

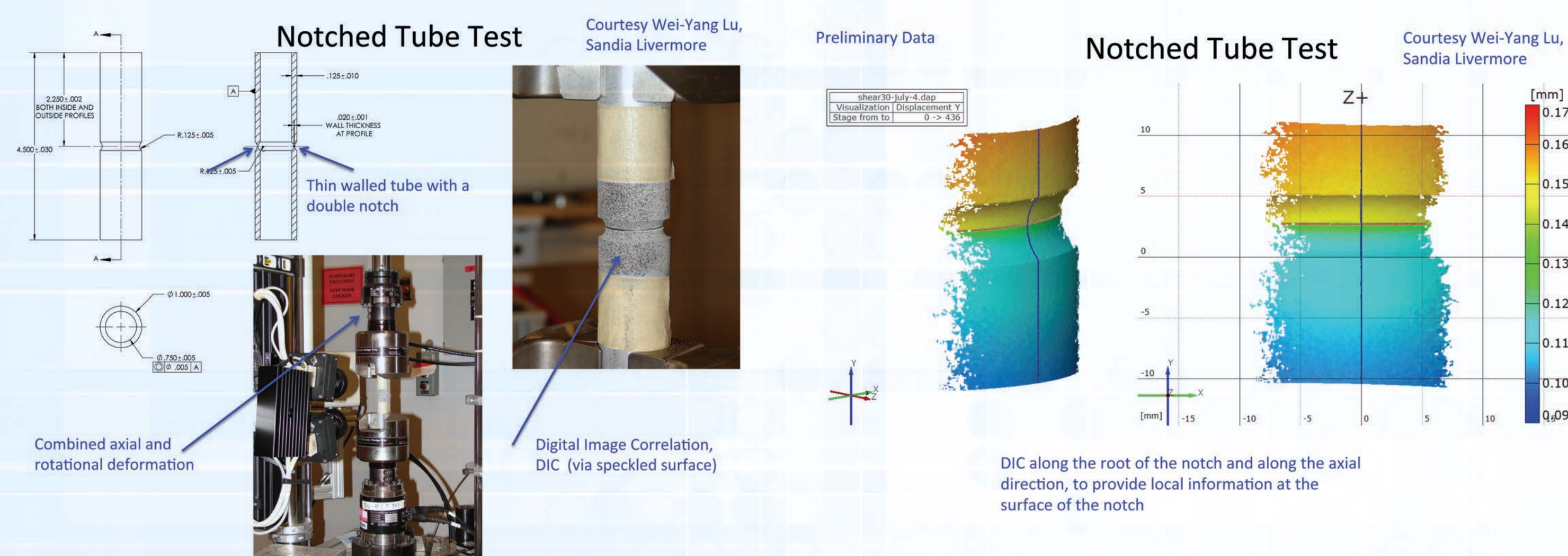
Studying Shear Dominated Ductile Behavior: Experimental and Computational Aspects

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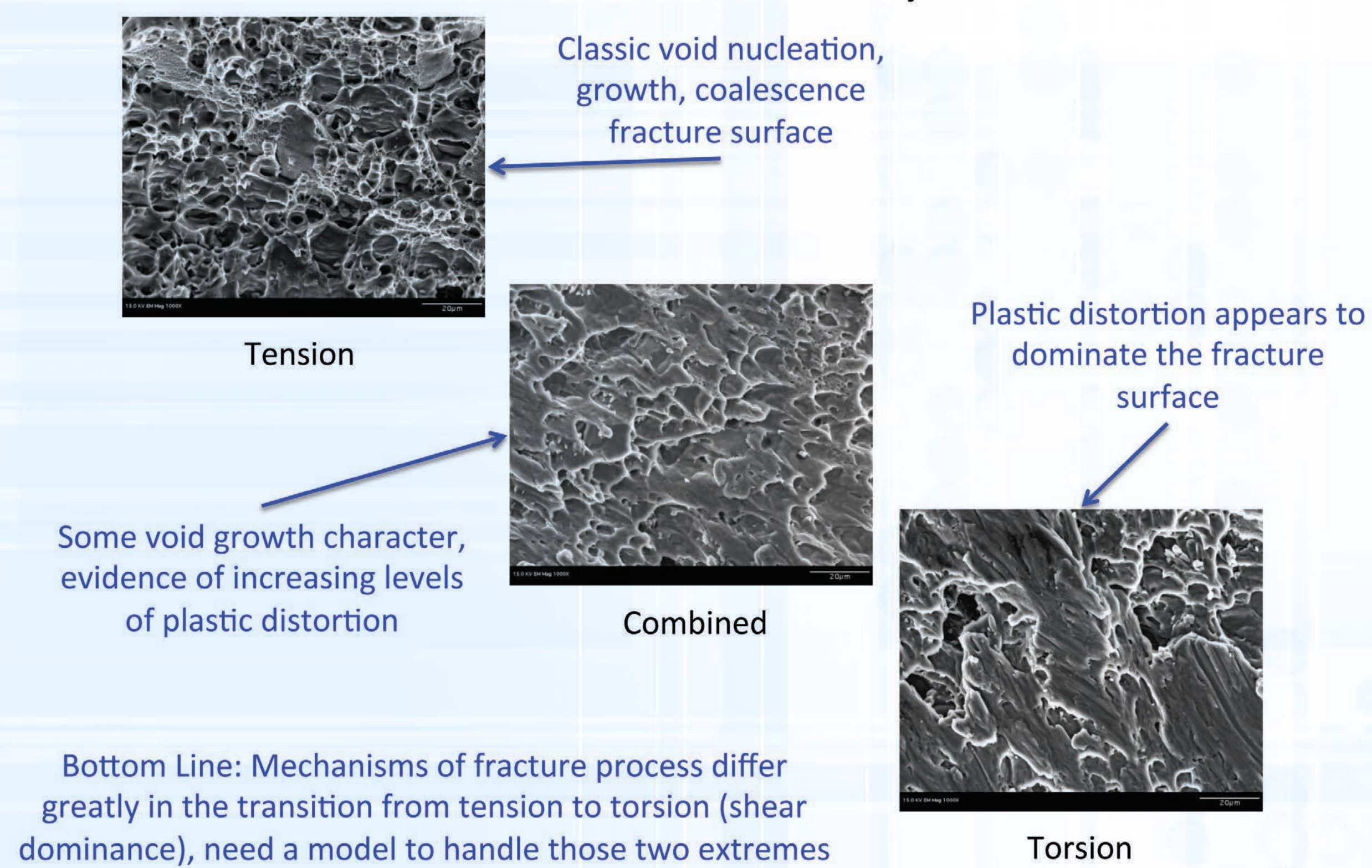
Project Objective

- Develop experimental methods and diagnostics to characterize ductile behavior in shear dominated loading regimes
- Formulate, verify, and validate additional physics introduced for shear dominated stress states

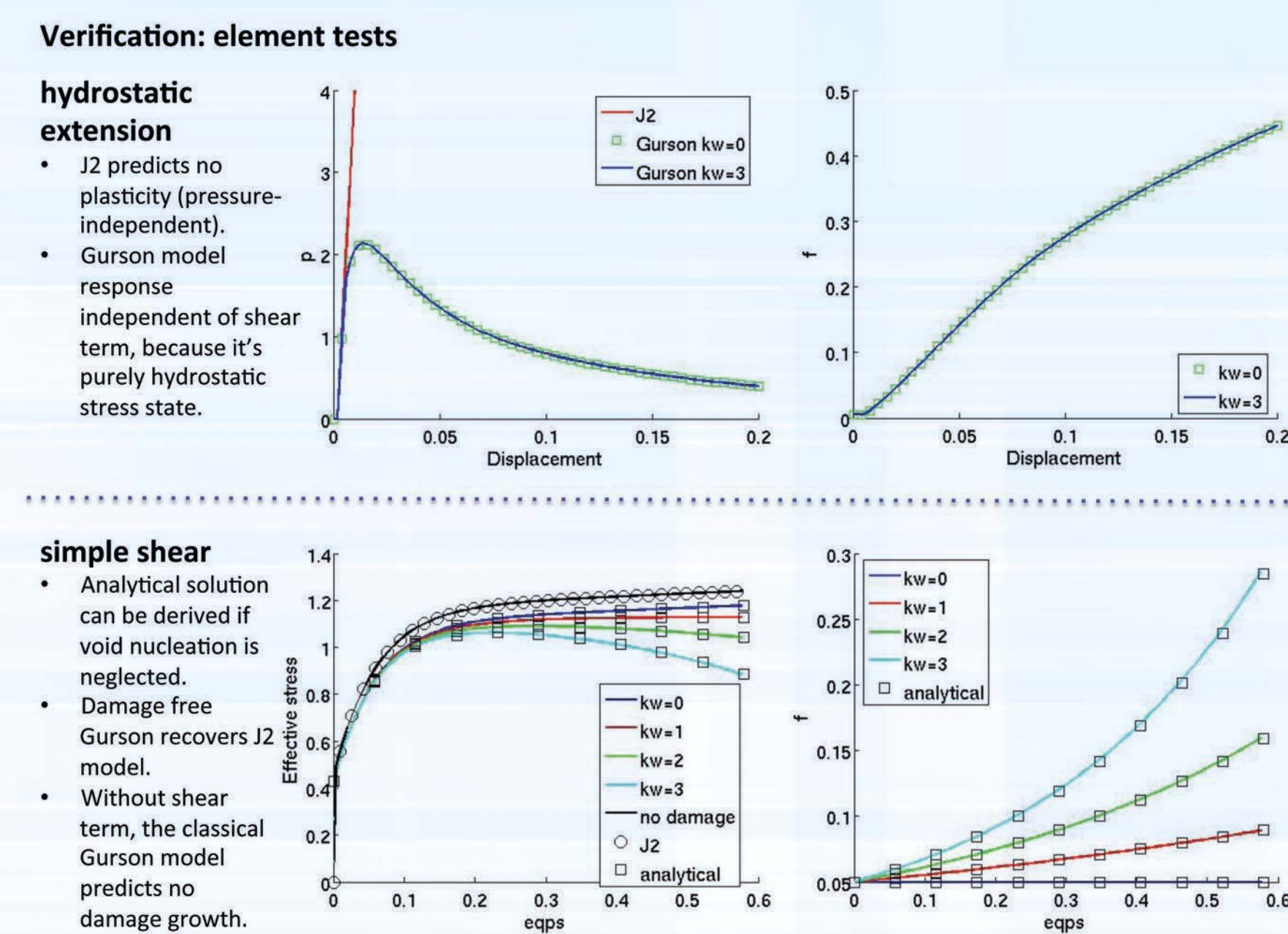
Experiment and Failure Surface



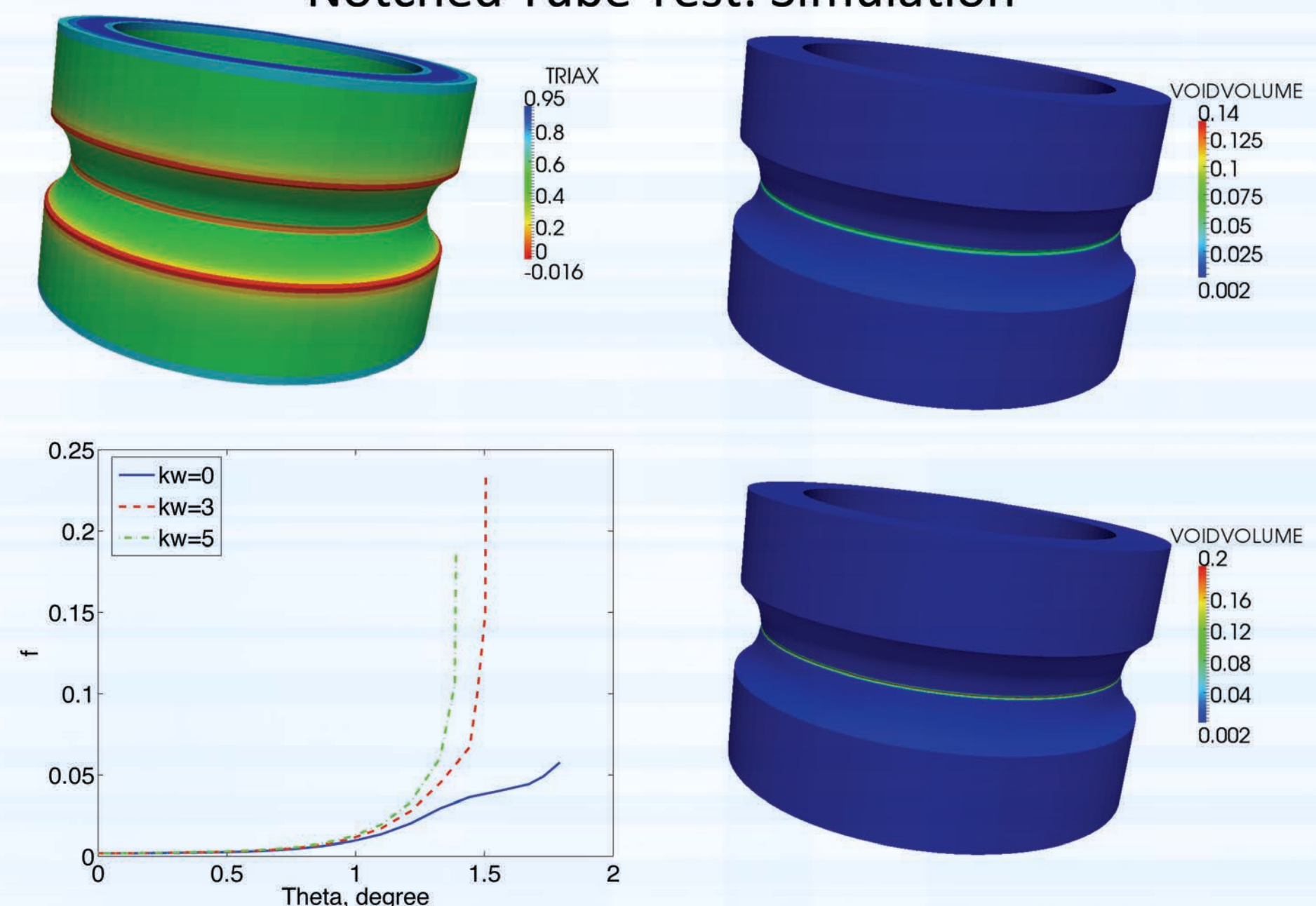
Failure Surface Analysis



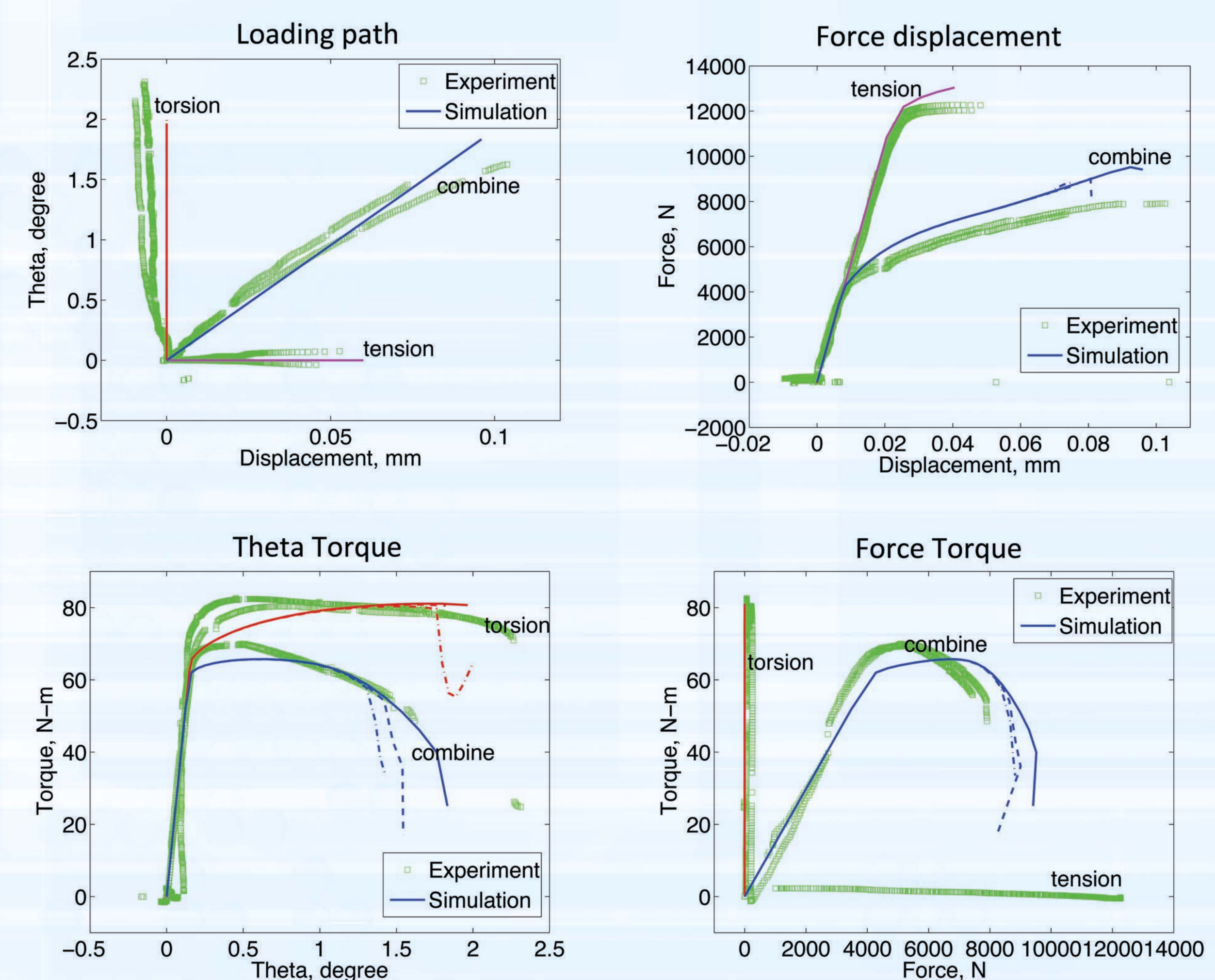
Model Verification



Preliminary Simulation Results



Preliminary Validation



Failure Model

Classical Gurson Damage Model

The macroscopic yield surface

$$\Phi(\tau, Y, f) = \frac{3}{2} \frac{s : s}{Y^2} + 2q_1 f \cosh\left(\frac{3q_2 p}{2Y}\right) - q_3 f^2 - 1 = 0$$

← pressure dependent

Shear Modification

Shear-modified damage growth law

Introducing third-stress-invariant dependent
[Nahshon-Hutchinson 2008, Tvergaard-Nielsen 2010, Xue-Wierzbicki 2008]

$$\omega(\tau) = 1 - \left(\frac{27J_3}{2\tau^3}\right)^2 \quad \text{where} \quad \tau_e := \sqrt{3/2} \|s\| \quad \text{effective stress}$$

$J_3 := \det(s)$ third stress invariant

$$\dot{f}_g = (1-f) \text{tr} \left(\gamma \frac{\partial \Phi}{\partial \tau} \right) + k_\omega f \frac{\omega(\tau)}{\tau_e} s : \left(\gamma \frac{\partial \Phi}{\partial \tau} \right)$$

k_ω material constant that sets the magnitude of the damage growth rate in pure shear states

Numerical Implementation and Integration

Strain energy function

$$\Psi = \Psi^{\text{vol}}[J_e] + \Psi^{\text{iso}}[\hat{b}_e]$$

The volumetric and isochoric parts

$$\Psi^{\text{vol}}[J_e] = \frac{1}{2} \kappa (\ln J_e)^2, \quad \Psi^{\text{iso}}[\hat{b}_e] = \frac{1}{4} \mu \ln \hat{b}_e : \ln \hat{b}_e$$

Local unknown vector (4x1)

$$\mathbf{X} = \{p, f, \varepsilon_q, \Delta\gamma\}$$

Local nonlinear system of equations (4x1)

$$R_1(\mathbf{X}) = \frac{1}{2} s : s - \frac{1}{2} \psi Y^2$$

$$R_2(\mathbf{X}) = p - p^{\text{tr}} + q_1 q_2 \kappa \Delta\gamma Y f \sinh(v)$$

$$R_3(\mathbf{X}) = f - f_n - q_1 q_2 (1-f) \Delta\gamma Y f \sinh(v) - \sqrt{\frac{2}{3}} \Delta\gamma k_\omega f \omega(\tau) \|s\| - A(\varepsilon_q - \varepsilon_{q(n)})$$

$$R_4(\mathbf{X}) = \varepsilon_q - \varepsilon_{q(n)} - \frac{\Delta\gamma}{Y(1-f)} (s : s + q_1 q_2 p Y f \sinh(v))$$

Iterative solution procedure like the Newton's method requires consistent linearisation, therefore the computation of local Jacobian matrix (4x4) $\mathbf{J} = \partial \mathbf{R} / \partial \mathbf{X}$

Analytic sensitivities are achieved via **Forward Automatic Differentiation (FAD)**

Dissipation inequality

$$D = -\tau : \left[-\frac{1}{2} L_v(b_e) \cdot b_e^{-1} \right] - h \dot{q} \leq 0$$

h hardening function
 q internal variable

Iterative method such as Newton's method requires consistent linearization. challenge lies in obtaining local Jacobian matrix

Conclusions and Future Work

- Experimental method and modeling effort for shear dominance shows promise
- Full validation study required
- Future work includes testing methodology for other alloys relevant to Sandia's mission

References

- SAND Number: 2012-8703C, SES 2012, October 10-12, 2012, Atlanta, GA - Qiushi Chen, Jakob T. Ostien, Wei-Yang Lu, "Modified Gurson Model for Shear-Dominated Ductile Failure Simulation - Numerical Integration, V&V"
- SAND Number: 2012-9888C, ASME IMECE 2012, November 13, 2012, Houston, TX - Qiushi Chen, Jakob T. Ostien, Wei-Yang Lu, "On the Numerical Simulation of Ductile Failure in Shear Dominated Stress States Using a Modified Finite Deformation Gurson Model"

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