A Methodology for Determining Internal Stresses in Multi-Component Materials

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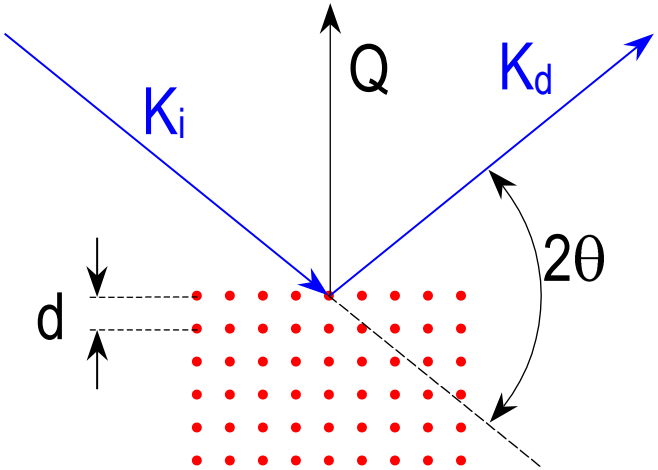
Internal stresses: Why do we care?

- Constitutive performance of structural materials
  - Operating environment and conditions
- Composites
  - Residual stresses in virgin materials
  - Both macro and micro residual/internal stresses

- Determine a safe operating space

Neutron diffraction

- In-situ measure internal *elastic* strains in bulk material
  - Spatially resolved
  - Changes due to applied "load":
    - Stress, Strain, Temperature, Environment…

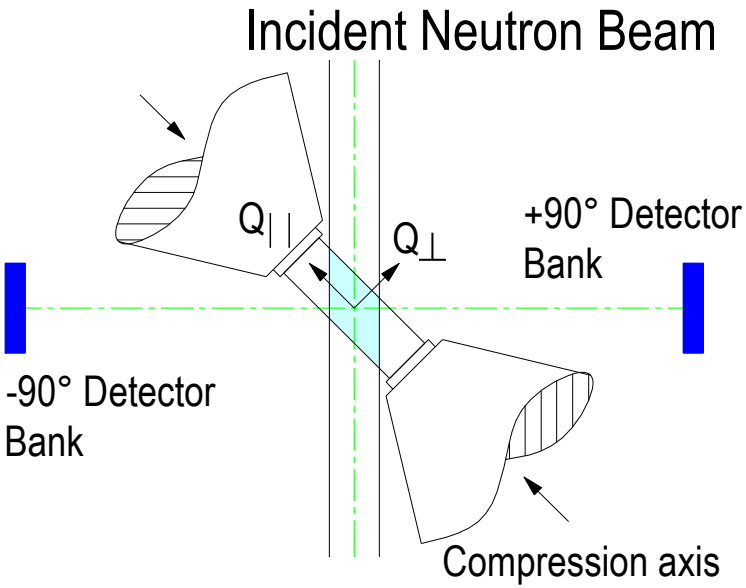


$$\lambda = 2d\sin\theta$$

$$\varepsilon_{hkl}^{el} = \frac{d_{hkl} - d_{hkl}^{0}}{d_{hkl}^{0}} = \frac{d_{hkl}}{d_{hkl}^{0}} - 1$$

SMARTS

- ±250 kN loading capability
- Measure // and ⊥ strains simultaneously
- 1500 kg translator table
- RT to 1500°C vacuum furnace (1800°C stand-alone)
- RT to -100°C vacuum cryo-stage



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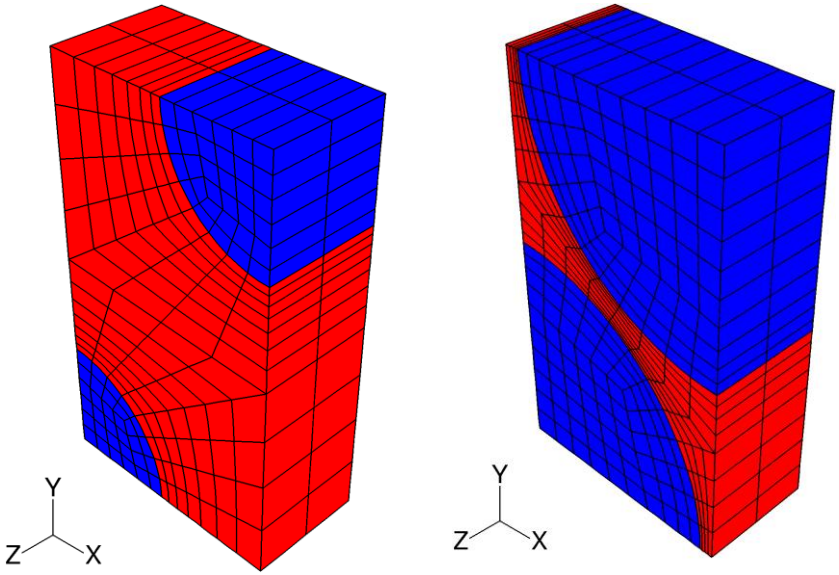
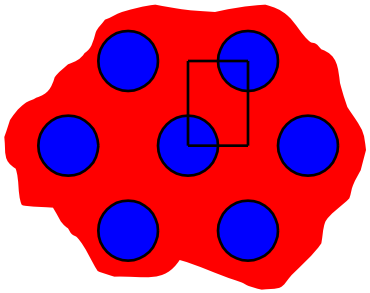
Finite Element Modeling

- Uniaxial fiber model
- Unit-cell model
  - Hexagonal fiber stacking
- Full 3D due to loading along fibers
- Plane strain assumption
  - Plane perpendicular to fibers stay plane
- 2nd order brick elements



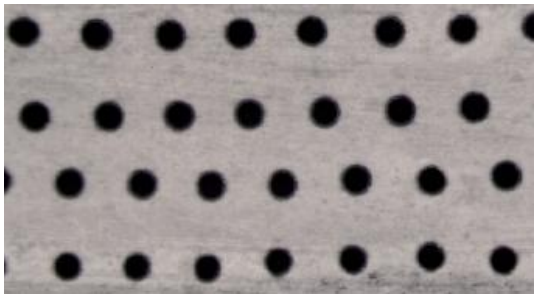
20% Mesh 80% Mesh



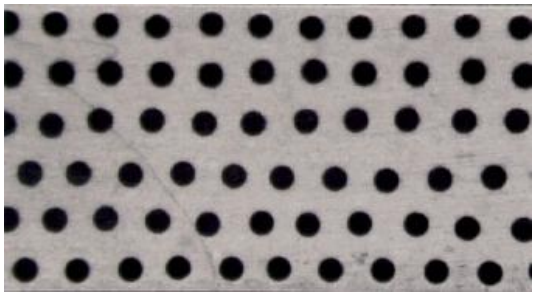
ABAQUS V6.3

Kanthal/Tungsten fiber composites

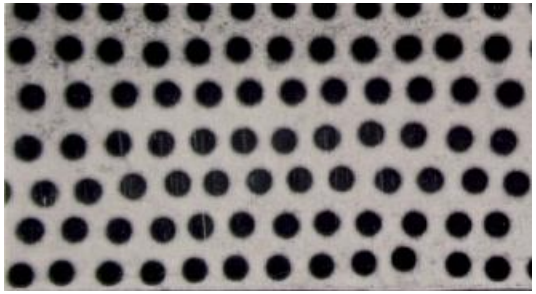
10%



20%



30%



- High temperature structural application
- Kanthal has good high temperature properties
  - Inherent corrosion/oxidization protection by forming an alumina case
  - 73.2% Fe, 21.0% Cr, 5.8% Al and 0.04%C
- Tungsten fibers increases strength
- Manufacture technique
  - Plasma sprayed
  - Mixed cubic and hexagonal stacking observed

Kanthal/Tungsten fiber composites

- Stress-free temperature assumed to be 650°C
  - Processed at 1065°C
  - 0.7-0.8*T_P
- Material parameters
  - "Bilinear elastic–plastic"

Table 1. Tungsten fibre thermomechanical properties used in the models.

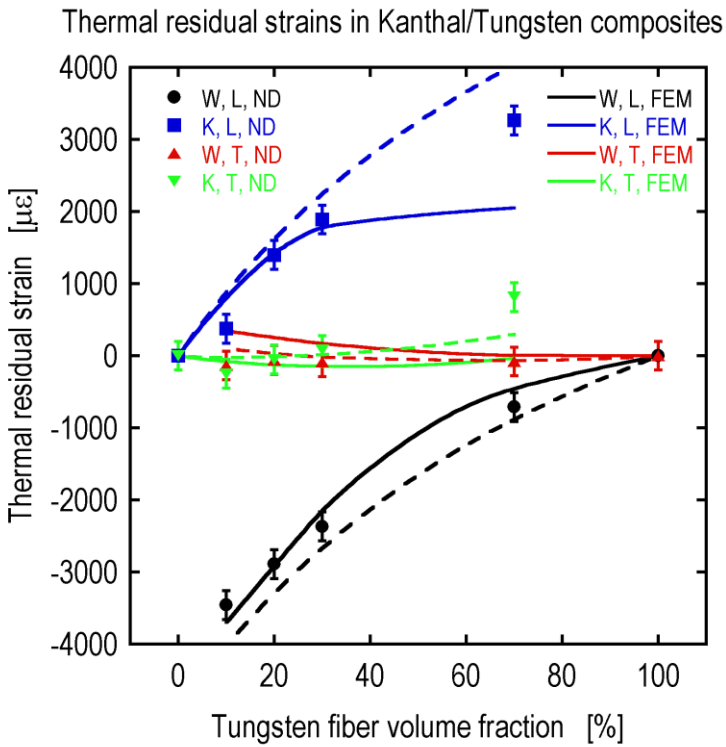
Temperature (°C)	Young's modulus (GPa)	Poisson's ratio	Yield stress (MPa)	Coefficient of thermal expansion (10^{-6} K^{-1})
26	395	0.28	1305	4.40
138	394	0.28	1179	4.42
251	393	0.28	1054	4.44
420	389	0.28	893	4.47
533	386	0.28	777	4.49
1000	360	0.28	550	4.56

Table 2. Kanthal: thermomechanical properties used in the models.

Temperature (°C)	Young's modulus (GPa)	Poisson's ratio	Yield stress (MPa)	Coefficient of thermal expansion (10^{-6} K^{-1})
26	202	0.28	530	9.58
138	196	0.28	520	9.68
251	183	0.28	465	10.08
420	172	0.28	375	10.80
533	162	0.28	275	11.38
1000	125	0.28	27	14.75

Rangaswamy et al., Phil Mag. 2003

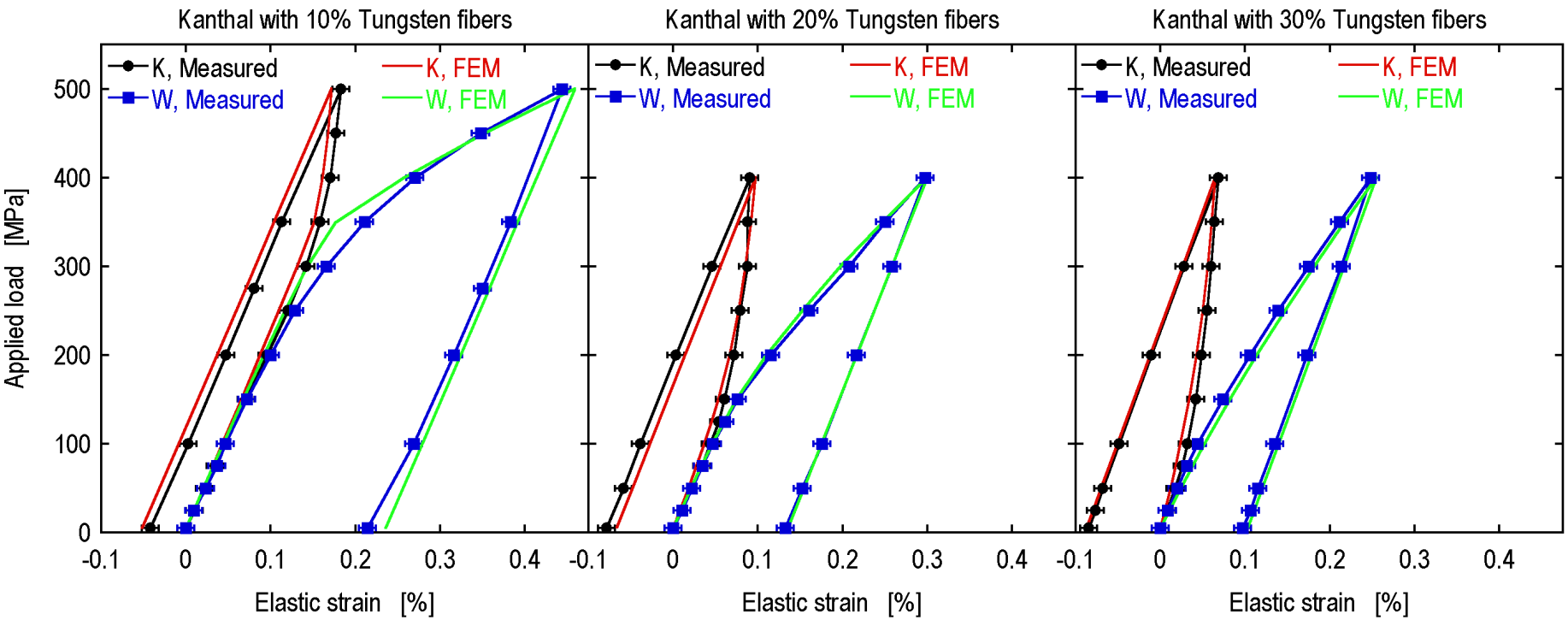
Kanthal/Tungsten fiber composites



- Thermal residual strains – measured and predicted
  - Large discrepancy for the matrix in the 70% composite
    - Increased yield strength due to grain refinement?
  - Transverse strains
    - Very heterogeneous elastic strain distribution

Rangaswamy et al., Phil Mag. 2003

Kanthal/Tungsten fiber composites



- In-situ loading strains – measured and predicted
  - Only yield region of 10% composite is outside error bars (±100με)

- Baseline for materials with well known properties

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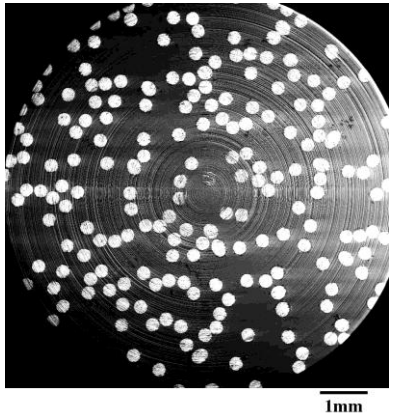
Kanthal/Tungsten fiber composites

- Conclusions
  - Thermal residual strains
    - Results for Kanthal (plastically deforming phase) inaccurate at high fiber volume fraction (70%)
    - Transverse strains are highly non-uniform and the agreement between model and measurements is not as good
  - In-situ loading strains
    - The modeling approach is capable of predicting the loading behavior taking into account the thermal residual strains
    - Caveat: Very small plastic region. Only one phase deforming plastically. Only about 0.3% macroscopic plastic strain

BMG/Tungsten fiber composites

- Bulk Metallic Glass matrix (Vitreloy 1)
  - High yield stress, low stiffness (high elastic limit)
  - Limited ductility due to shear banding
- Composites were cast in Stainless steel tubes



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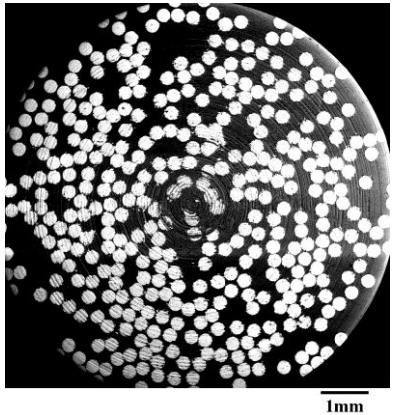
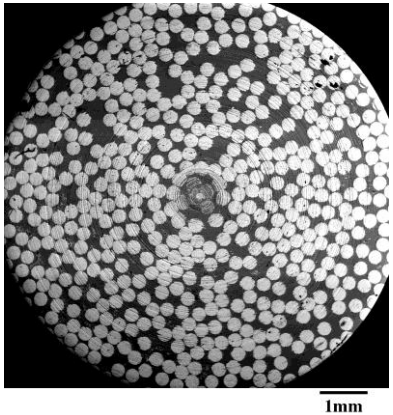
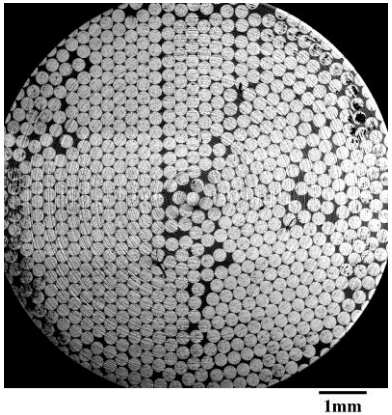


40%

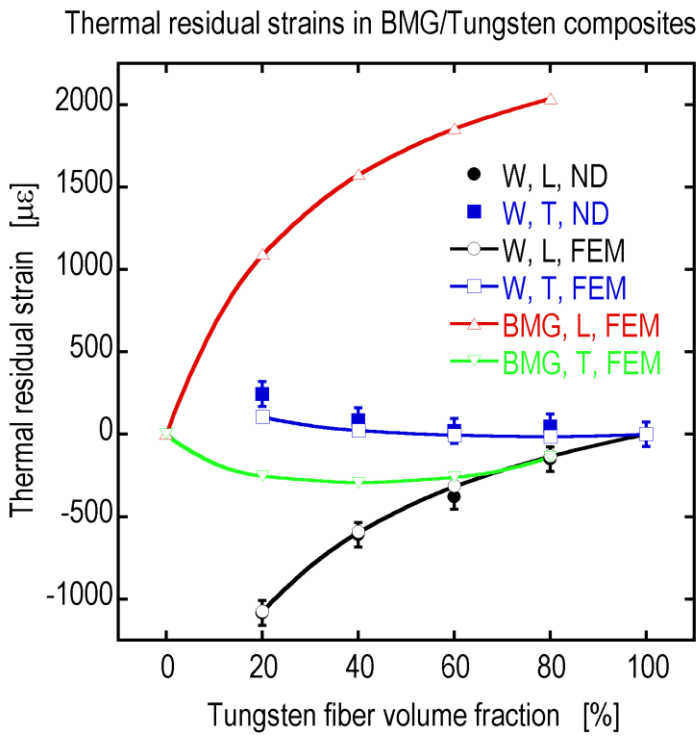


60%



80%

BMG/Tungsten fiber composites



- Thermal residual strains – measured and predicted
  - Best agreement longitudinal
  - Uniformity of strains in the longitudinal direction
  - No plastic deformation predicted during cooling

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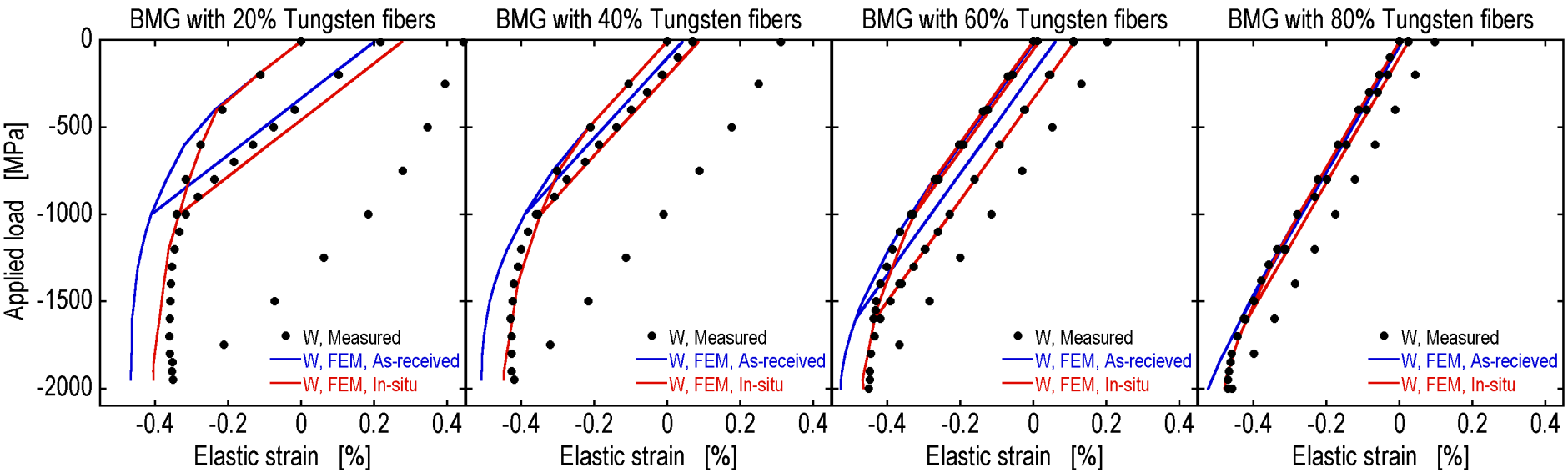
BMG/Tungsten fiber composites



- In-situ loading strains
  - Elastic strains in Tungsten only

Blue line: FEM with literature data

Red line: FEM with refined material parameters

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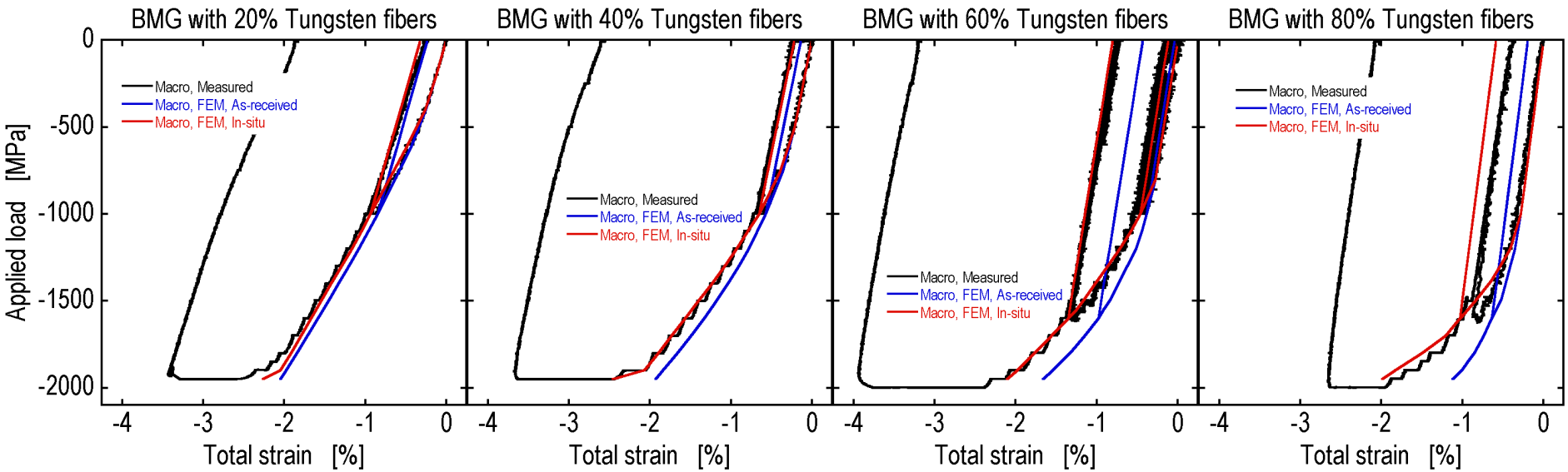
BMG/Tungsten fiber composites



- Macroscopic loading curves
  - Flat parts are constant load holds for the neutron diffraction measurements

Blue line: FEM with literature data

Red line: FEM with refined material parameters

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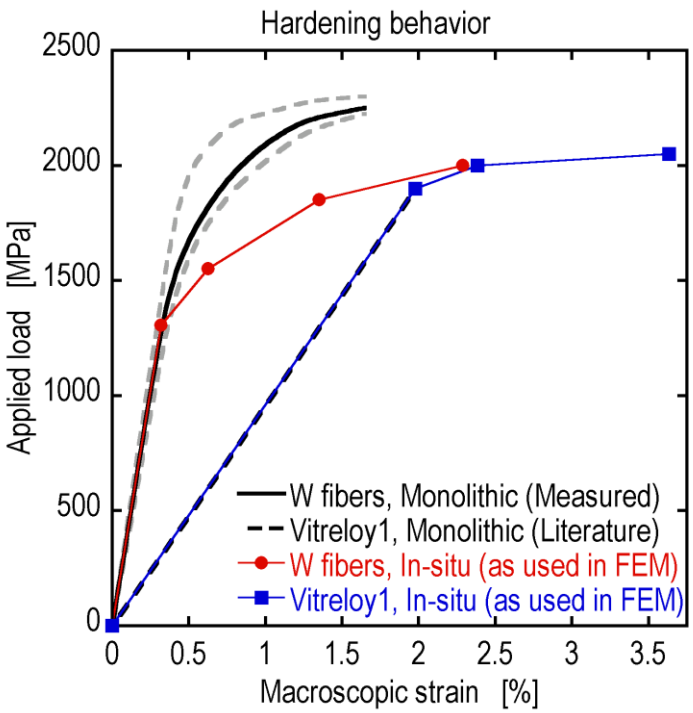
BMG/Tungsten fiber composites

- Conclusions
  - Method suggest that the properties of the Tungsten fibers have changed
    - Less hardening
    - More ductility
  - Some ductility in BMG is necessary to give good agreement with measured data



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SMARTS Expert

- Implement automated modeling of load sharing and phase stresses in composites using FEM
- Implement automated modeling of single crystal elastic constants using SCM

Conclusions

- Combined measurement and modeling scheme to determine in-situ material properties
  - Successfully tested for Kanthal/Tungsten composites
  - Suggest changes in material parameters for BMG/Tungsten composites