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Temperature Dependent Virtual Fields Method Calibration in MatCal

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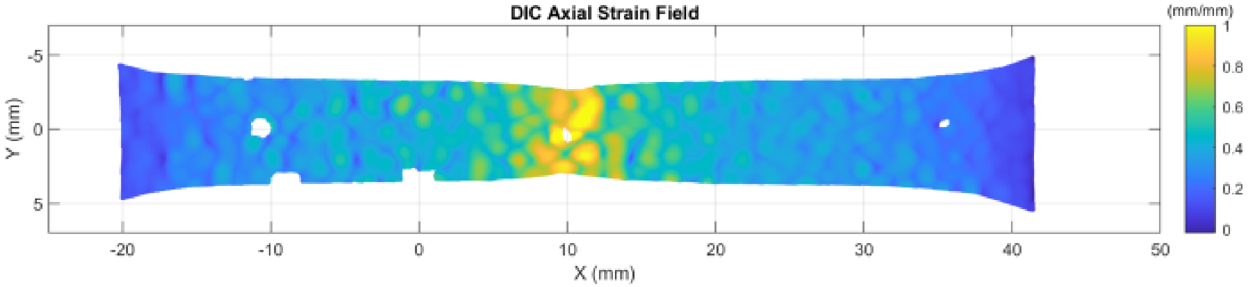
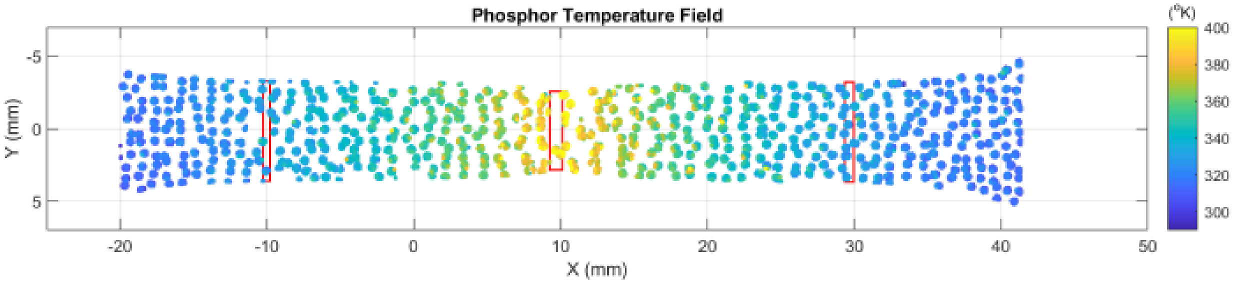
About me

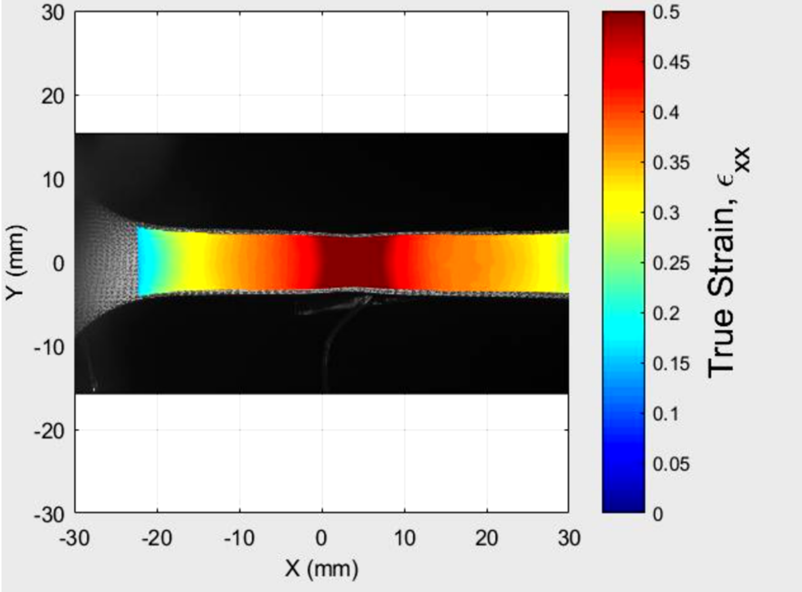
- Undergraduate student at University of California, Irvine
  - B.S. in Computer Science and Engineering, 2022
- Org 08751
  - Started October, 2020
- Working on MatCal development team
  - General code maintenance
  - Plotting features
  - Thermal VFM
- Mentored by Matthew Kury

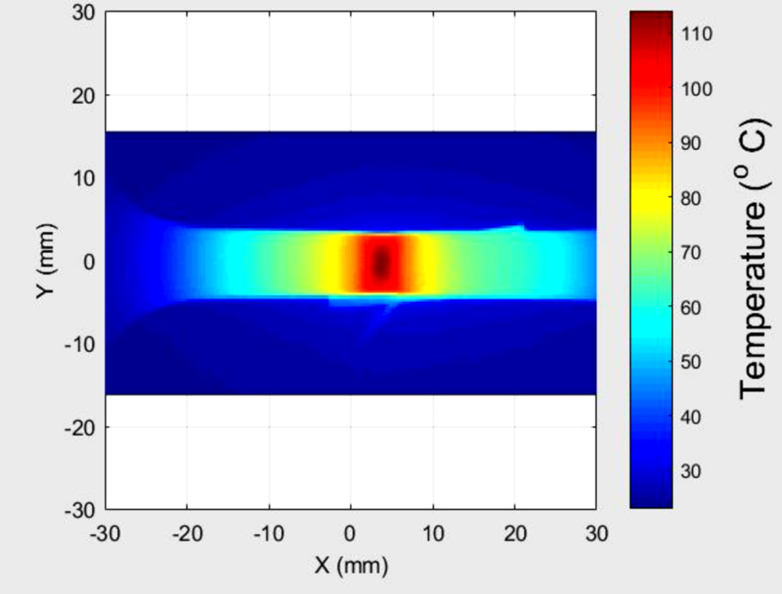
Full-field data is becoming more readily available to analysts

- Calibration of material models to full-field data is a relatively new tool
  - Trying to develop standardized approach
- Full-field data potentially allows for more information to be extracted from a single experiment
  - Reduce number of experiments needed
- We have tools to record full-field displacement and temperature data
  - Digital Image Correlation (DIC)
  - IR cameras
  - Thermophosphors



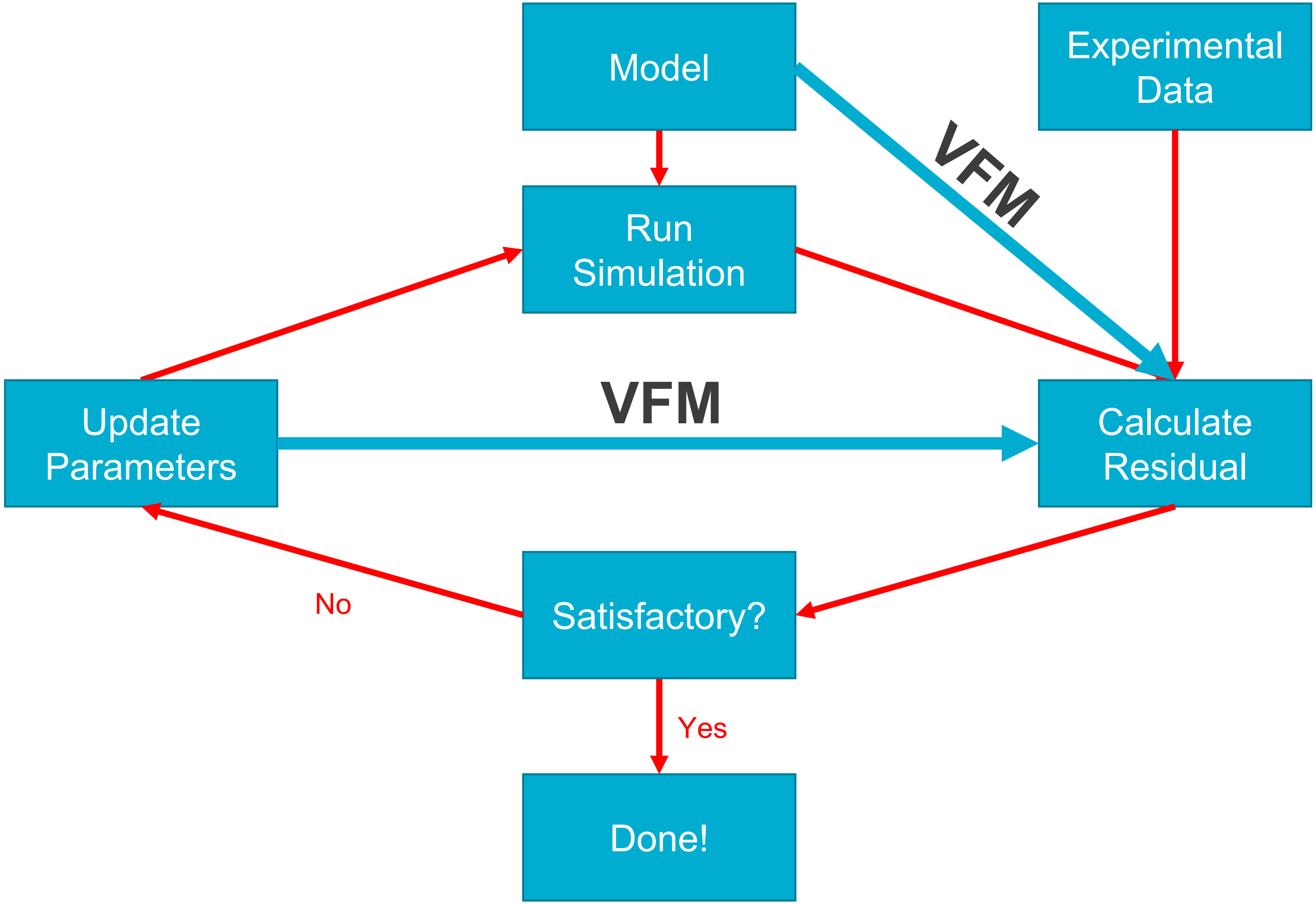






[1]E. Jones, A. Jones, C. Winters

VFM offers fast calibration to full-field data



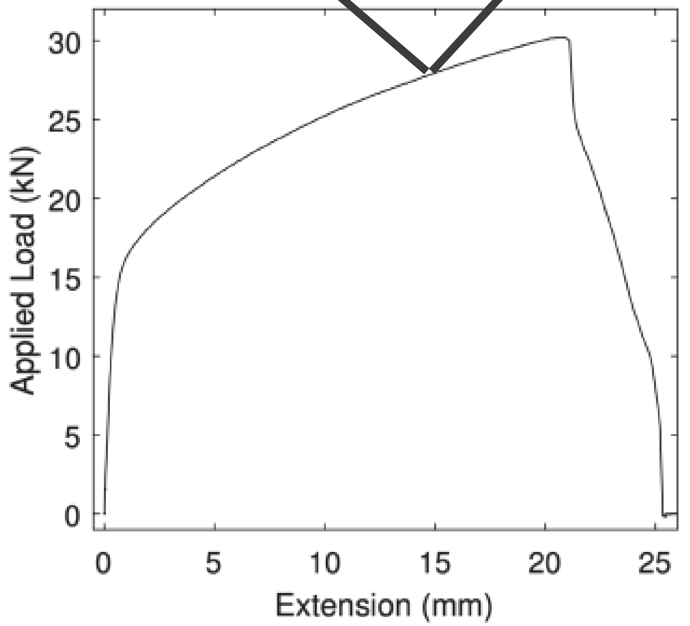
Digital Image Correlation (DIC) Drives the VFM Calibration Loop

$$R = P_{ext} - P_{int}(\underline{p})$$

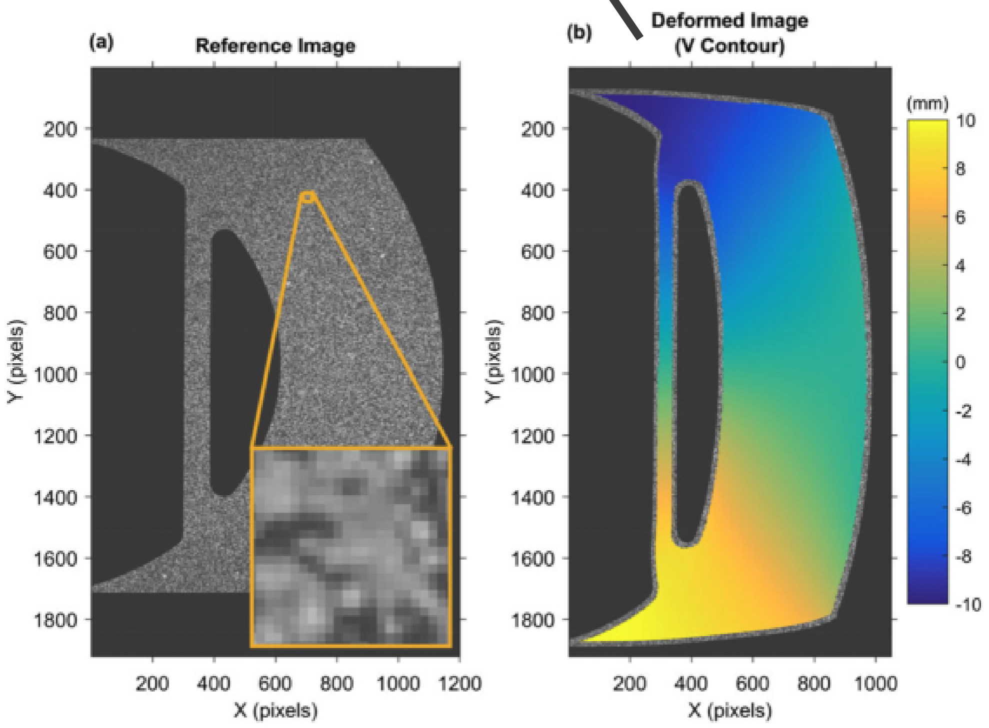
Optimization Tool

$$P_{ext} = \int_{\Gamma} \boxed{\underline{n}\cdot\underline{\underline{\sigma}}}\,\underline{\omega}\, d\Gamma = \int_{\Gamma} \boxed{\underline{\tau}}\,\underline{\omega}\, d\Gamma$$

$$P_{int}(\underline{p}) = \int_{\Omega} \underline{\underline{\sigma}}(\underline{p}, \nabla_s \underline{v}) : \nabla \underline{\omega}\, d\Omega$$



Use load-extension measurements to supply the external forces



Material parameters and image data produce local stress computations

Selection Of Virtual Fields

$$P_{ext} = \int_\Gamma \underline{\tau}\,\underline{\omega}\, d\Gamma \qquad \mathrm{P}_{int}(\underline{p}) = \int_\Omega \underline{\underline{\sigma}}(\underline{p}) : \nabla\underline{\omega}\, d\Omega$$

- Virtual fields in VFM must be kinematically admissible.
- In VFM, virtual fields are assigned prior to the optimization:

Current

- Tested manually defined virtual fields for elastic-plastic problems[2]
  - $\omega_x = \cos\left(\frac{\pi y}{h}\right) \qquad \omega_y = \frac{2y+h}{2h}$

Future

- Optimized virtual fields based on experimental noise[3]
  - Better management of experimental noise
- Optimized virtual fields based on stress/stress sensitivity[4]
  - Focus on regions containing more informative material evolutions

[2] J. Kim, et al., *Exper. Mech.* **2014**, 54, 1189.
[3] S. Avril, et al., *Comp. Mech.* **2004**, *34*(6), 439.
[4] A. Marek, et al., Comp. Mech. **2017**, 60, 409.

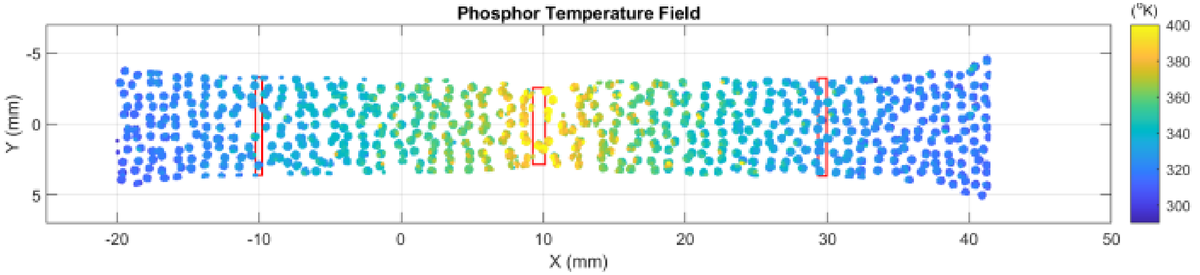
VFM tools expanded to include temperature sensitivity

$$P_{int}(\underline{p}) = \int_{\Omega} \underline{\underline{\sigma}}(\underline{p}, \nabla_s \underline{v}) : \nabla \underline{\omega} \, d\Omega$$

$$P_{int}(\underline{p}, \theta(\underline{x})) = \int_{\Omega} \underline{\underline{\sigma}}(\underline{p}, \nabla_s \underline{v}, \theta(\underline{x})) : \nabla \underline{\omega} \, d\Omega$$

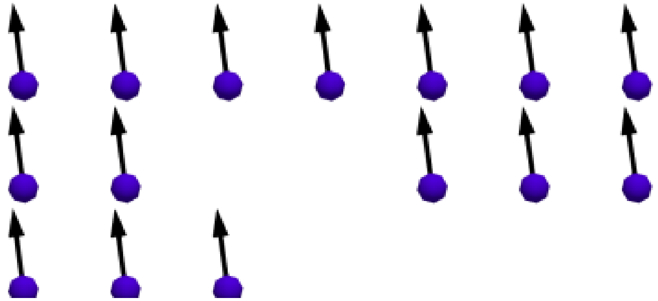
1. Collect experimental data
2. Project data onto mesh
3. Supply mesh to input deck
4. Perform VFM calibration

Digital Image and Temperature Data Projected onto Mesh

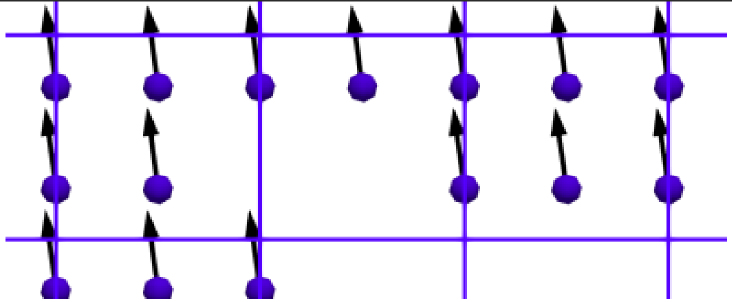


[1]

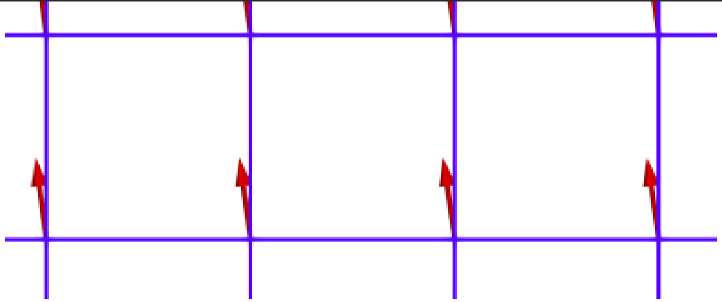
```
mat = Material("matcal", material_file, "j2_plasticity")
projector = CSVFieldSeriesProjector(dic_data_series, reference_meshfile, thickness)
projector.project_fields("Ux", "Uy")
vfm_model = VFMUniaxialTensionModel(mat, projector)
vfm_model.prescribe_temperature('temp')
```



Digital image data received as a point cloud



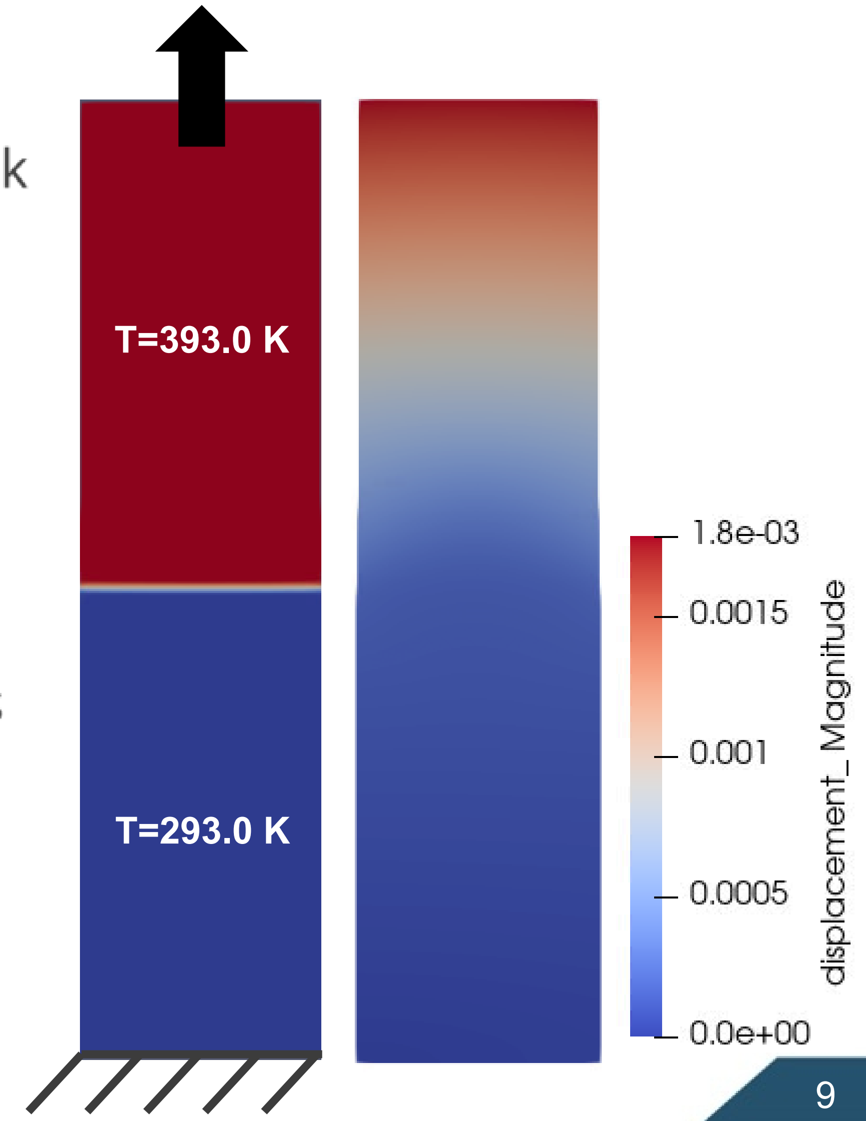
Two dimensional mesh overlayed on point cloud data



l2-least squares projection maps cloud data to mesh

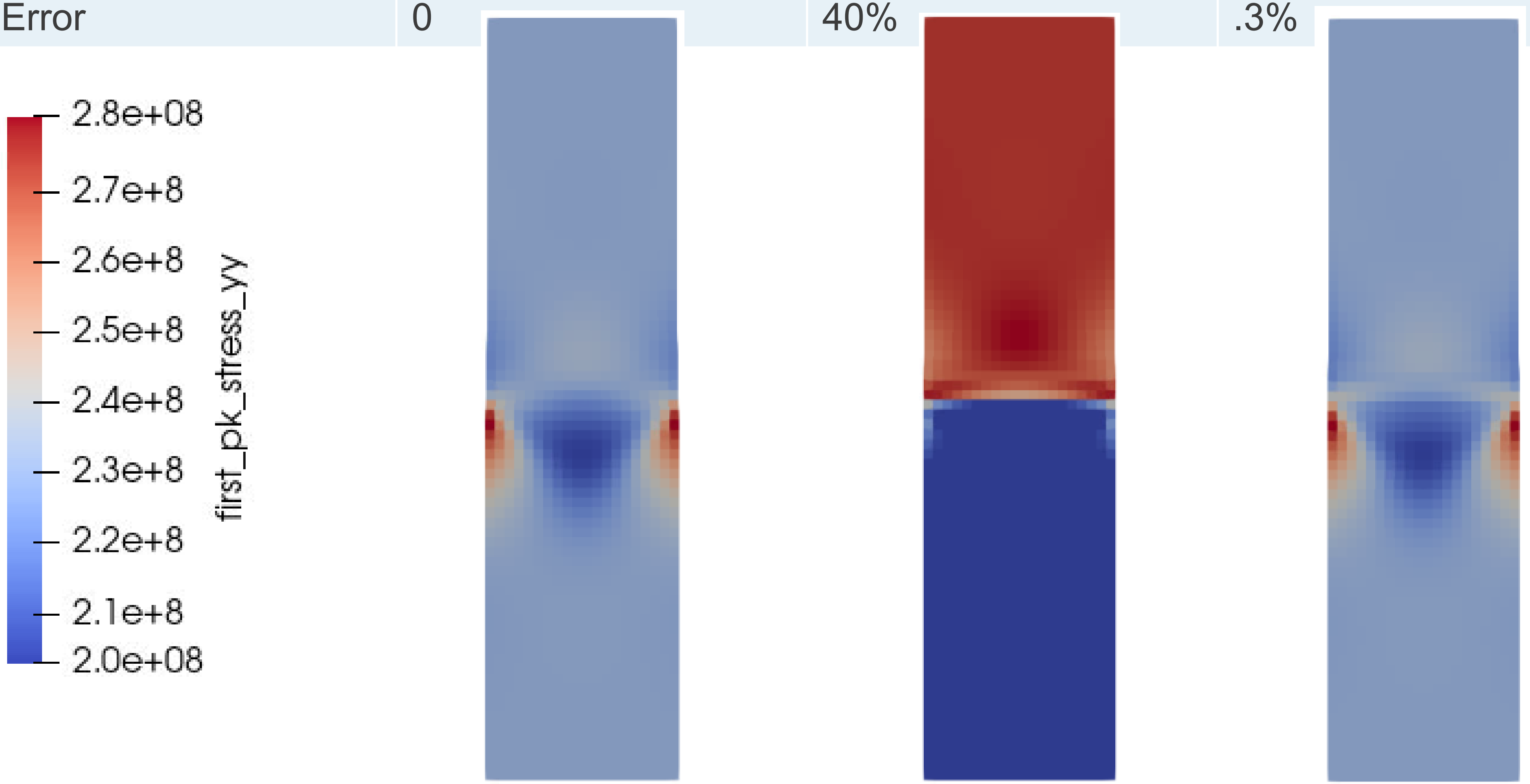
Synthetic uniaxial tension specimen used for testing

- Uniaxial tension test on rectangular bar specimen
  - Prescribed displacement
- Simulated data using j2 plasticity model with Johnson-Cook temperature multiplier
- $\bar{\sigma}(\bar{\epsilon}^p, \dot{\bar{\epsilon}}^p, \theta) = \tilde{\sigma}_y(\bar{\epsilon}^p)\hat{\sigma}(\dot{\bar{\epsilon}}^p)\breve{\sigma}(\theta)$
- $\tilde{\sigma}_y(\bar{\epsilon}^p) = \boxed{\sigma_y} + A(\bar{\epsilon}^p)^n$
- $\hat{\sigma}(\dot{\bar{\epsilon}}^p) = 1$
- $\breve{\sigma}(\theta) = 1 - (\frac{\theta - \theta_{ref}}{\theta_{melt} - \theta_{ref}})^M$
- Fixed values demonstrate temperature-dependent effects
- Calibrated for yield stress using VFM with prescribed temperature



Temperature dependent VFM successfully calibrates yield stress

	Test data	VFM w/o temperature	VFM w/ temperature
Yield stress	2.00e8	1.20e8	1.99e8
Error	0	40%	.3%



Summary

- Full-field data is becoming more readily available to analysts
- VFM offers fast calibration to full-field data by avoiding a full FE solve
- Existing VFM tools in MatCal have been extended to include spatially dependent temperature data
- Effectiveness demonstrated through example calibration

Questions?

Digital Image Correlation (DIC) Drives the VFM Calibration Loop

$$R = P_{ext} - P_{int}(\underline{p})$$

$$P_{int}(\underline{p}) = \int_{\Omega} \underline{\underline{\sigma}}(\underline{p}) : \nabla \underline{\omega} \, d\Omega$$

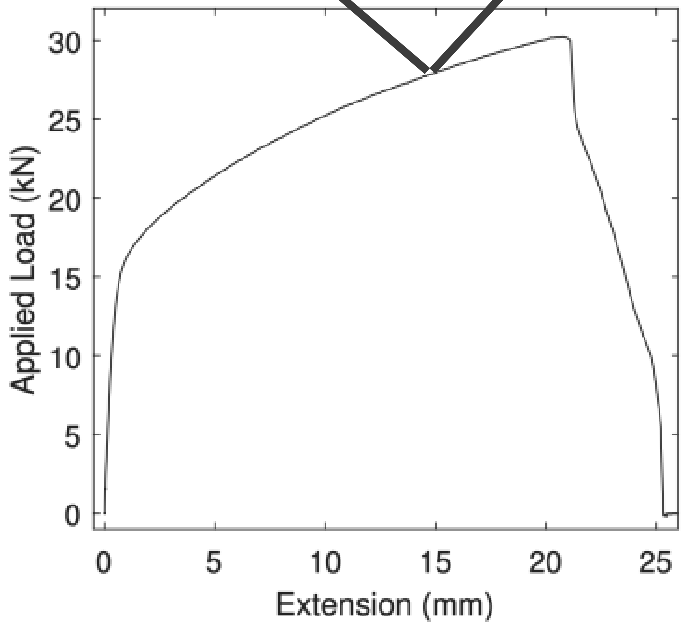
$$\underline{\underline{\sigma}} = \int_t \overset{\circ}{\underline{\underline{\sigma}}} dt \qquad \overset{\circ}{\underline{\underline{\sigma}}} = \underline{\underline{C}}(\underline{p})\underline{\underline{D}}_e$$

$$\underline{\underline{D}}_e = \underline{\underline{D}} - \underline{\underline{D}}_p$$

$$\underline{\underline{D}} = \nabla_s \underline{v} \qquad \underline{\underline{D}}_p = \widehat{\underline{\underline{D}}_p}(\underline{\underline{\sigma}}, \epsilon_p, \underline{p}, \ldots)$$

Optimization Tool

$$P_{ext} = \int_{\Gamma} \underline{n} \cdot \underline{\underline{\sigma}}\, \underline{\omega} \, d\Gamma = \int_{\Gamma} \underline{\tau}\, \underline{\omega} \, d\Gamma$$



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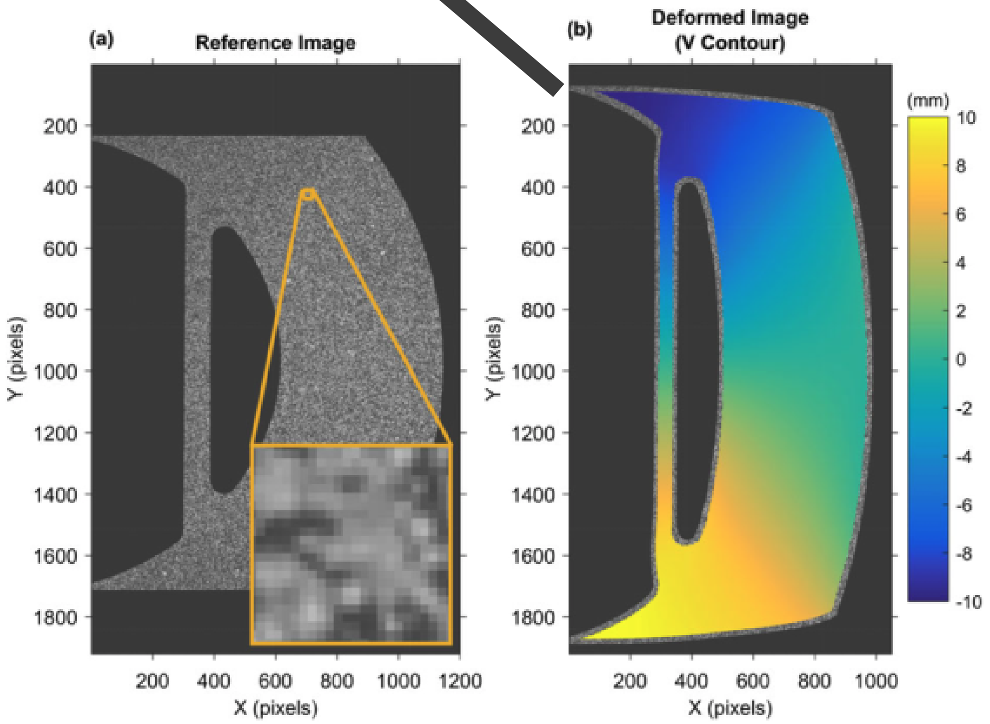

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