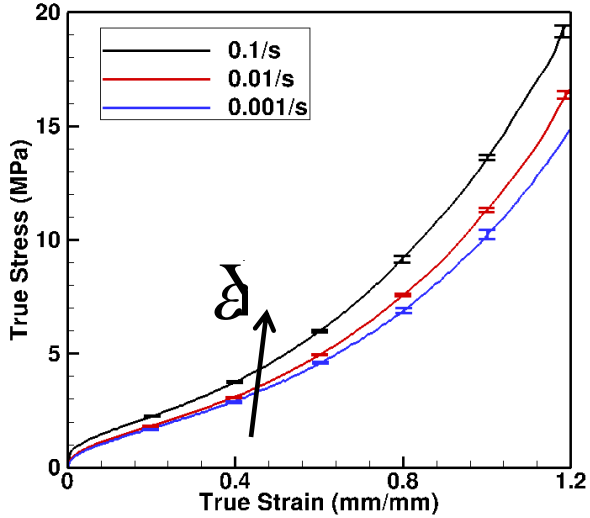
- Storage modulus curve shows two transition temperatures
  - First corresponds to the glass transition temperature (Tg) at -40° C
  - Second at -10° C possibly due to fillers

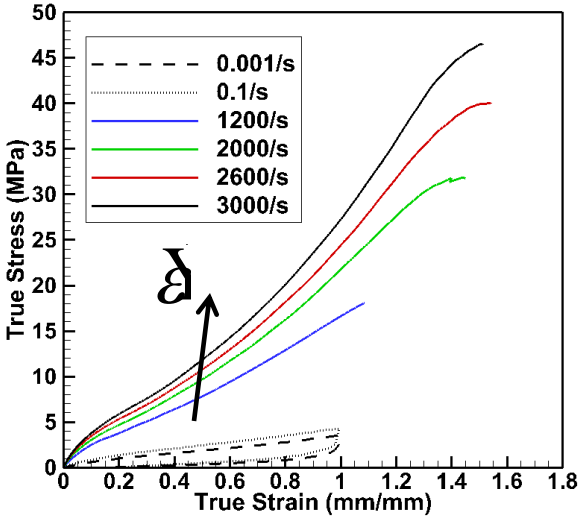




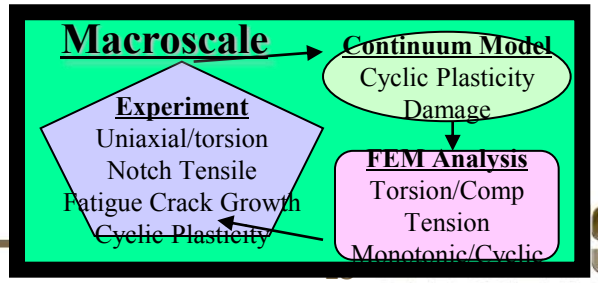
Results: Rate Dependence



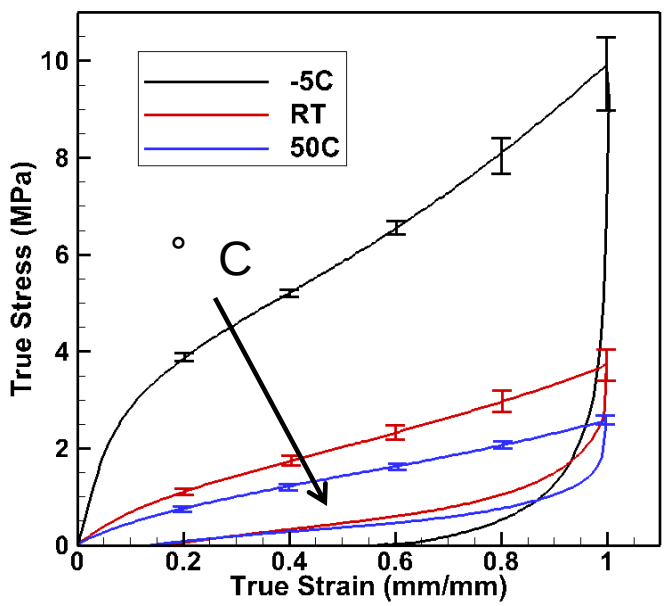


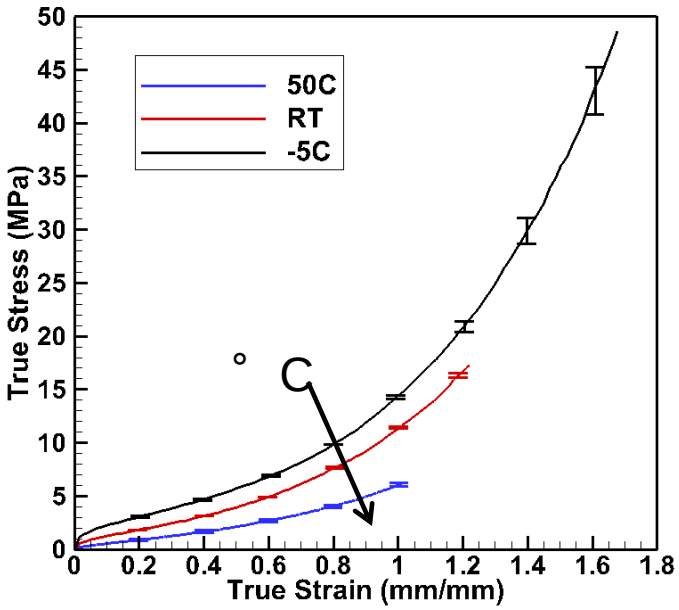


- Rate dependence – material stiffened with increasing strain rate
- Compression – strong hysteresis and residual plastic strain



Results: Temperature Dependence

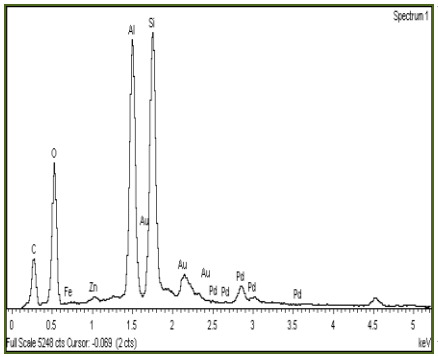


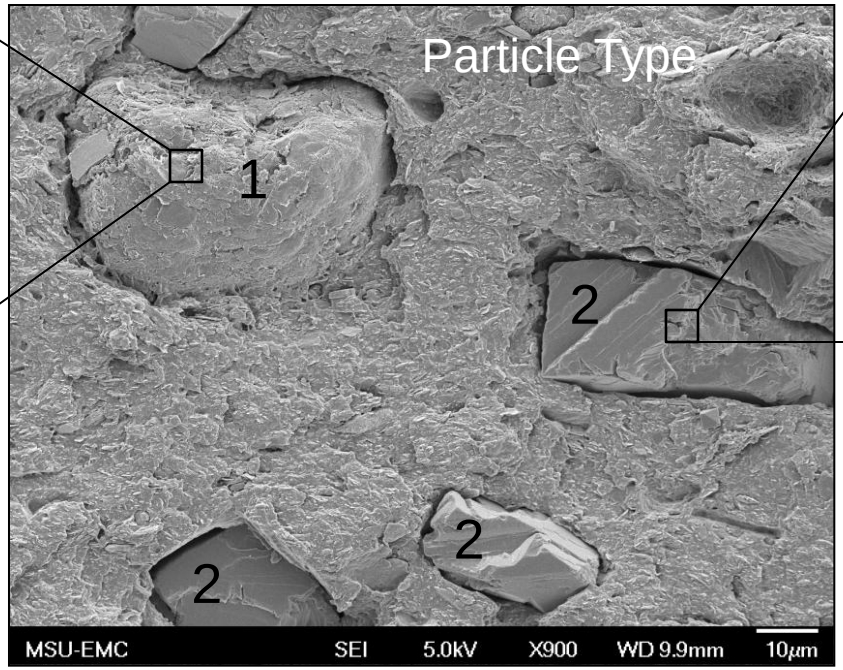


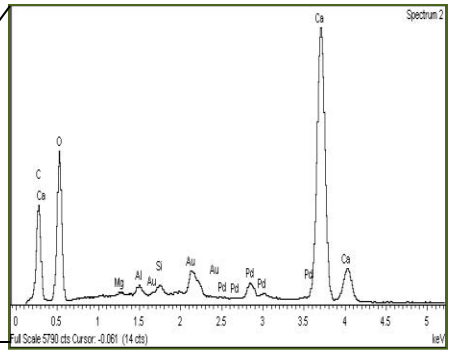
- Temperature dependence – material softened and had an increase in strain to failure at higher temperatures

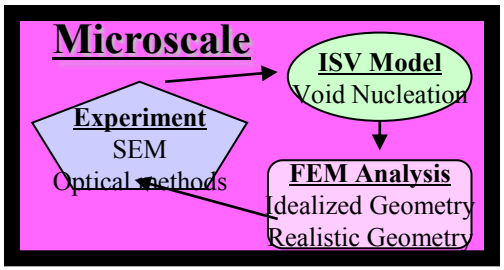
Results: Microstructure for Monotonic Loading

- Particle debonding
  - Major mechanism of failure
  - 0.5 – 200 μm particles debonded during deformation
  - Large particles are (1) agglomerations of aluminosilicate (clay) and (2) ground calcium carbonate

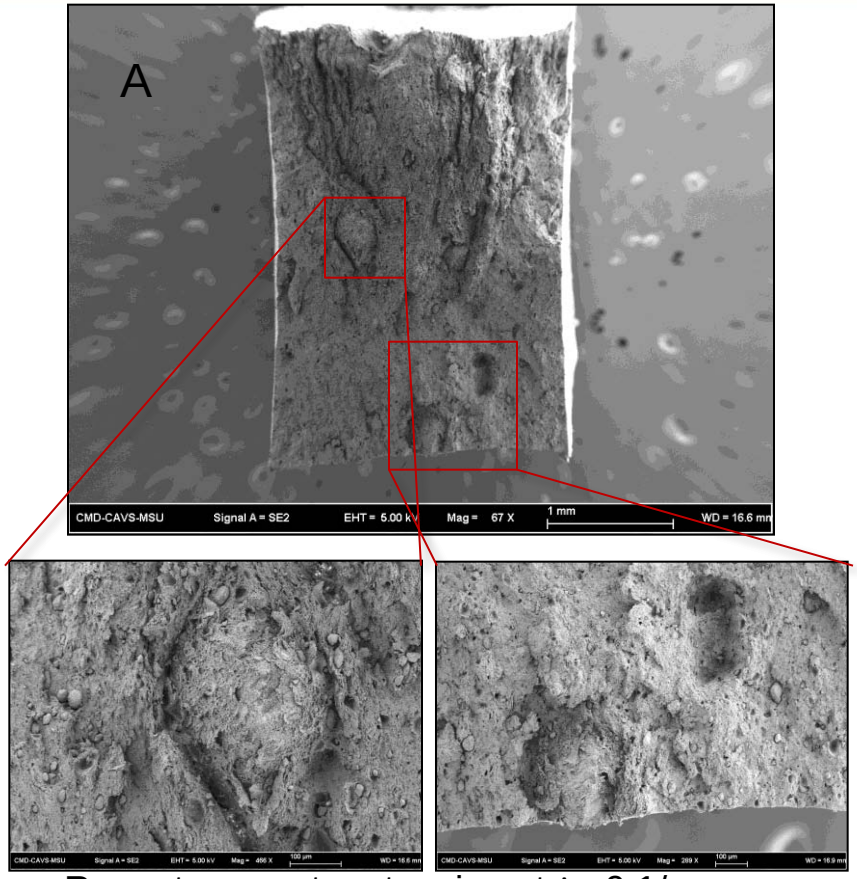


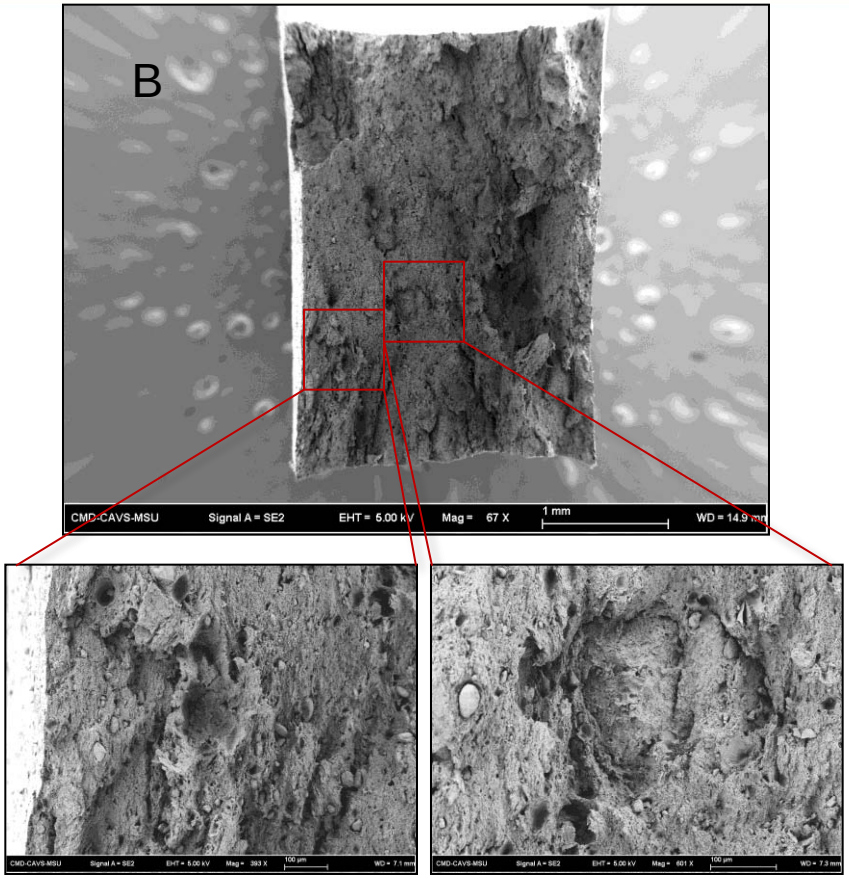






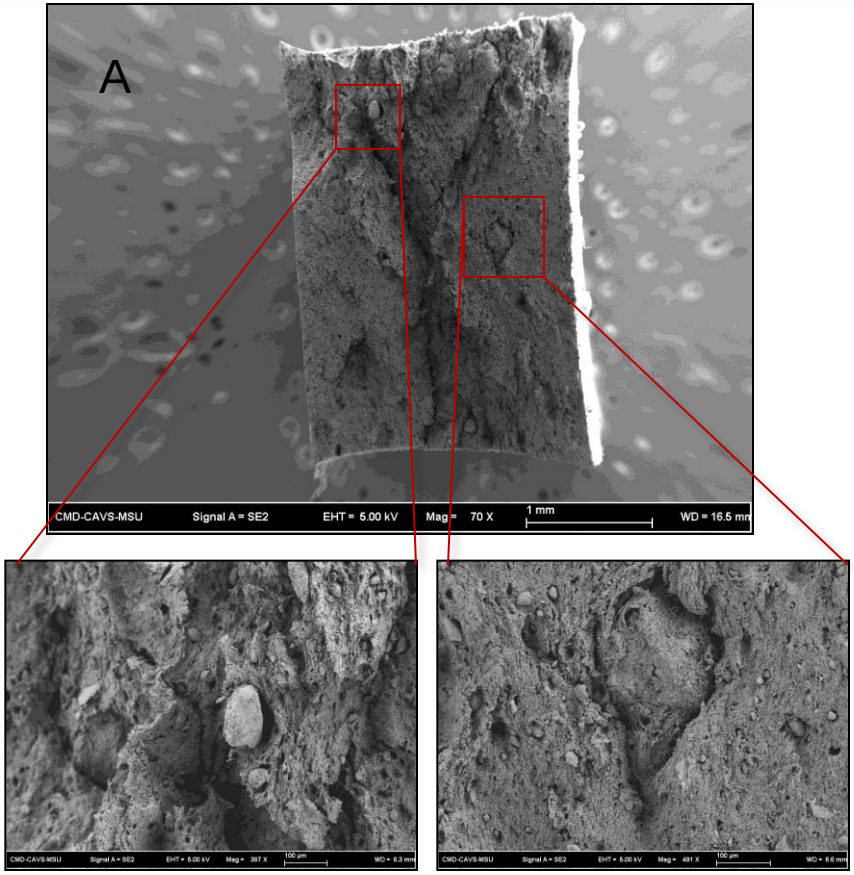
Results: Microstructure for Monotonic Loading - ε̇ = 0.1/s

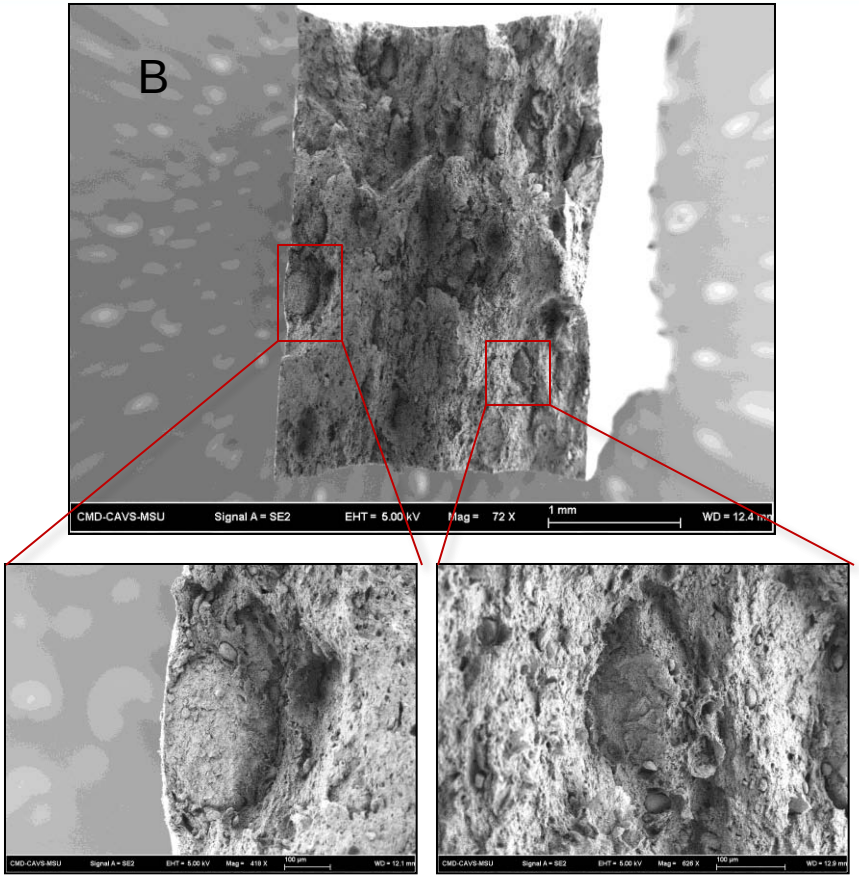




- Room temperature tension at ε̇= 0.1/s
- Specimen A failed at a lower strain than specimen B
- Specimen A showed a slightly weaker stress-strain response than specimen B
- Due to the large agglomerates of undispersed aluminosilicate and particles debonding from the matrix

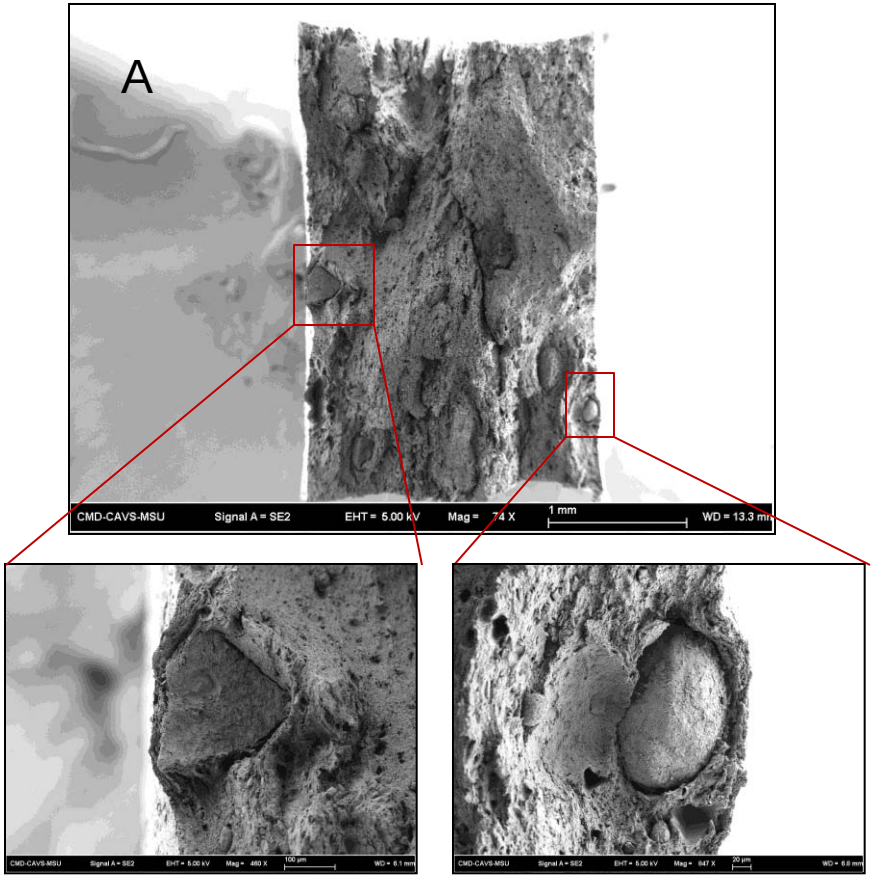
Results: Microstructure for Monotonic Loading - $\dot{\varepsilon}$ = 0.01/s

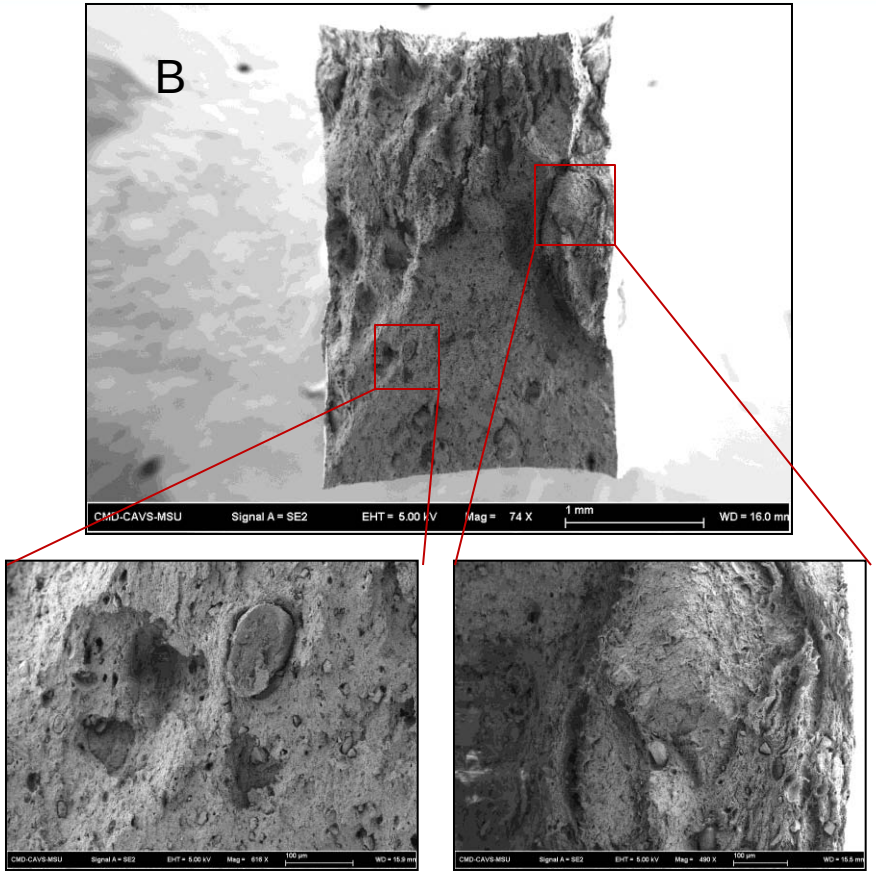




- Room temperature tension at $\dot{\varepsilon}$= 0.01/s
- Specimen A failed at a lower strain than specimen B
- Due to the large agglomerates of undispersed aluminosilicate and particle debonding

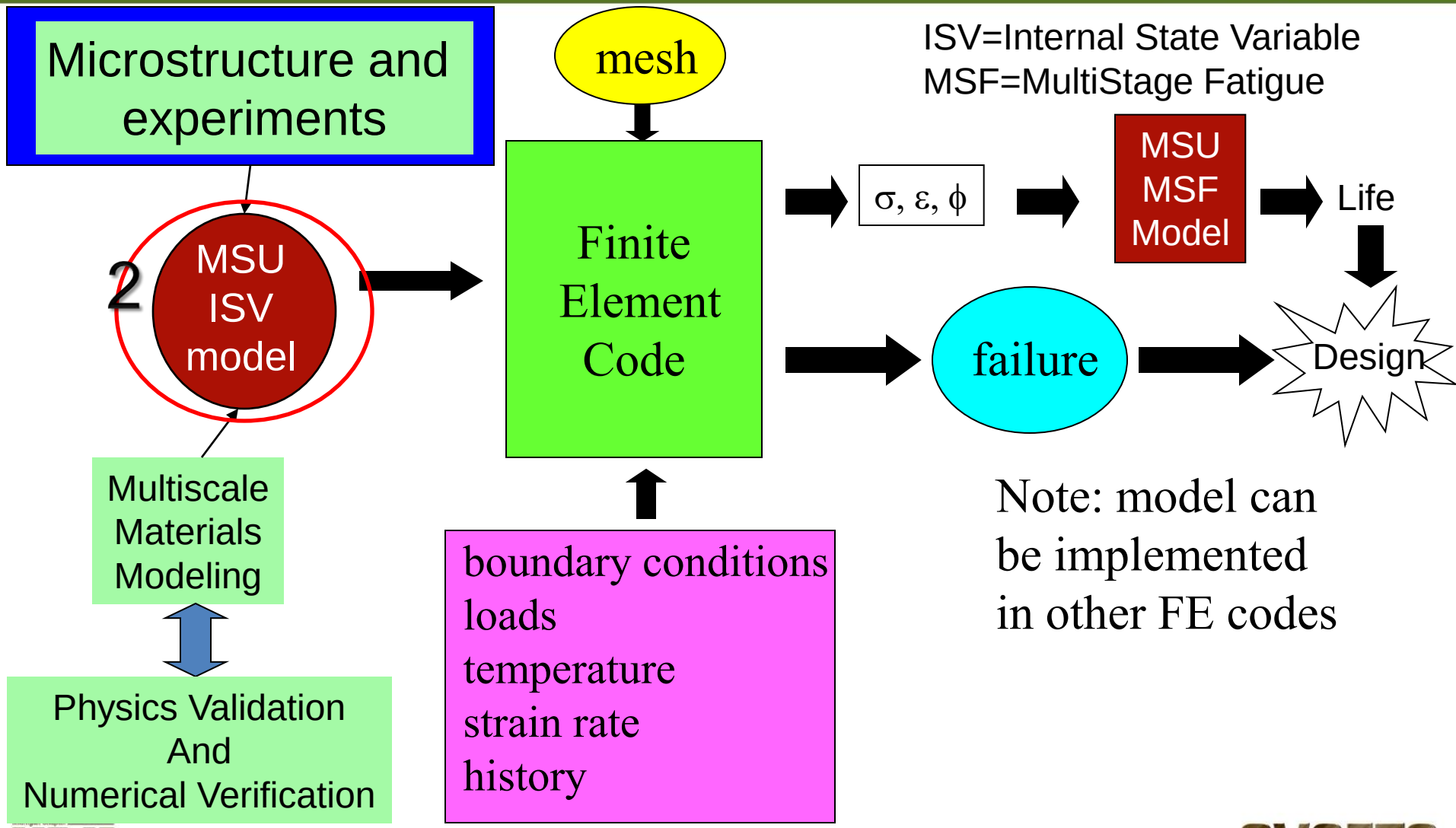
Results: Microstructure for Monotonic Loading - $\dot{\varepsilon}$ = 0.001/s





- Room temperature tension at $\dot{\varepsilon}$= 0.001/s
- Specimen A failed at a lower strain than specimen B
- Due to the large agglomerates of undispersed aluminosilicate and particle debonding

Macroscale MSU ISV/MSF Models Implementation and Use

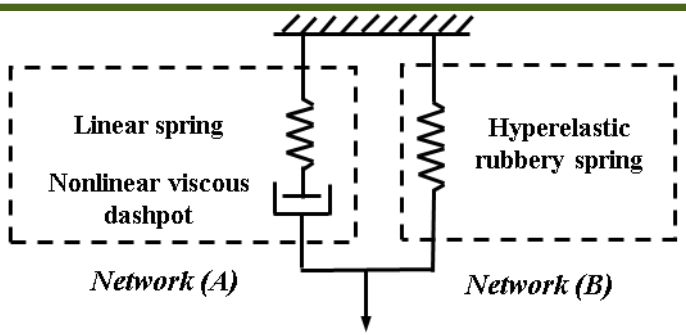


ISV Model: Approach

- Large variety of models exists for polymers: Krempl (1995), Tervoort (1998), Boyce et al. (1988), Richeton et al. (2007), L. Anand et al. (2009),…

Rheological representation of the constitutive model

- **Model generally used for polymers are:**
  - **based on spring/dashpot**

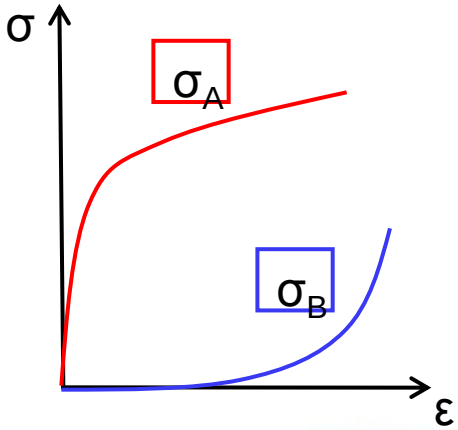


$$\sigma = \sigma_A + \sigma_B$$

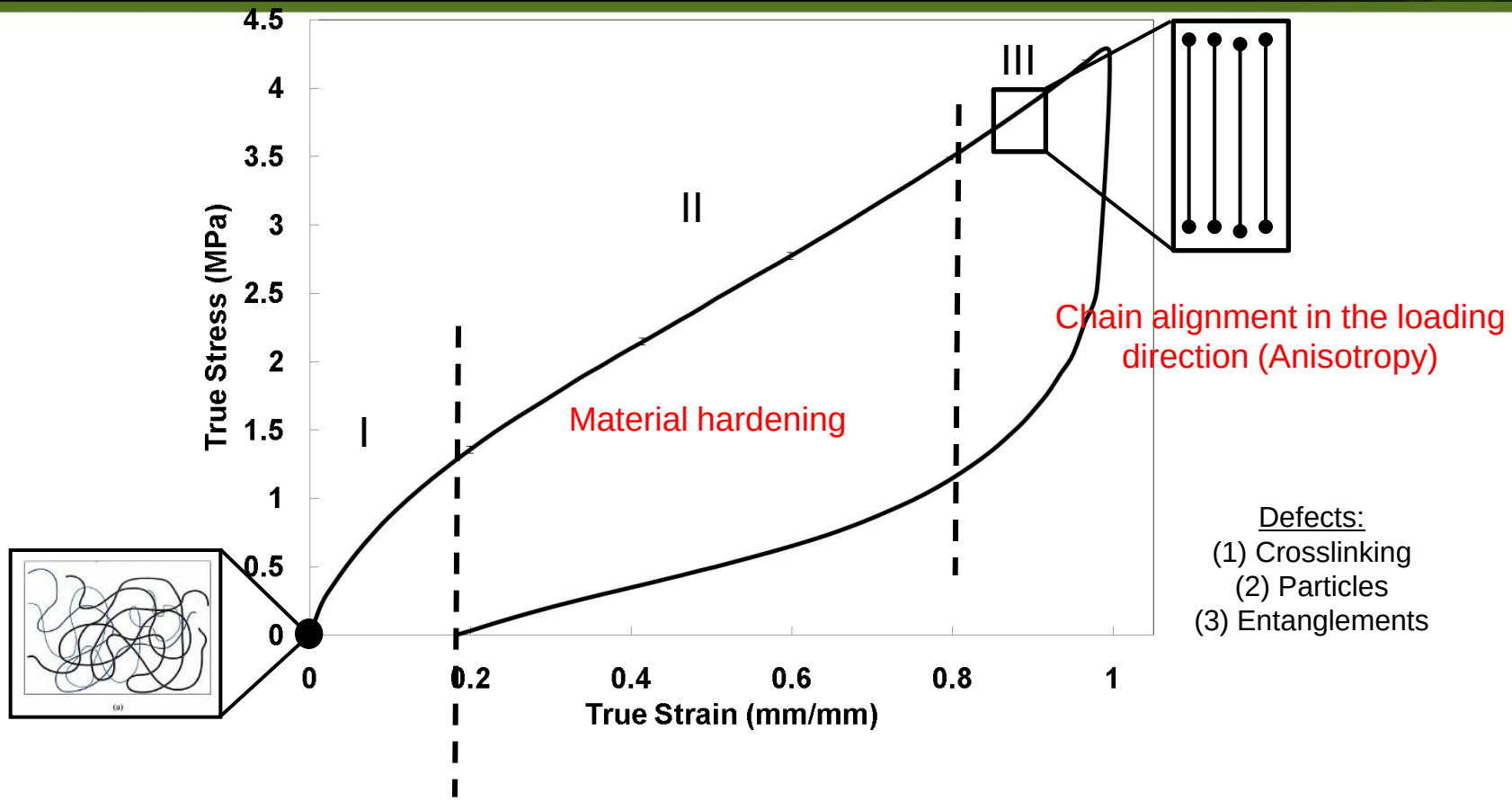
Hierarchical Multiscale Approach

- **Development of ISV material model:**

- Kinematics
- Thermodynamics → select physically-based ISVs



ISV Model: Extension to Elastomers



Defects:
(1) Crosslinking
(2) Particles
(3) Entanglements

Regime I: Hyperelastic mechanism induced by bond stretching/rotation

Regime II: Strain hardening induced by crosslinking, entanglements, and particles

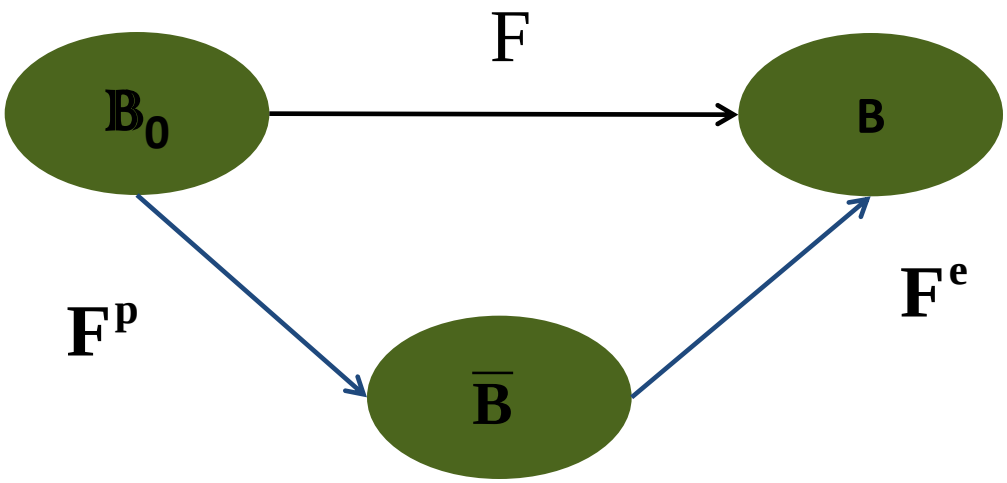
Regime III: Chain alignment and chain stretching between crosslinking and possible chain crystallization

ISV Model: Development for Amorphous Polymers

$$\mathbf{F} = \mathbf{F}^{\mathbf{e}}\mathbf{F}^{\mathbf{p}}$$

$\mathbf{F}^{\mathbf{e}}$: elastic mechanisms such as bond stretching and chains rotation/torsion inducing the different conformations of the intramolecular structure

$\mathbf{F}^{\mathbf{p}}$: time-dependent inelastic mechanisms such as permanent chains stretching and rotating but also the dissipative mechanism due to the relative slippage of molecular chains



ISV Model: Kinematics and Thermodynamics

- Multiplicative decomposition of deformation gradient

$$\mathbf{F} = \mathbf{F}^{\mathbf{e}}\mathbf{F}^{\mathbf{p}}$$ Deformation gradient

Kroner-Lee decomposition

$$J^{e} = \det \mathbf{F}^{\mathbf{e}}\,;\; J^{p} = \det \mathbf{F}^{\mathbf{p}}\,;$$

- Kinematics $\rightarrow$ velocity gradient $\mathbf{l}$:

$$\mathbf{l} = \dot{\mathbf{F}}\mathbf{F}^{-1}$$

$$\mathbf{l} = \mathbf{l}^{\mathbf{e}} + \mathbf{F}^{\mathbf{e}}\overline{\mathbf{L}}^{\mathbf{p}}\mathbf{F}^{\mathbf{e}-1}$$

  - $\mathbf{l}^{\mathbf{e}} = \dot{\mathbf{F}}^{\mathbf{e}}\mathbf{F}^{\mathbf{e}-1}\,;\quad \mathbf{l}^{\mathbf{e}} = \mathbf{d}^{\mathbf{e}} + \mathbf{w}^{\mathbf{e}}$
  - $\overline{\mathbf{L}}^{\mathbf{p}} = \dot{\mathbf{F}}^{\mathbf{p}}\mathbf{F}^{\mathbf{p}-1}\,;\quad \overline{\mathbf{L}}^{\mathbf{p}} = \overline{\mathbf{D}}^{\mathbf{p}} + \overline{\mathbf{W}}^{\mathbf{p}}$

Decomposition into symmetric and skew part

- Assumption on plastic flow
  - $J^{p} = 1$ Flow is incompressible
  - $\overline{\mathbf{W}}^{\mathbf{p}} = \mathbf{0}$ Flow is irrotational
- Thermodynamics

Clausius-Duhem inequality (Gurtin and Coleman, 1967; Gurtin and Anand, 2003)

$$\frac{D}{Dt}\int_{B} J^{e-1}\dot{\bar{\psi}}\,dv \le \int_{B} \boldsymbol{\sigma} : \mathbf{l}\,dv \quad \xrightarrow{\text{localize integrals}} \quad \overline{\mathbf{S}} : \mathbf{F}^{eT}\mathbf{d}^{\mathbf{e}}\mathbf{F}^{\mathbf{e}} + \overline{\mathbf{M}} : \overline{\mathbf{D}}^{\mathbf{p}} - \dot{\bar{\psi}} \ge 0$$

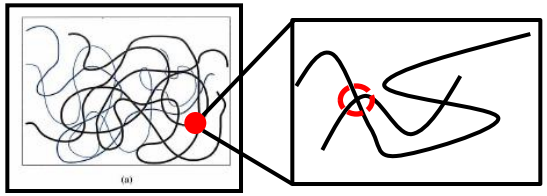
$$\overline{\mathbf{S}} = J^{e-1}\mathbf{F}^{e-1}\boldsymbol{\sigma}\mathbf{F}^{e-T} \qquad \overline{\mathbf{M}} = \overline{\mathbf{C}}^{e}\overline{\mathbf{S}}$$

ISV Model: Kinematics and Thermodynamics

- Helmholtz Free Energy:

strain/stretch -like internal state variables

$$\overline{\psi} = \hat{\overline{\psi}}\left(\overline{\mathbf{C}}^{\mathbf{e}}, \overline{\Pi}\right); \ \overline{\Pi} = \left\{\boxed{\overline{\xi}_1, \overline{\xi}_2, \overline{\mathbf{E}}^{\overline{\boldsymbol{\beta}}}}\right\}$$



$\overline{\xi}_1$: Strain field induced by internal strain field related to the intermolecular chain interaction in Regime I and II (van der Waals forces mainly)

$\overline{\xi}_2$: Strain field induced internal strain field related to the crystallization in Regime III

$\overline{\mathbf{E}}^{\overline{\boldsymbol{\beta}}}$: Stretch-like tensor giving direction-dependent (kinematic) hardening effect induced by the chain stretching between entanglements/crosslinking at large strain

$$\dot{\overline{\psi}} = \frac{\partial \hat{\overline{\psi}}}{\partial \overline{\mathbf{C}}^{\mathbf{e}}} : \dot{\overline{\mathbf{C}}}^{\mathbf{e}} + \frac{\partial \hat{\overline{\psi}}}{\partial \overline{\xi}_1} : \dot{\overline{\xi}}_1 + \frac{\partial \hat{\overline{\psi}}}{\partial \overline{\xi}_2} : \dot{\overline{\xi}}_2 + \frac{\partial \hat{\overline{\psi}}}{\partial \overline{\boldsymbol{\beta}}} : \dot{\overline{\boldsymbol{\beta}}}$$

- Clausius-Duhem Inequality:

$$\left[\overline{\mathbf{S}} - 2\frac{\partial \overline{\psi}}{\partial \overline{\mathbf{C}}^{\mathbf{e}}}\right] : \mathbf{F}^{\mathbf{e}\mathbf{T}}\mathbf{d}^{\mathbf{e}}\mathbf{F}^{\mathbf{e}} + \overline{\mathbf{M}} : \overline{\mathbf{D}}^{\mathbf{p}} - \left(\underbrace{\frac{\partial \hat{\overline{\psi}}}{\partial \overline{\xi}_1}}_{\overline{\kappa}_1} : \dot{\overline{\xi}}_1 + \underbrace{\frac{\partial \hat{\overline{\psi}}}{\partial \overline{\xi}_2}}_{\overline{\kappa}_2} : \dot{\overline{\xi}}_2 + \underbrace{\frac{\partial \hat{\overline{\psi}}}{\partial \overline{\boldsymbol{\beta}}}}_{\overline{\boldsymbol{\alpha}}} : \dot{\overline{\boldsymbol{\beta}}}\right) \geq 0$$

ISV Model: Summary

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

Elasticity: Cauchy Stress

$$\mathbf{F} = \mathbf{F}^{e}\mathbf{F}^{p};\quad \mathbf{F}^{e} = \mathbf{R}^{e}\mathbf{U}^{e};\quad \mathbf{F}^{e*} = \left(J^{e}\right)^{-1/3}\mathbf{F}^{e};\quad \mathbf{b}^{e*} = \mathbf{F}^{e*}\mathbf{F}^{e*T}$$

$$\boldsymbol{\tau} = \mathbf{F}^{e}\overline{\mathbf{S}}\mathbf{F}^{eT};\quad \boldsymbol{\tau} = \hat{\mu}_{B}^{*}\,\mathbf{dev}\left(\mathbf{b}^{e*}\right) + \hat{K}_{B}\left(J^{e}\right)\mathbf{1};\quad \boldsymbol{\sigma} = J^{e-1}\boldsymbol{\tau}$$

Inelastic Flow rule

$$\dot{\mathbf{F}}^{p} = \overline{\mathbf{L}}^{p}\mathbf{F}^{p};\ \overline{\mathbf{L}}^{p} = \overline{\mathbf{D}}^{p} + \overline{\mathbf{W}}^{p};\ \overline{\mathbf{D}}^{p} = \frac{1}{\sqrt{2}}\dot{\gamma}^{p}\,\overline{\mathbf{N}}^{p};\quad \overline{\mathbf{W}}^{p} = 0$$

$$\dot{\gamma}^{p} = \dot{\gamma}_{0}^{p}\left[\sinh\left(\frac{\overline{\tau} - \left(\overline{\kappa}_{1} + \alpha_{p}\overline{\pi}\right)}{Y}\right)\right]^{m};\quad \overline{\mathbf{N}}^{p} = \frac{\overline{\mathbf{DEV}}\left(\overline{\mathbf{M}} - \overline{\boldsymbol{\alpha}}\right)}{\left\|\overline{\mathbf{DEV}}\left(\overline{\mathbf{M}} - \overline{\boldsymbol{\alpha}}\right)\right\|}$$

$$\overline{\tau} = \frac{1}{\sqrt{2}}\left\|\overline{\mathbf{DEV}}\left(\overline{\mathbf{M}} - \overline{\boldsymbol{\alpha}}\right)\right\|\ ;\quad \overline{\pi} = -\frac{1}{3}\overline{\mathrm{Tr}}\left(\overline{\mathbf{M}}\right)$$

$$\overline{\kappa}_{1} = C_{\kappa_{1}}\,\overline{\xi}_{1}\ ;\quad \overline{\boldsymbol{\alpha}} = C_{\alpha}\,\overline{\mathbf{E}}^{\overline{\boldsymbol{\beta}}}$$

Evolution Equations

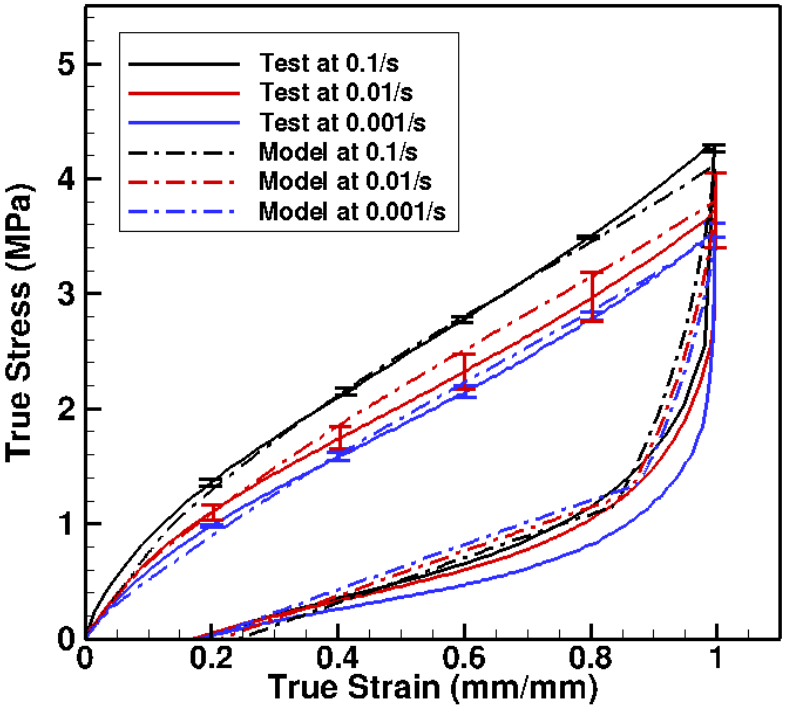
$$\dot{\overline{\xi}}_{1}^{*} = h_{0}\left(1 - \frac{\overline{\xi}_{1}}{\overline{\xi}^{*}}\right)\dot{\overline{\gamma}}^{p};$$

$$\dot{\overline{\mathbf{E}}}^{\overline{\boldsymbol{\beta}}} = \left(R_{s_{1}} + R_{s_{2}}\left\|\overline{\mathbf{E}}^{\overline{\boldsymbol{\beta}}}\right\|^{2}\right)\overline{\mathbf{D}}^{p}$$

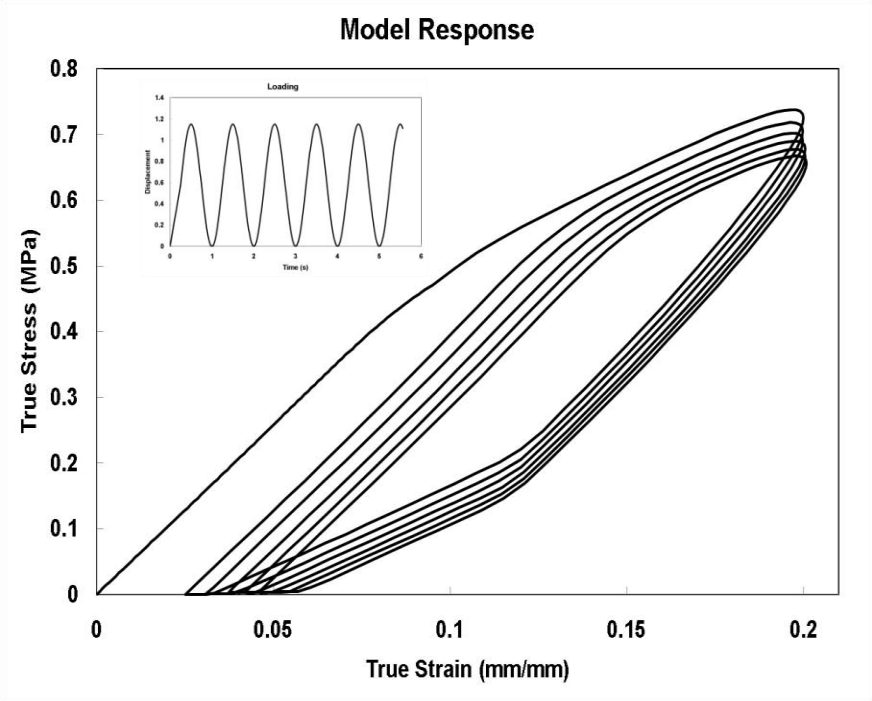
Parameters

$$\left\{\mu, \dot{\gamma}_{p}^{0}, m, \alpha_{p}, Y, h_{0}, \overline{\xi}_{10}, \overline{\xi}_{0}^{*}, \overline{\xi}_{sat}^{*}, R_{S1}, R_{S2}, C_{\kappa_{1}}, C_{\alpha}, \lambda_{L}, \mu_{R}\right\}$$

ISV Model: Model to Experiment Comparsion

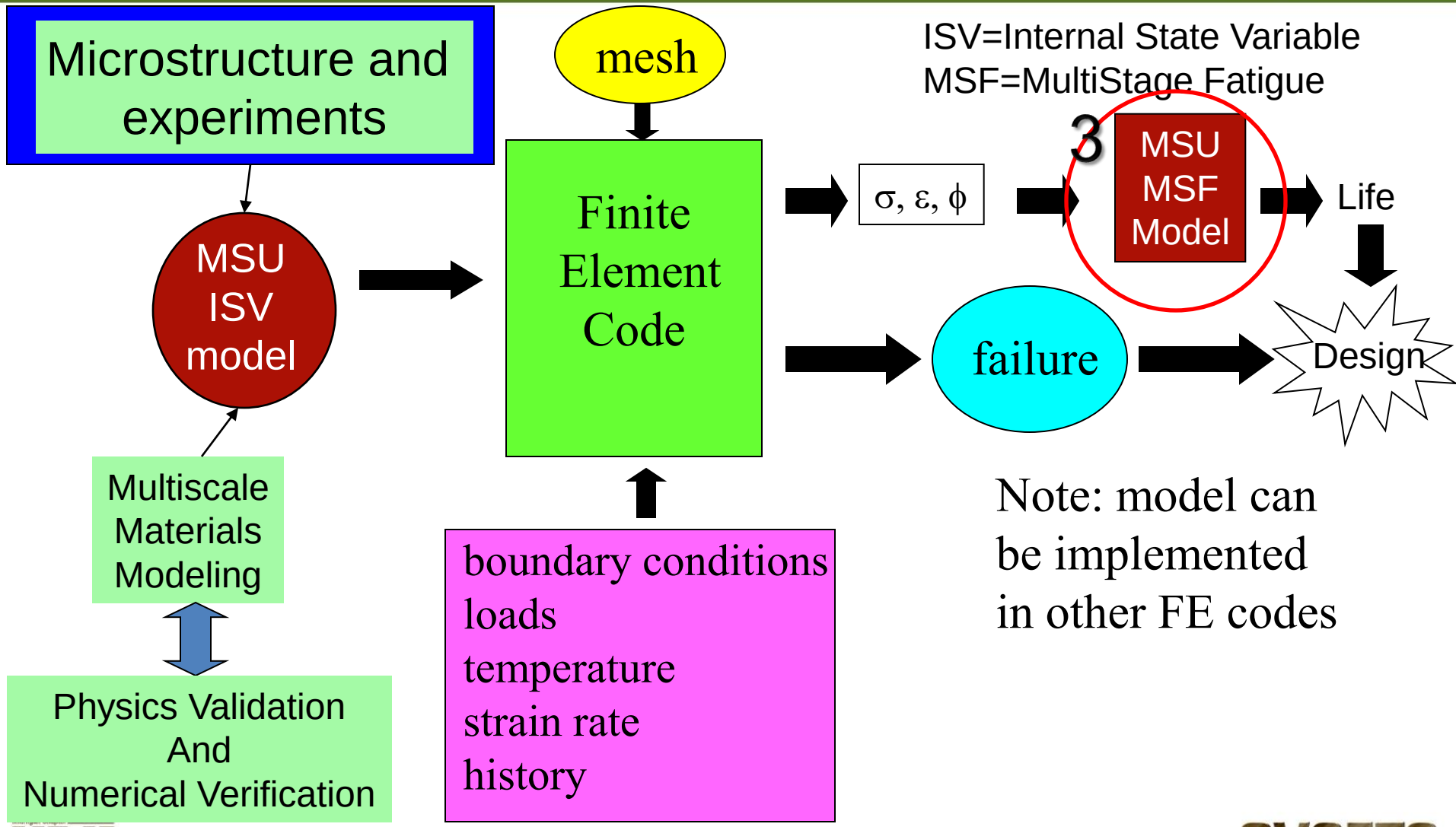


ISV model predicts loading path, unloading path and time dependence



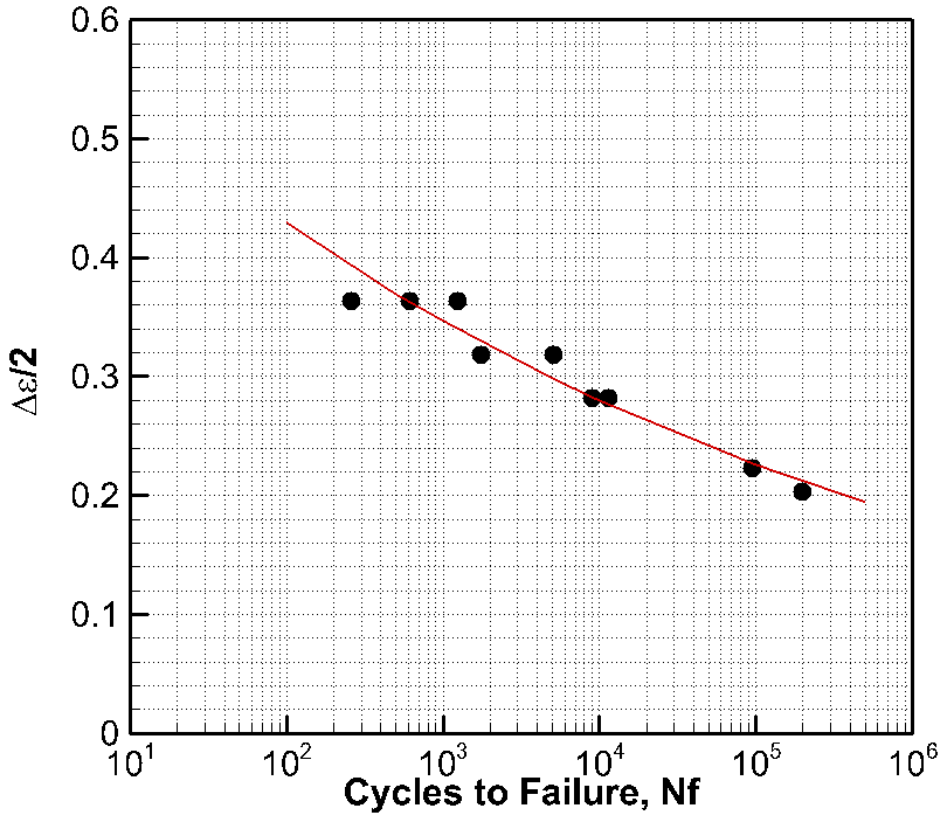
ISV model response under cyclic loading at 1 Hz. It shows significant hysteresis in the first cycle and cyclic relaxation

Macroscale MSU ISV/MSF Models Implementation and Use



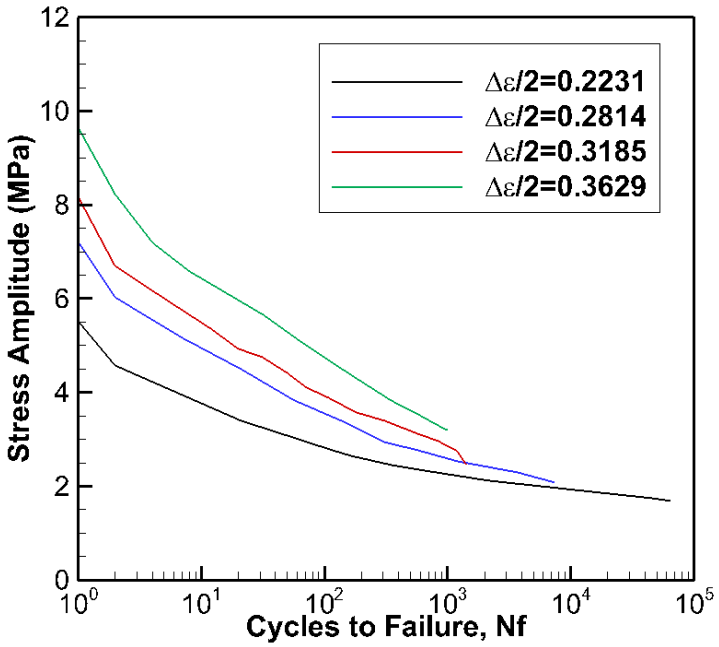
Note: model can be implemented in other FE codes

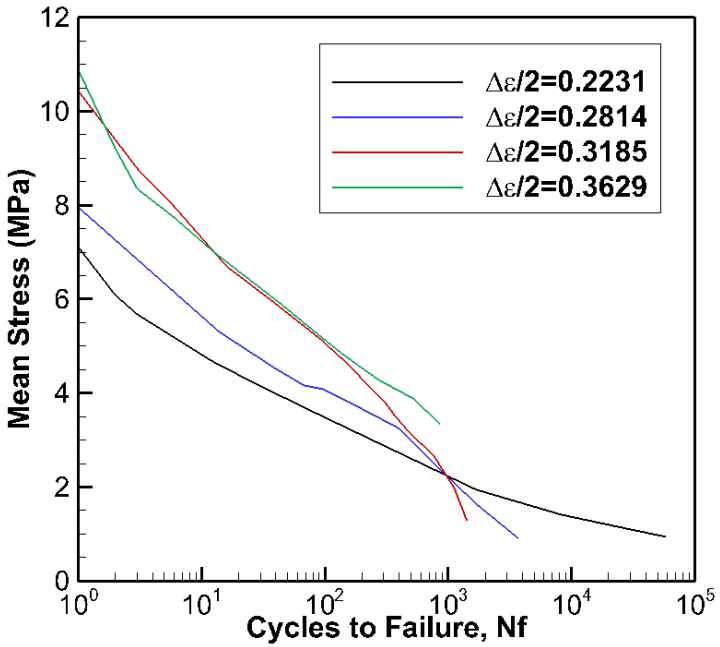
Results: Fatigue Life



- Power law fit: $\frac{\Delta\varepsilon}{2} = 0.6587\left(N_f\right)^{-0.093}$

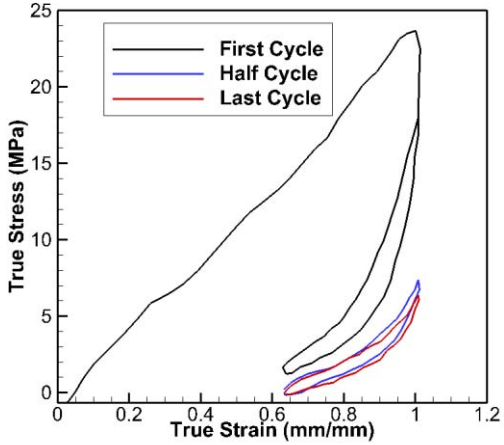
Results: Fatigue Loading



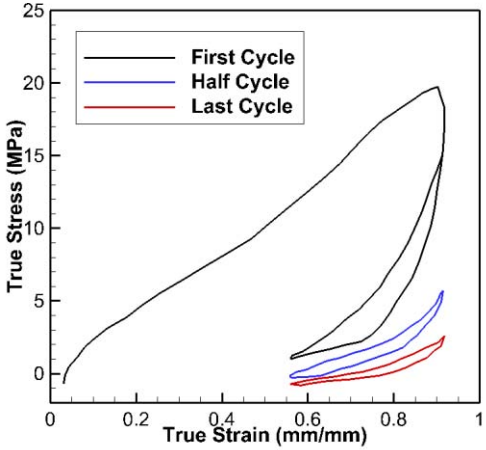


- Significant cyclic stress softening occurred for all strain amplitudes

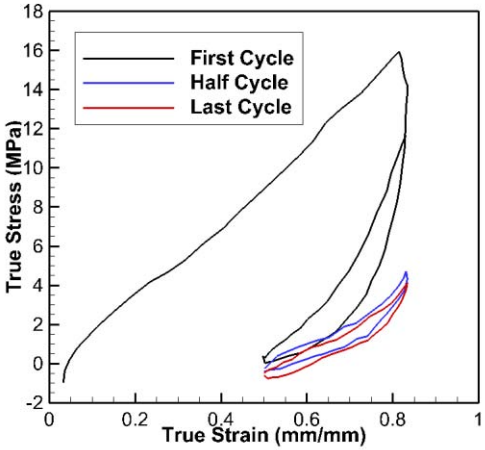
Results: Hysteresis



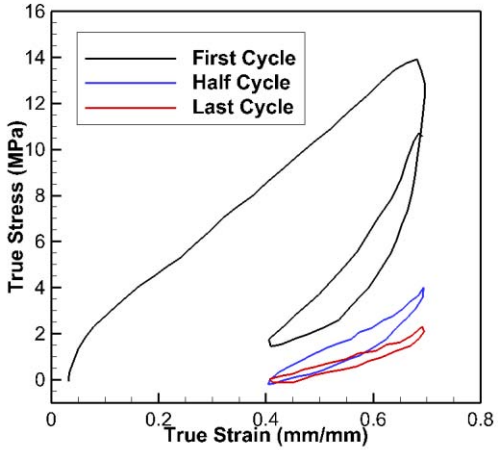
Δε/2 = 0.36



Δε/2 = 0.32

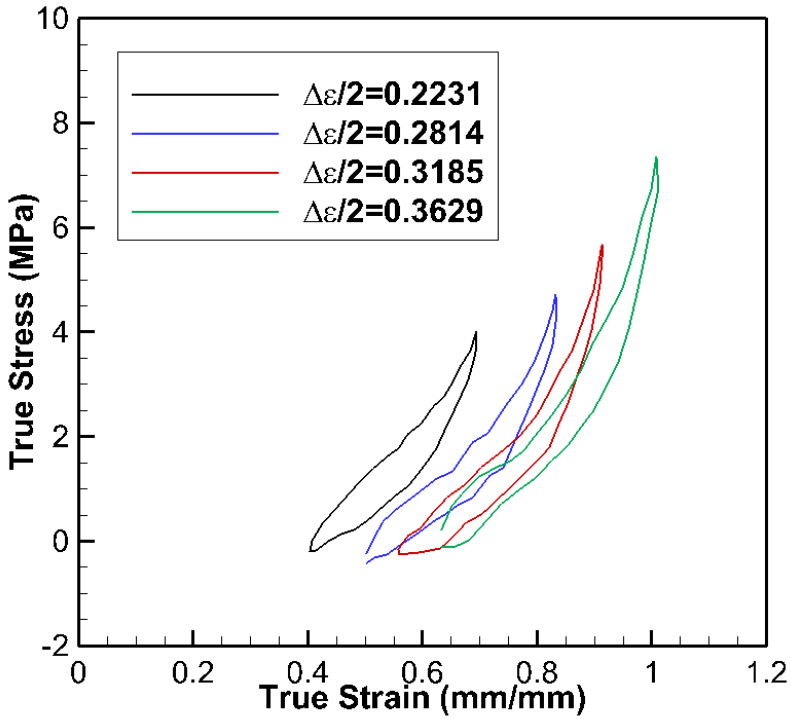


Δε/2 = 0.28

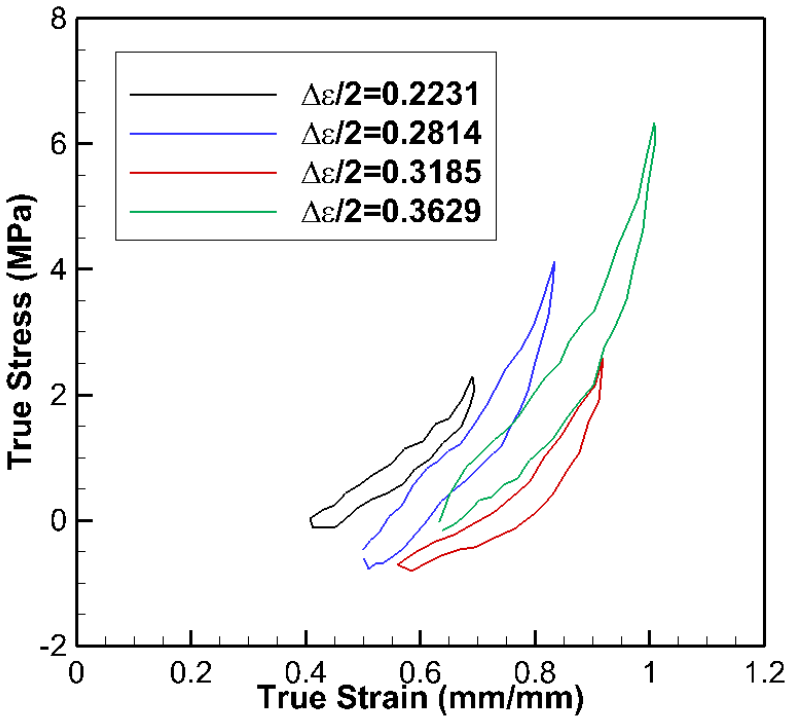


Δε/2 = 0.22

Results: Hysteresis



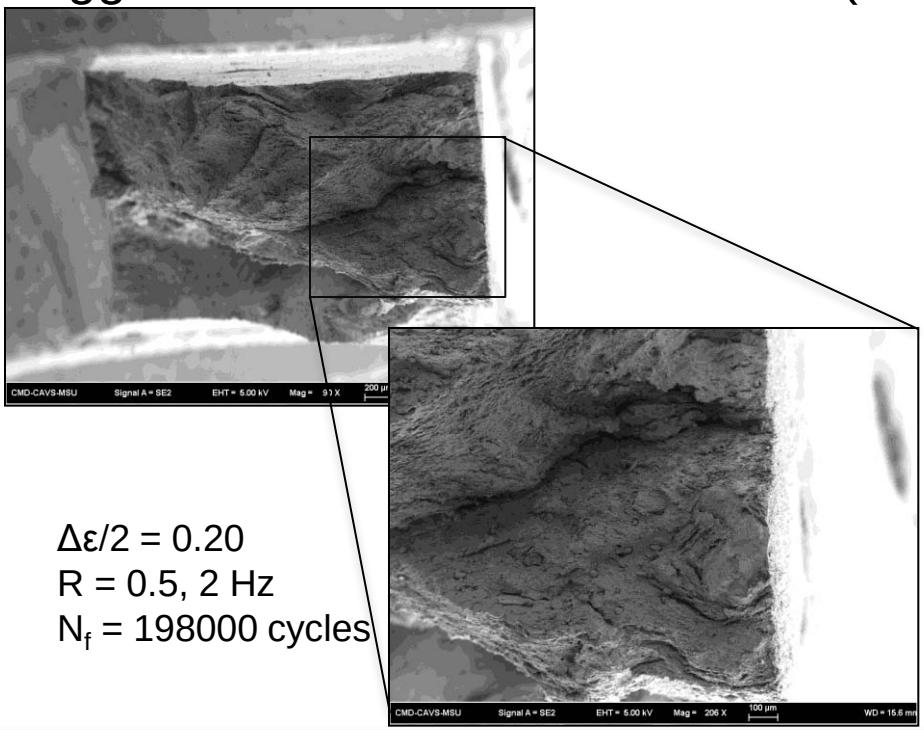
Half cycle at strain amplitudes of 0.22, 0.28, 0.32 and 0.36.



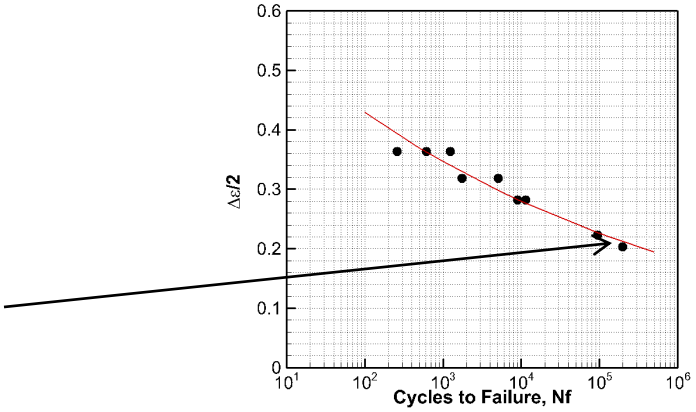
Last cycle at strain amplitudes of 0.22, 0.28, 0.32 and 0.36.

Results: Microstructure for Fatigue Loading

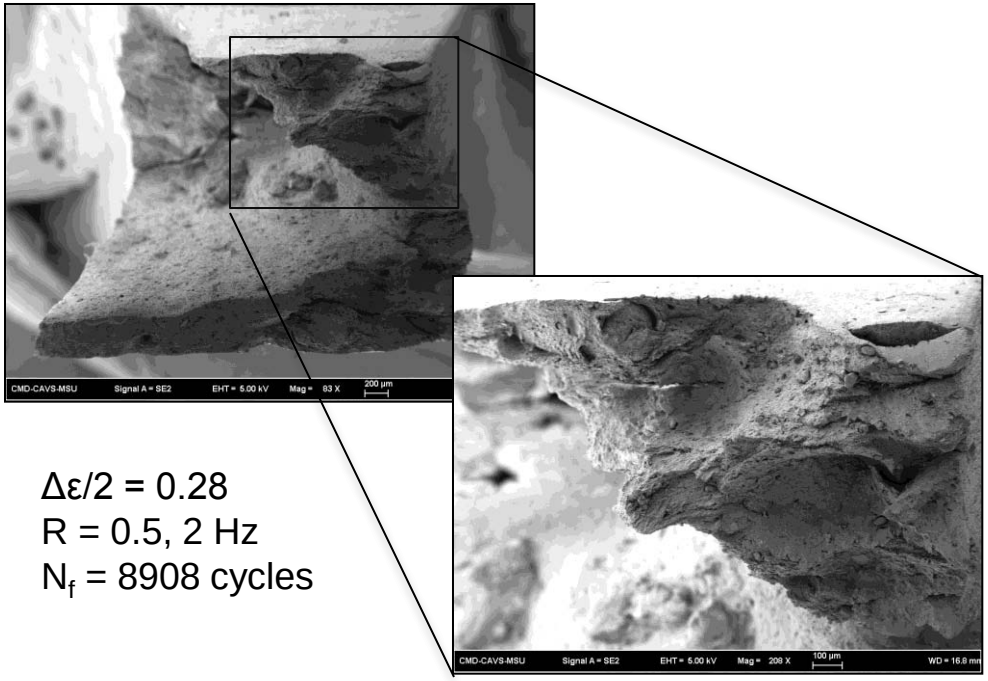
- Particle debonding
  - 0.5 – 200 μm particles debonded during deformation
  - 100 – 200 μm particles initiated significant fatigue cracks
  - 2 particles in length scale of focus: calcium carbonate and agglomerations of aluminosilicate (clay)



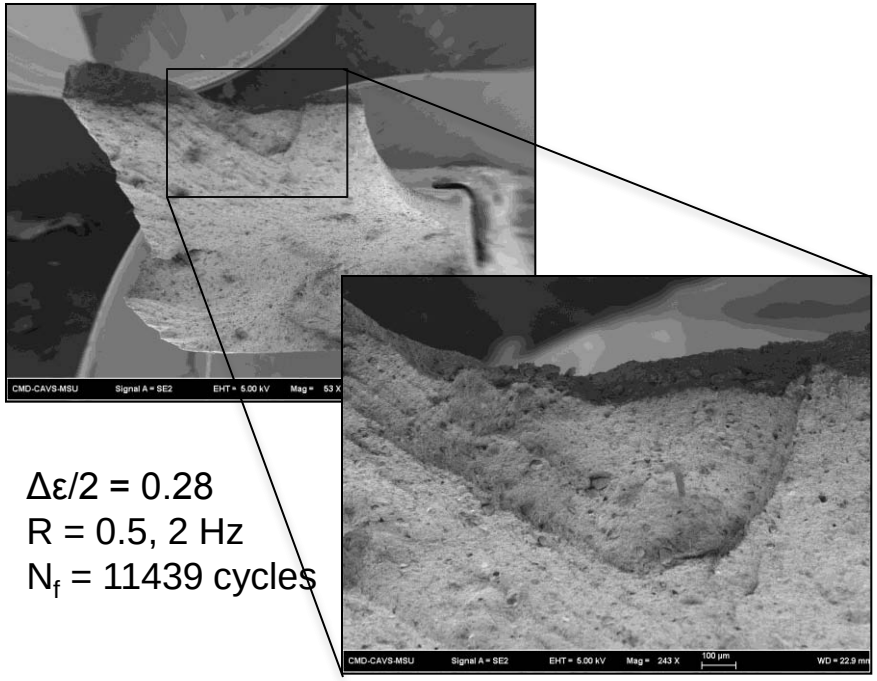
$\Delta\varepsilon/2 = 0.20$
R = 0.5, 2 Hz
N_f = 198000 cycles



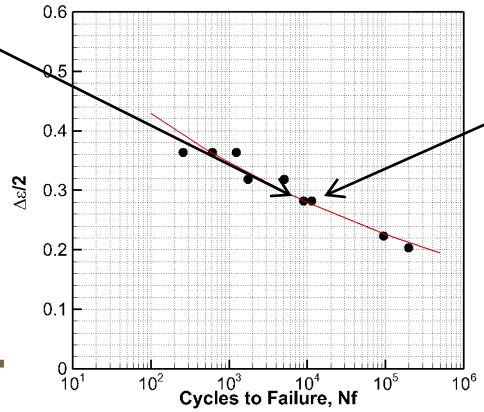
Results: Microstructure for Fatigue Loading



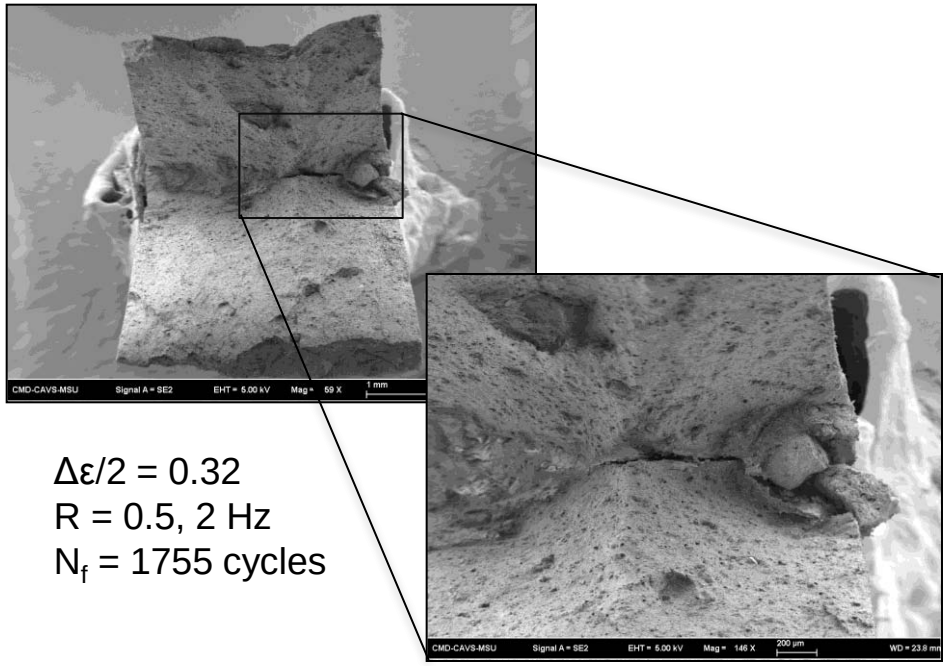
$\Delta\varepsilon/2 = 0.28$
$R = 0.5$, 2 Hz
$N_f = 8908$ cycles



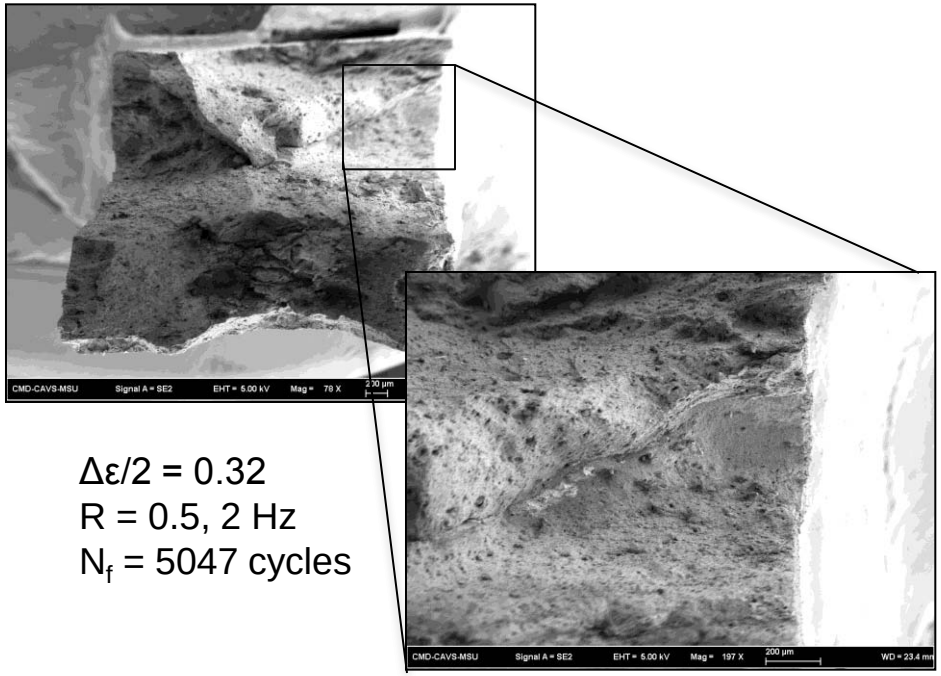
$\Delta\varepsilon/2 = 0.28$
$R = 0.5$, 2 Hz
$N_f = 11439$ cycles



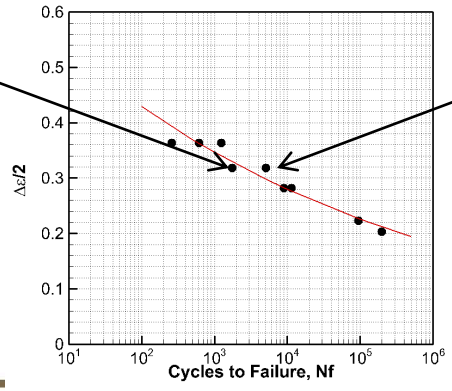
Results: Microstructure for Fatigue Loading



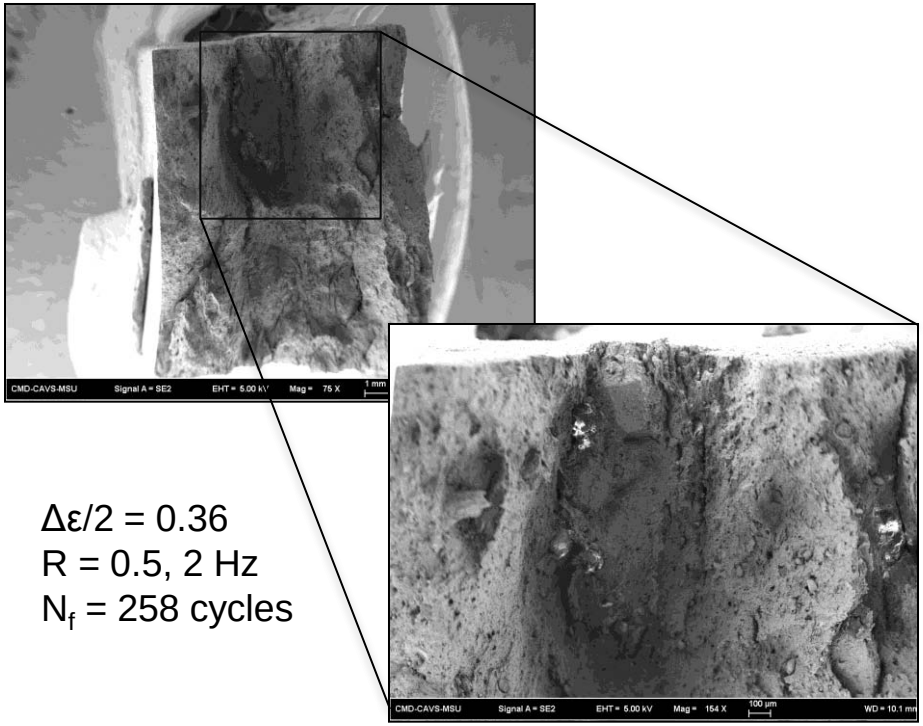
$\Delta\varepsilon/2 = 0.32$
R = 0.5, 2 Hz
N_f = 1755 cycles



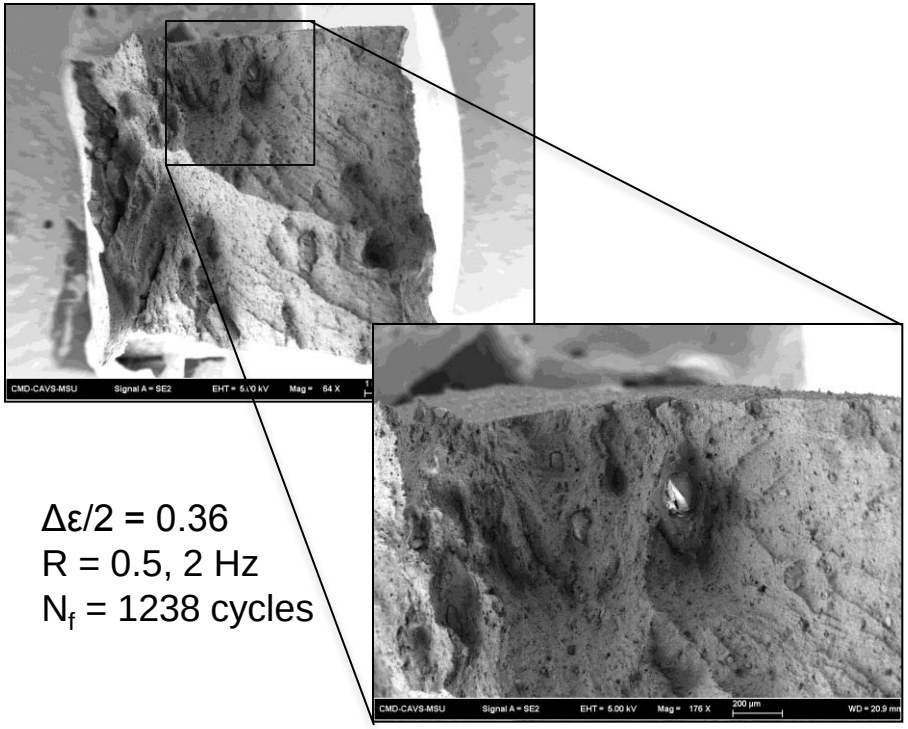
$\Delta\varepsilon/2 = 0.32$
R = 0.5, 2 Hz
N_f = 5047 cycles



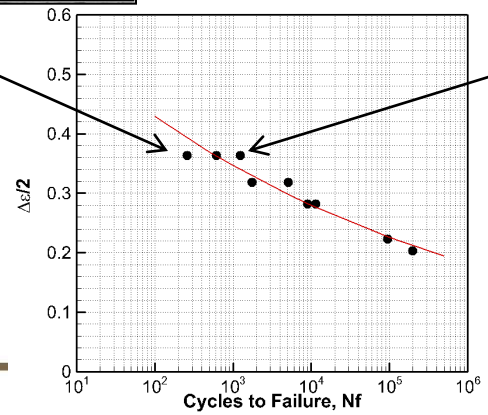
Results: Microstructure for Fatigue Loading



$\Delta\varepsilon/2 = 0.36$
$R = 0.5$, 2 Hz
$N_f = 258$ cycles



$\Delta\varepsilon/2 = 0.36$
$R = 0.5$, 2 Hz
$N_f = 1238$ cycles



MultiStage Fatigue Model

$$N_{total}=N_{inc}+N_{MSC}+N_{PSC}+N_{LC}$$

Incubation

$$\frac{\Delta\gamma^{P}_{\max}}{2}=C_{inc}N^{\alpha}_{inc} \qquad C_{inc}=C_n+z(C_m-C_n) \text{ and } C_n=0.24\left(1-\langle R\rangle\right)$$

MSC/PSC Growth

$$\left(\frac{da}{dN}\right)_{MSC/PSC}=G\left(\Delta CTD-\Delta CTD_{TH}\right)$$

Initial crack size

$$a_i=0.5625\hat{D}_p$$

$$\Delta CTD=\underbrace{f(\phi)C_{II}(1)\left[\frac{U\Delta\hat{\sigma}}{S_u}\right]^n a}_{\text{HCF loading dominated}}+\underbrace{C_I(1)\left(\frac{\Delta\gamma^{p}_{\max}}{2}\right)^2_{macro}}_{\text{LCF loading dominated}}$$

$$f(\phi)=1+\omega\left\{1-\exp\left(-\frac{\phi}{2\phi_{th}}\right)\right\}$$ Porosity term

ΔCTD_{th} =nonpropagating crack threshold

$$\Delta\hat{\sigma}=2\theta\left[\frac{3}{2}\frac{\Delta\sigma'_{ij}}{2}\frac{\Delta\sigma'_{ij}}{2}\right]^{0.5}+(1-\theta)\Delta\sigma_1$$ Multiaxial term

$$U=\frac{1}{1-R}$$ Mean stress term

LC Growth

$$\left(\frac{da}{dN}\right)_{LC}=A(T-T_0) \quad \text{for} \quad T_0<T<T_A$$

$$\left(\frac{da}{dN}\right)_{LC}=BT^{\beta} \quad \text{for} \quad T_A<T<T_C$$

$a_i \geq 250\,\mu\text{m}$, or

$$\frac{da}{dN}=\max\left[\left(\frac{da}{dN}\right)_{MSC/PSC},\left(\frac{da}{dN}\right)_{LC}\right]$$

McDowell, et al., 2003

Conclusions

- DMA testing was performed to investigate the viscoelastic properties and transition temperatures
- Material exhibited time and temperature dependence
- Debonding of calcium carbonate particles and aluminosilicate agglomerates on the order of 50 to 200 μm lead to specimen failure for monotonic loading and initiated fatigue cracks under fatigue loading
- The ISV model captures both loading and unloading as well as rate dependence

Conclusions

- The MSF model equations need to be extended to elastomeric materials as well as calibrated and validated on SBR
- Fatigue experiments need to be conducted at lower strain amplitudes to investigate the high cycle fatigue response of the material

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