Development of Advanced DIC Analysis Methods for CAE Forming and Crash Models

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GREAT DESIGNS IN STEEL™

Overview

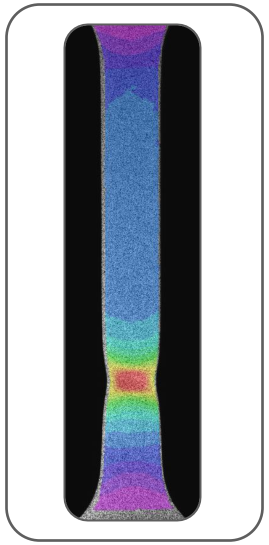
- Material Model Development
- Methodology for DIC Data → Material/Fracture Model
- DIC Lengthscale Analysis → Trends and recommendations for users
- DIC Data Processor Tool → GUI, Analysis scripts

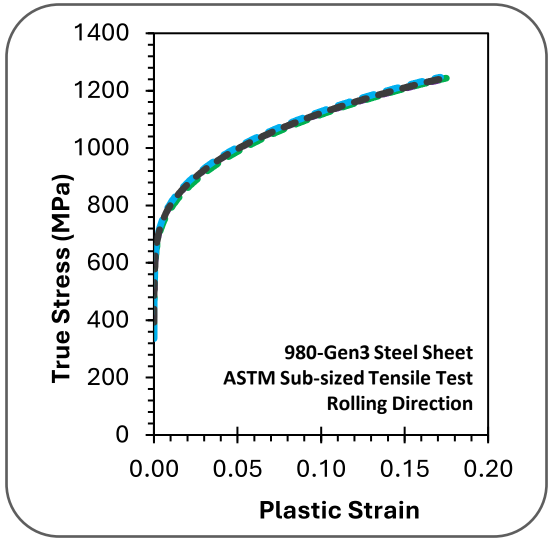
Material Card Development

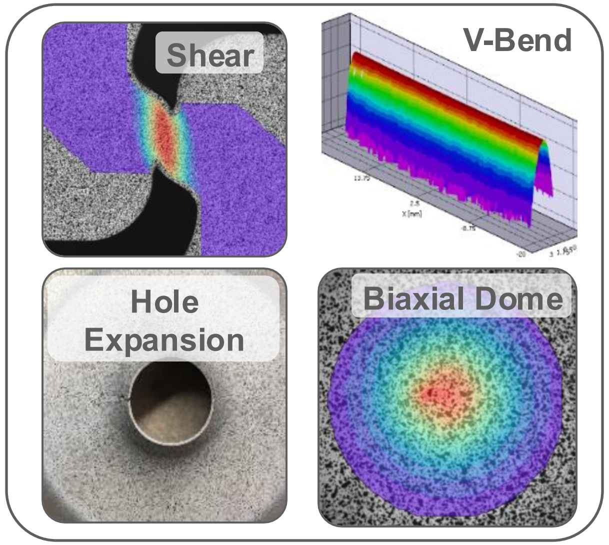
- Material development will always be company, analyst, software, budget specific
- Immediate standardization is not the target but reaching a general consensus is achievable
- Focus on areas of overlap and standardization of DIC for coupon tests, data structure and develop easy-to-use analysis scripts

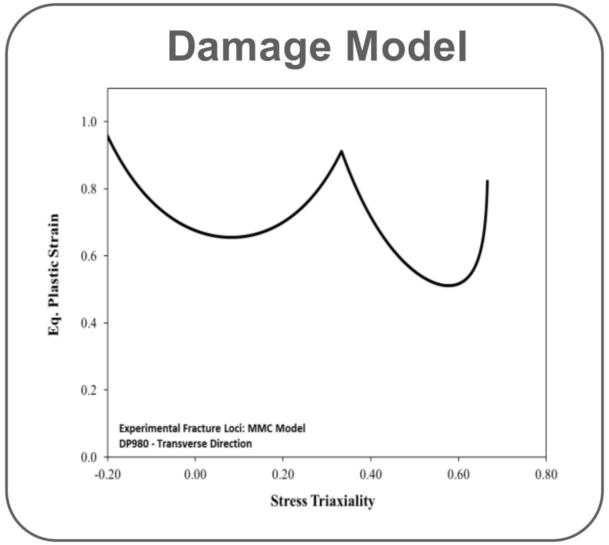
Constitutive Hardening Characterization

Fracture Characterization





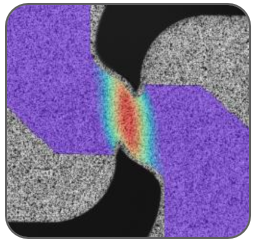




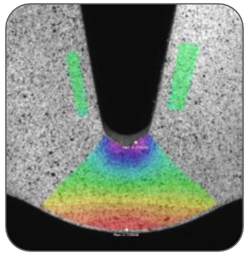
Direct Method for Proportional Fracture Characterization

- Direct method selects coupon tests without necking to use DIC to construct the fracture locus

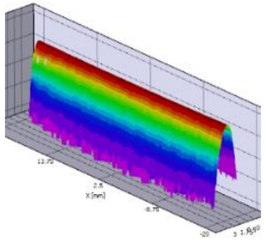
1. Plane Stress Characterization Tests for Sheet



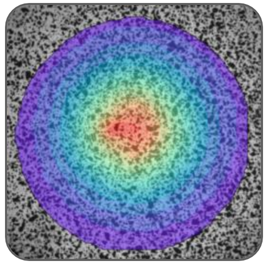
Shear



In-Plane Bend



V-Bend



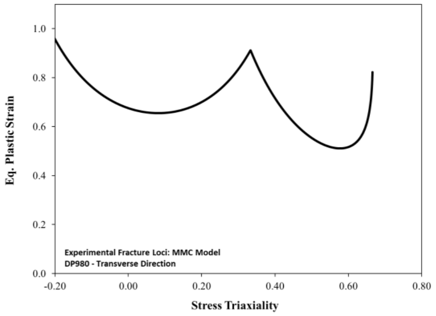
Biaxial Dome

2. Experimental Fracture Locus

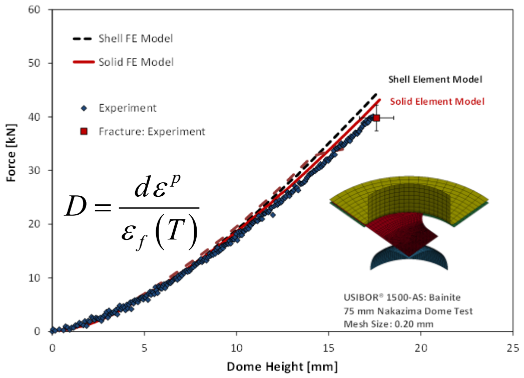
- Assume failure locus form & calibrate with 4 points

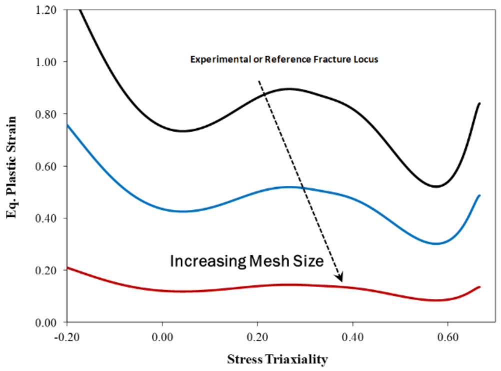
$$\varepsilon_f^{\exp} = \varepsilon^{UW}\left(T, a_{1-4}\right) \longrightarrow$$

Physically meaningful
fracture locus: Not an FE construct



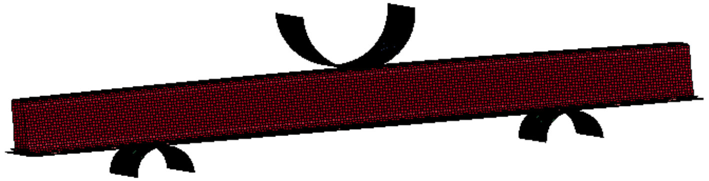
3. Stress State Dependent Regularization





4. Apply to Structural Components

Static & Dynamic Conditions

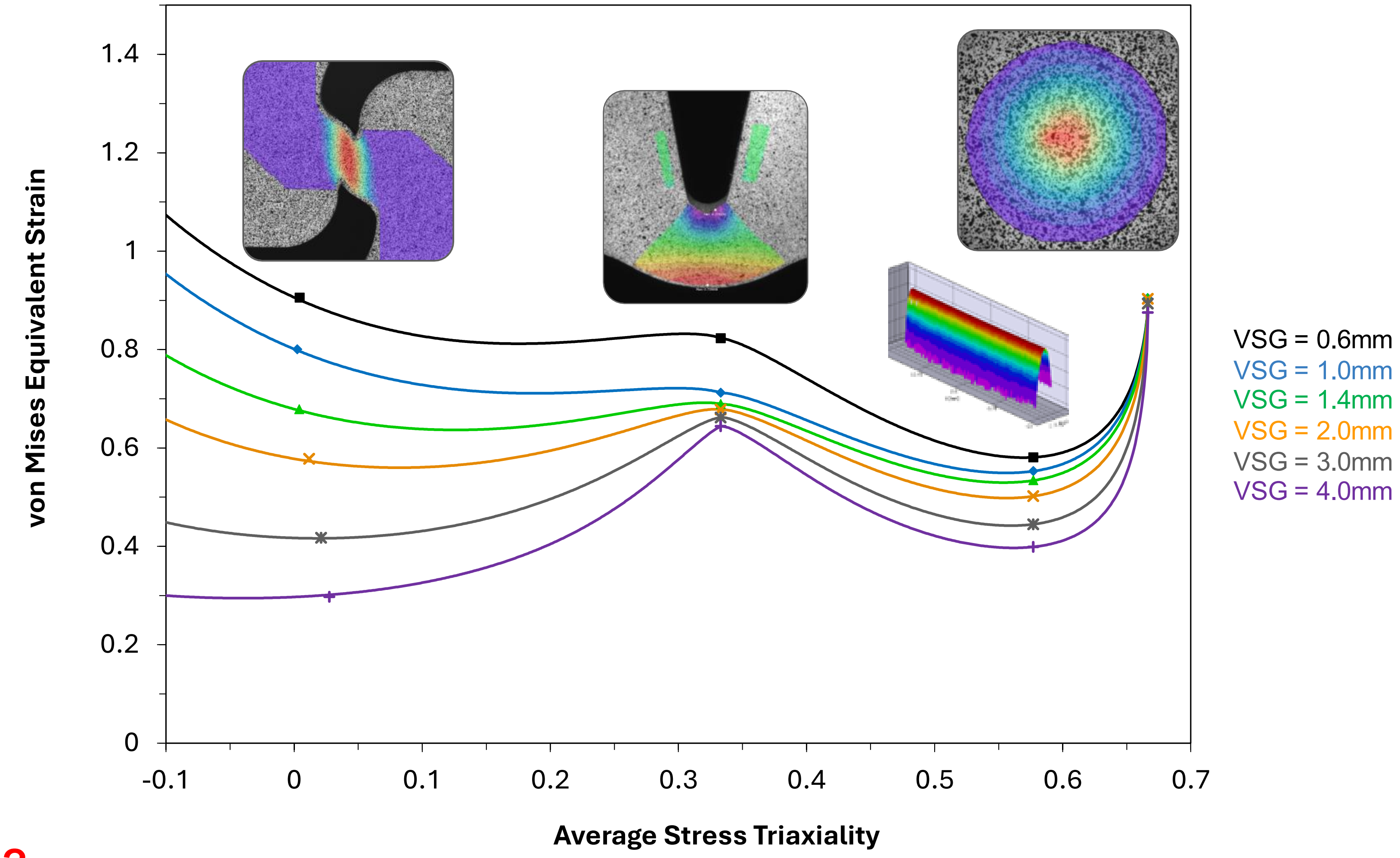


Ex: 3-Point Bend & Axial Crush

Variation of Fracture Loci with Test Coupons and VSG: 980-GEN3

“Proportional” fracture loci:

- Shear,
- In-Plane Bend,
- VDA Bend,
- Biaxial R10mm

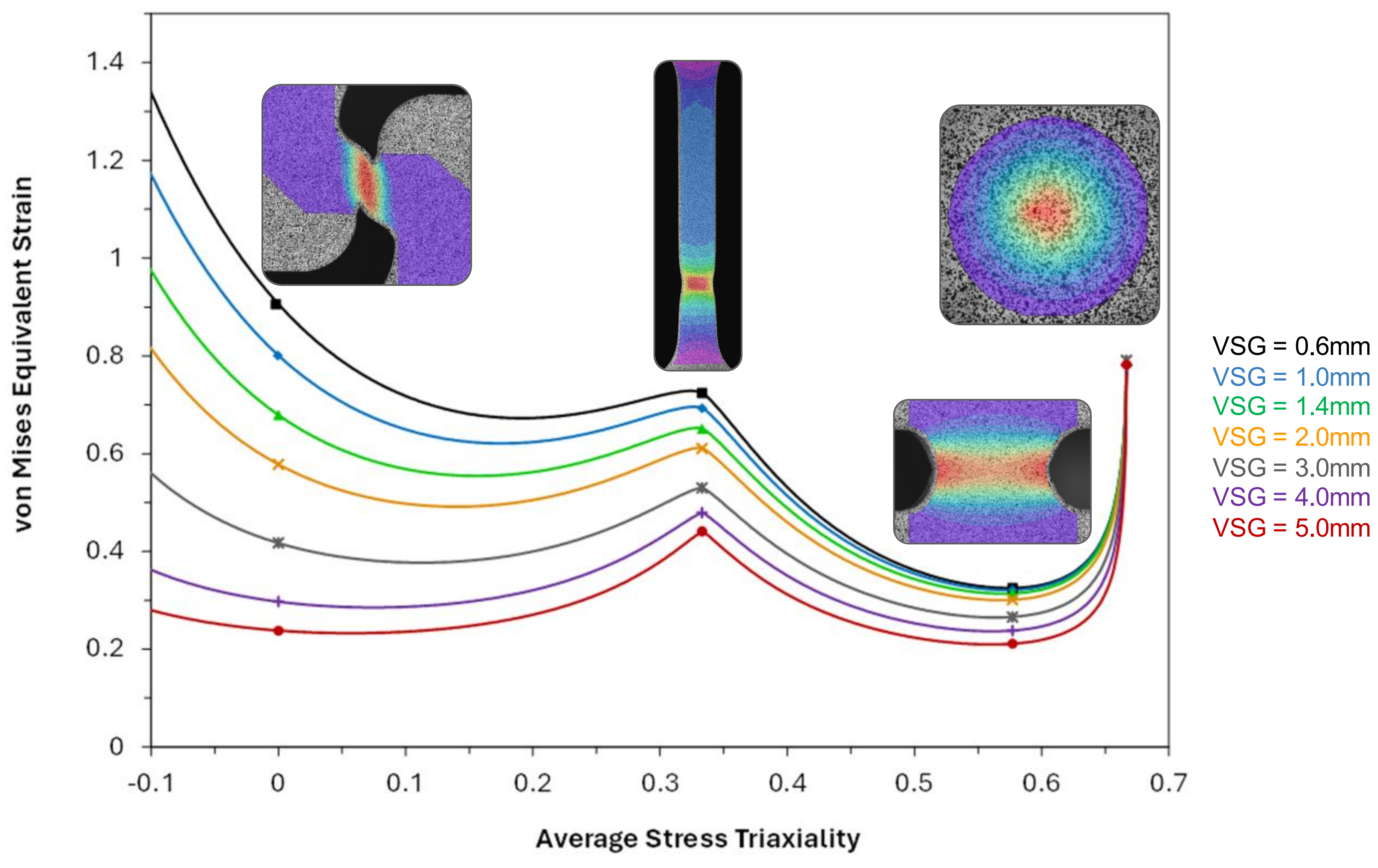


Which VSG does your testing use?

Variation of Fracture Loci with Test Coupons and VSG: 980-GEN3

“Conventional” fracture loci:

- Shear,
- ASTM-E8,
- Plane Strain Notch,
- Biaxial R50mm



Project Overview

Goal:

Implement consistent material characterization practices using digital image correlation with emphasis upon supporting CAE simulation and correlation.

Impact:

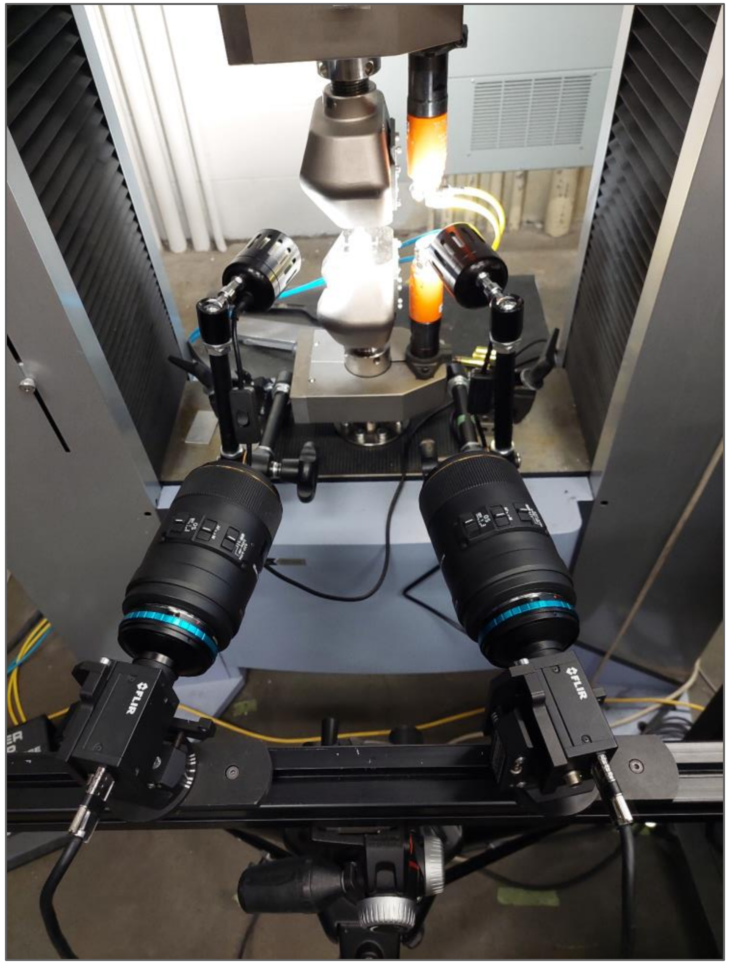
This project is expected to:

- Establish a consensus on DIC material test procedures for material characterization
- Support the creation of approved forming and fracture material cards
- Support machine learning based research programs

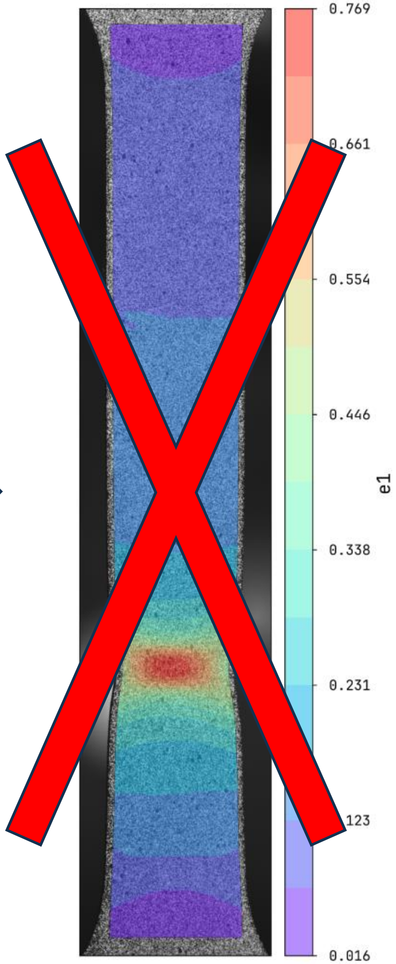
Common Use of DIC Data in Material Model Calibration

What are we doing with the data?

DIC Setup

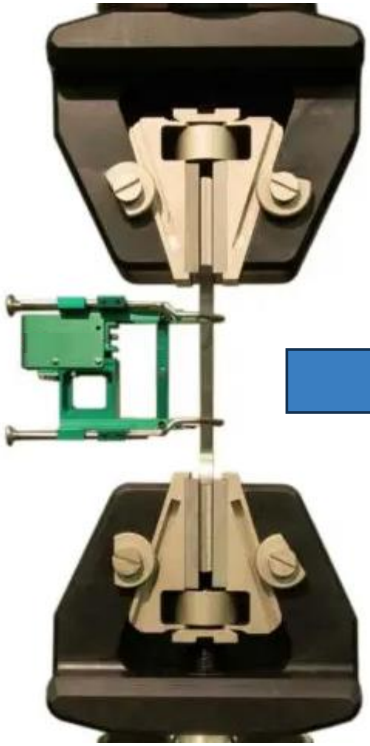


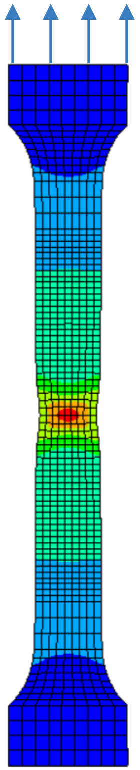
Full-field Surface
Data Acquired



Typical Usage in Inverse Modelling
→ DIC only for Displacement

Local strains from model

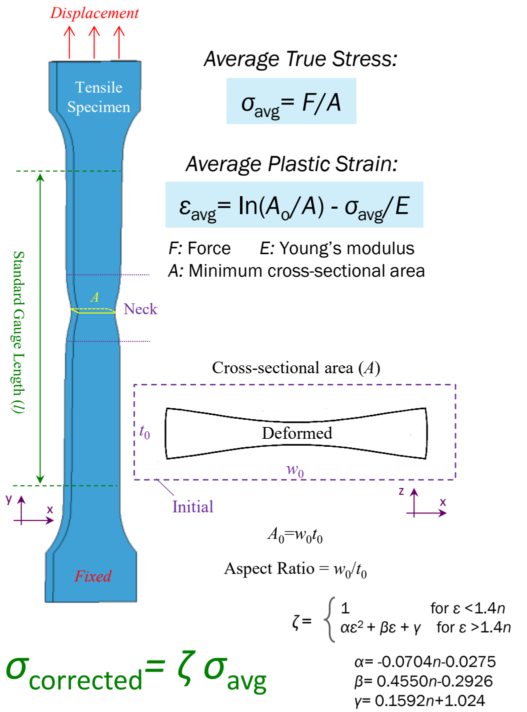




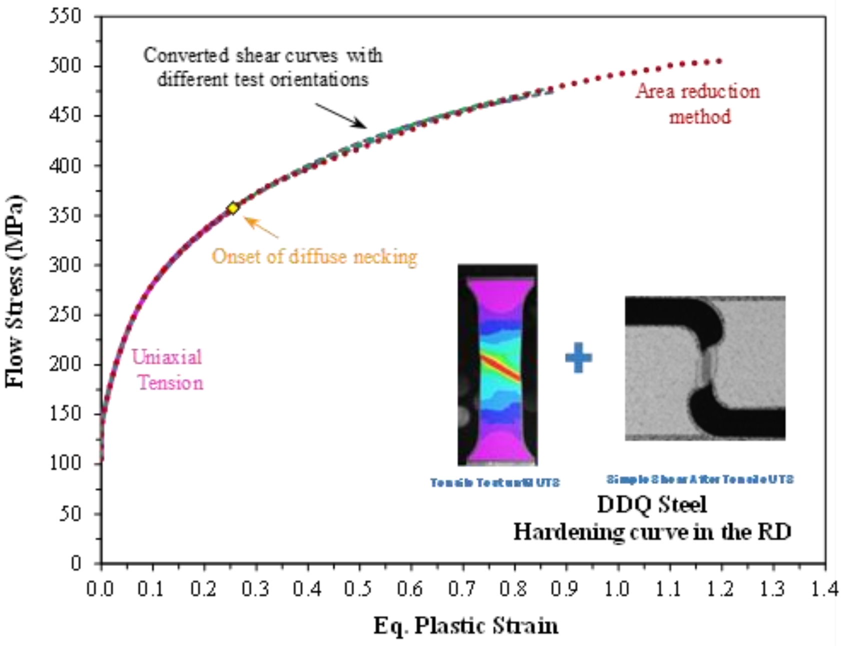
Using the DIC Data: Flow Curves to Large Strains

- UW developed ARM and Shear-based methodology to leverage DIC strain data
- Efficient method to characterize hardening without inverse FEA
- **Experimental true stress – plastic strain curve can be directly imported to LS-Dyna**

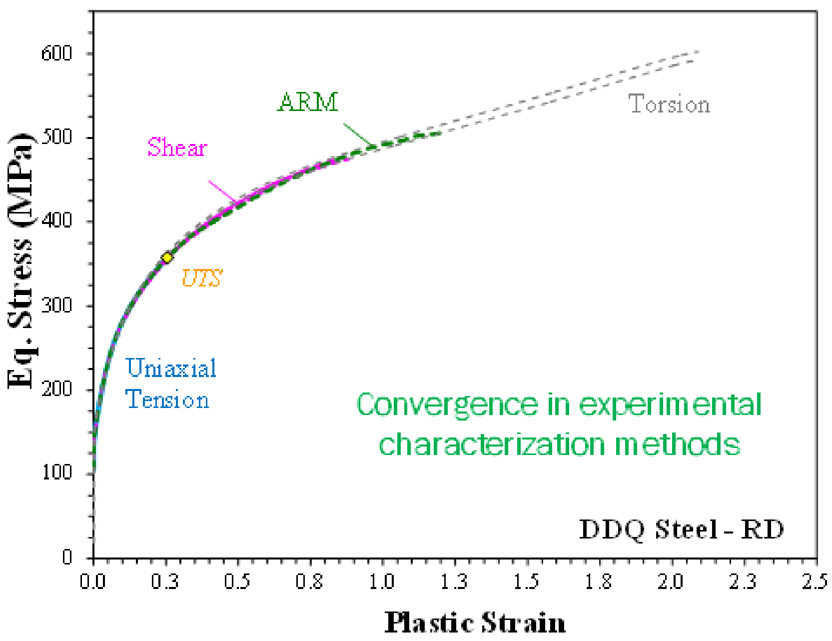
Area Reduction Method (ARM)



Shear Conversion Method



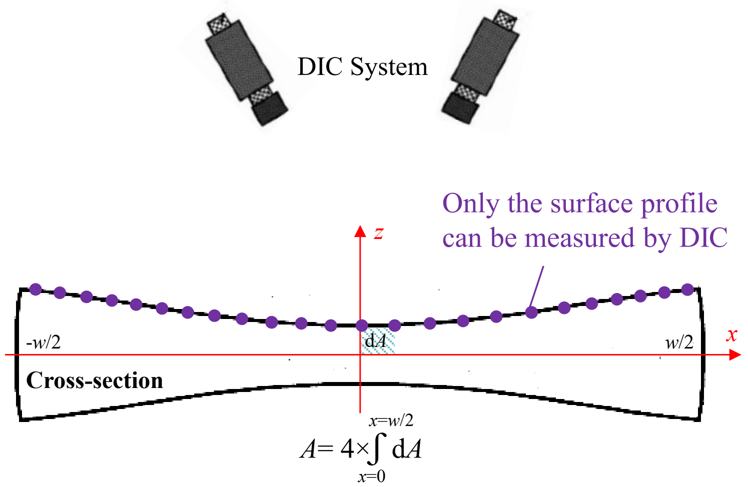
Comparison with In-Plane Torsion Shear Conversion: Tests done at ETH Zurich by Prof. Dirk Mohr

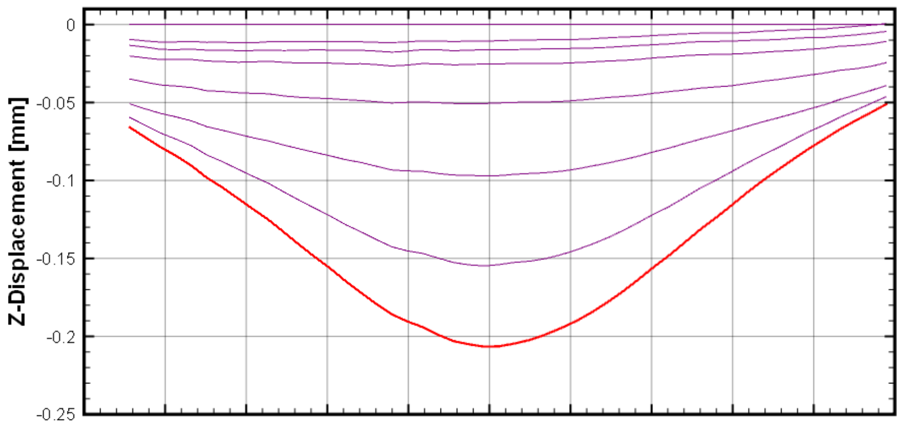


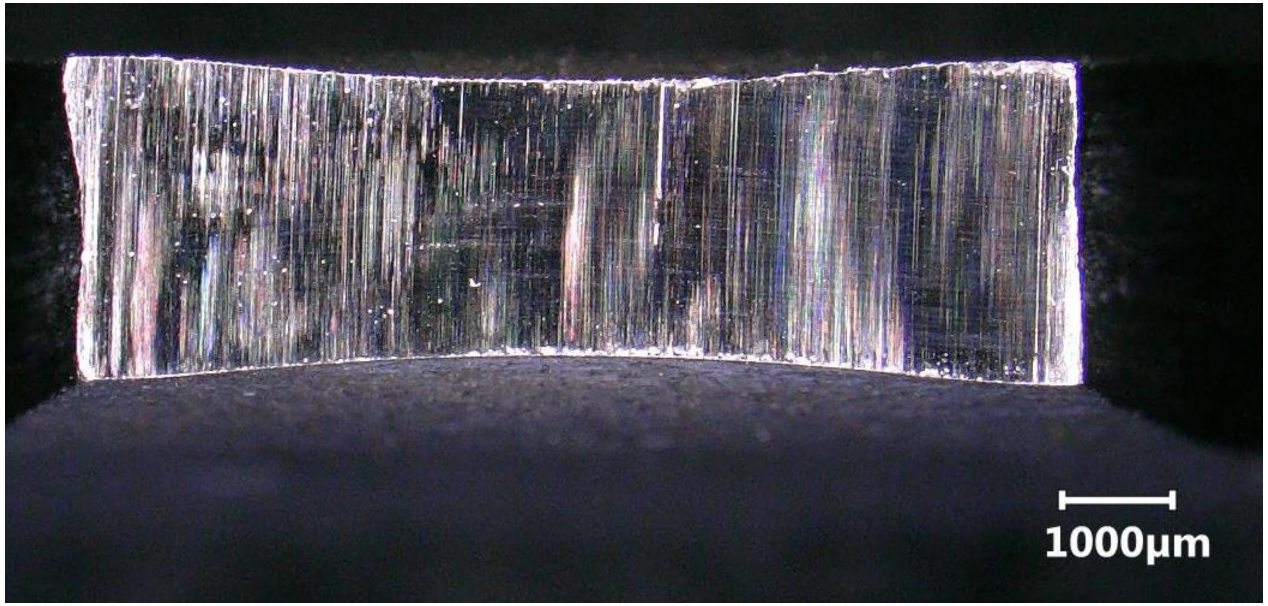
A. Abedini, et al. (2022), Forces in Mechanics 7
Abedini A, Noder J, Kohar C, Butcher C, *Mechanics of Materials*, 2020, 148:103419

Application of ARM to 980GEN3 Steel

- The cross-sectional area was measured directly using stereo DIC using surface co-ordinates.
  - Accurate to 1-2% strain



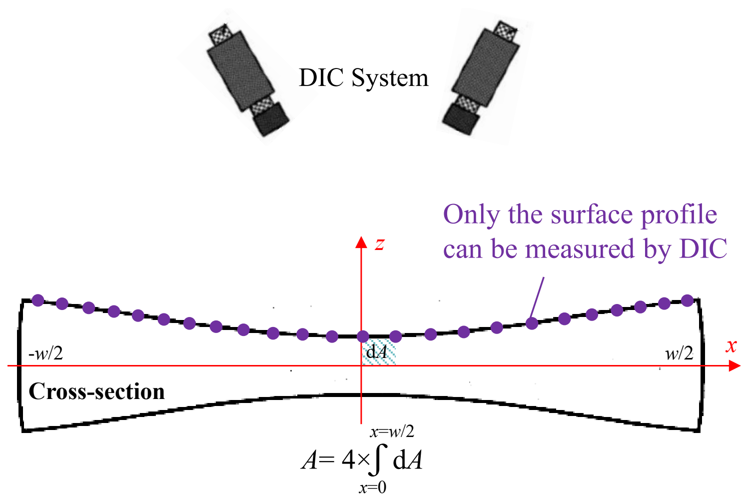


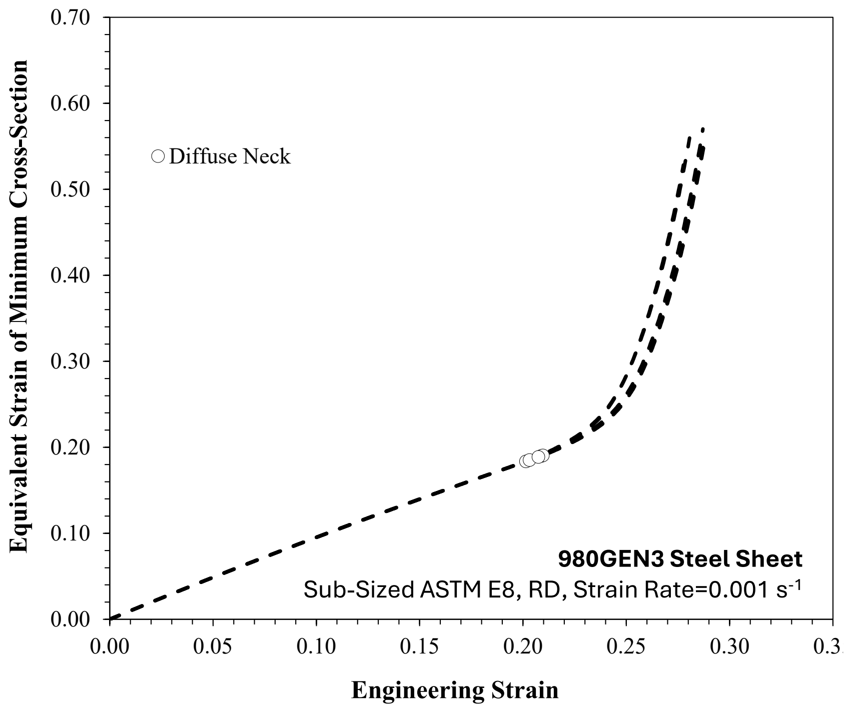


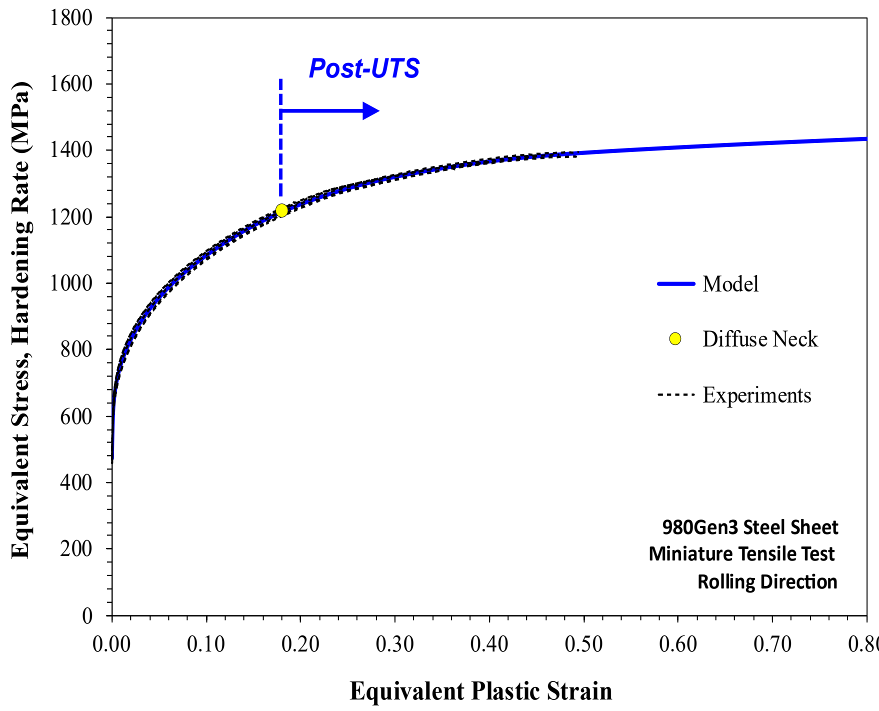
	Initial	Cross-Section Measurement		DIC Z-Displacement		Difference
Repeat	A_0 [mm^2]	A_f [mm^2]	ε_{Area} [-]	A_f [mm^2]	ε_{Area} [-]	$\Delta\varepsilon_{Area}$ [-]
1	8.801	6.647	0.281	6.726	0.269	**0.012**
2	8.801	5.848	0.409	5.749	0.425	**-0.016**
3	8.793	6.181	0.353	6.138	0.359	**-0.006**

Application of ARM to 980GEN3 Steel

- The cross-sectional area was measured directly using stereo DIC using surface co-ordinates.
- Local eq. strain of minimum cross-section area goes to up to ~2.5x the uniform elongation
- **The ARM gives eq. stress response to ~50% strain for 980GEN3 steel.**





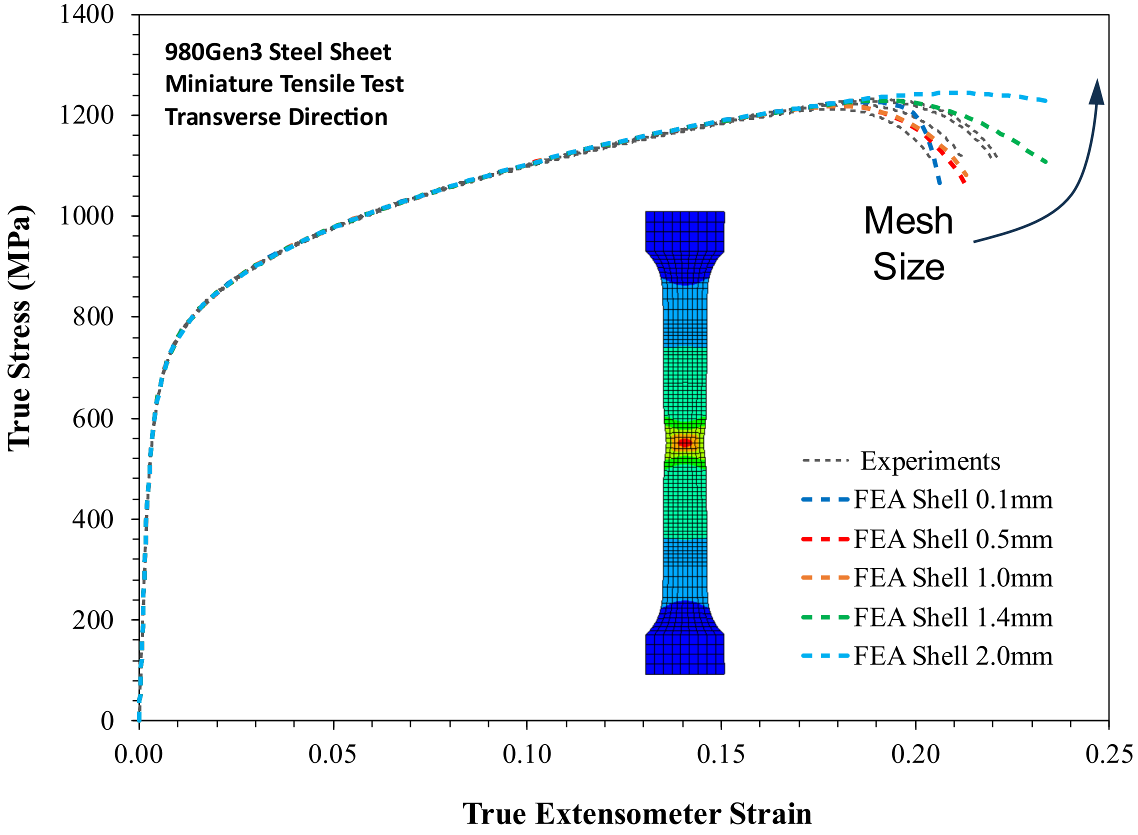


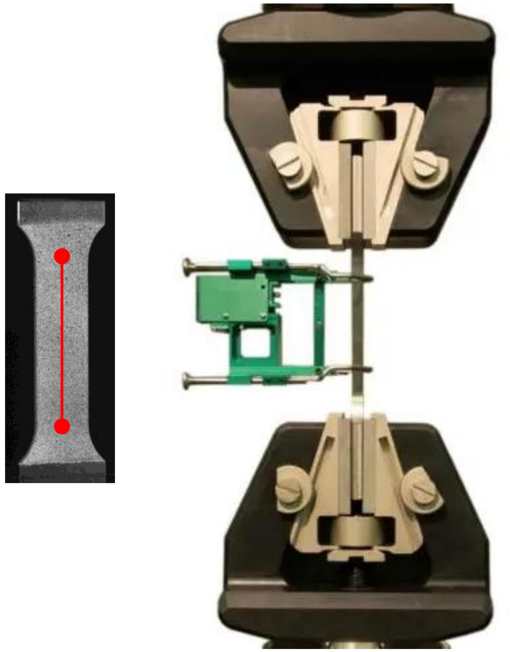
Abedini, A., Narayanan, A. and Butcher, C., 2022. An investigation into the characterization of the hardening response of sheet metals using tensile and shear tests with surface strain measurement. *Forces in Mechanics*, 7, p.100090.

Uniaxial Tension DIC Data: Engineering Stress-Strain

- Common CAE correlation uses global force-displacement response for a tensile test (Engineering Stress-Strain)
  - Treats the DIC data as an expensive extensometer
  - DIC used for qualitative strain contours

$$\sigma_{true} = \frac{F}{A_0}\left(1 + \epsilon_{eng}\right)$$

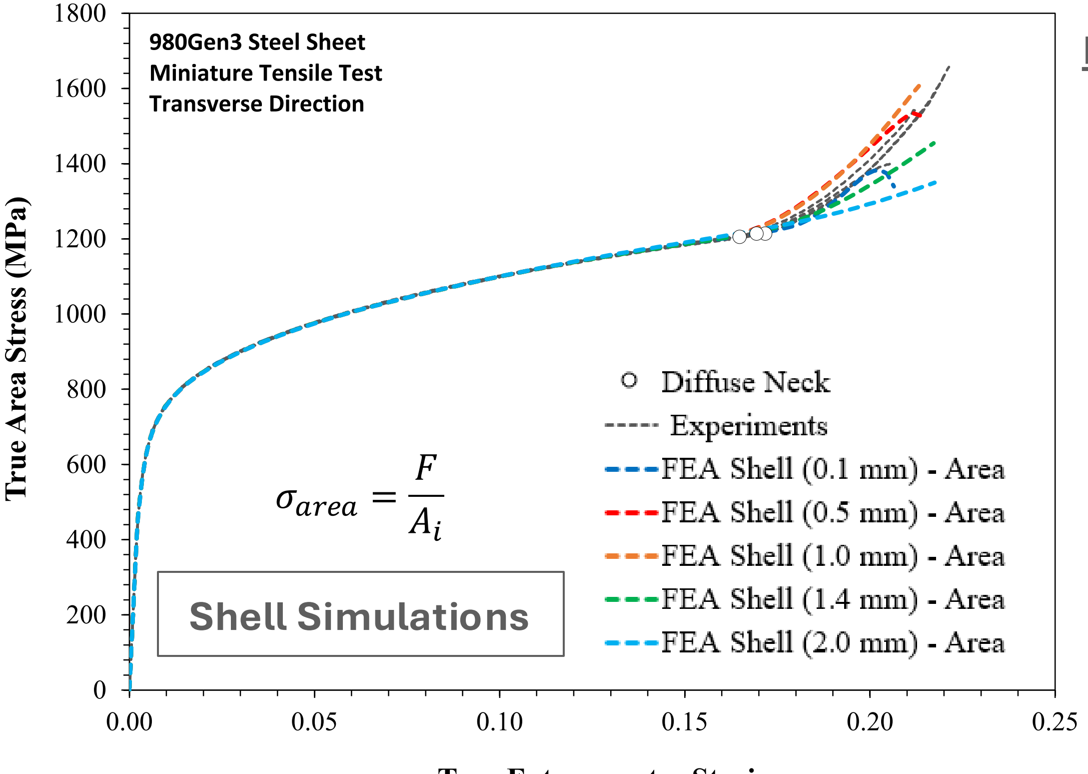




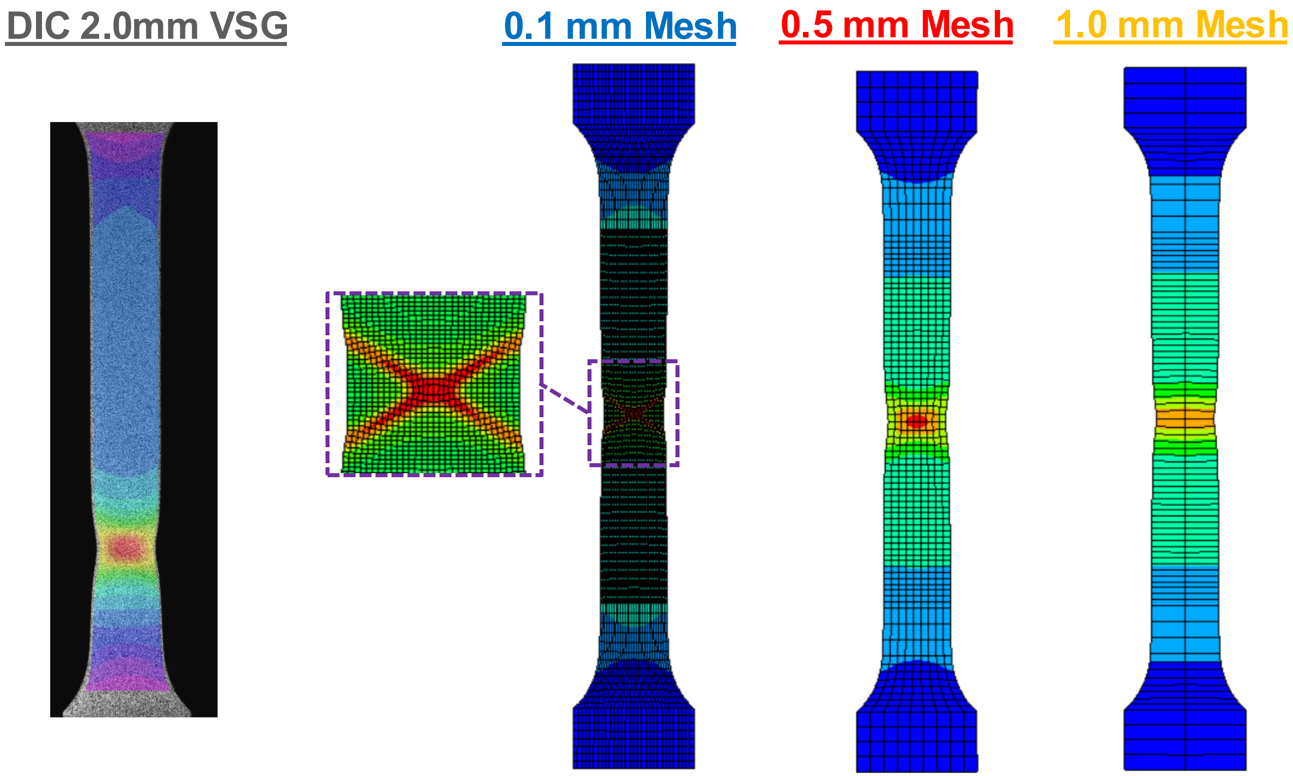
$$\epsilon_{true} = \ln\left(1 + \epsilon_{eng}\right)$$

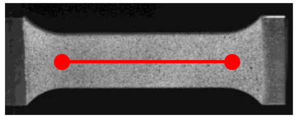
Uniaxial Tension DIC Data: Area Stress and Extensometer Strain

- We can also show the **True Area Stress** versus **Extensometer True Strain**
- Highlights the strengthening occurring as the neck forms
- Model is under predicting this behaviour – difficult to observe without area stress



$$\sigma_{area} = \frac{F}{A_i}$$

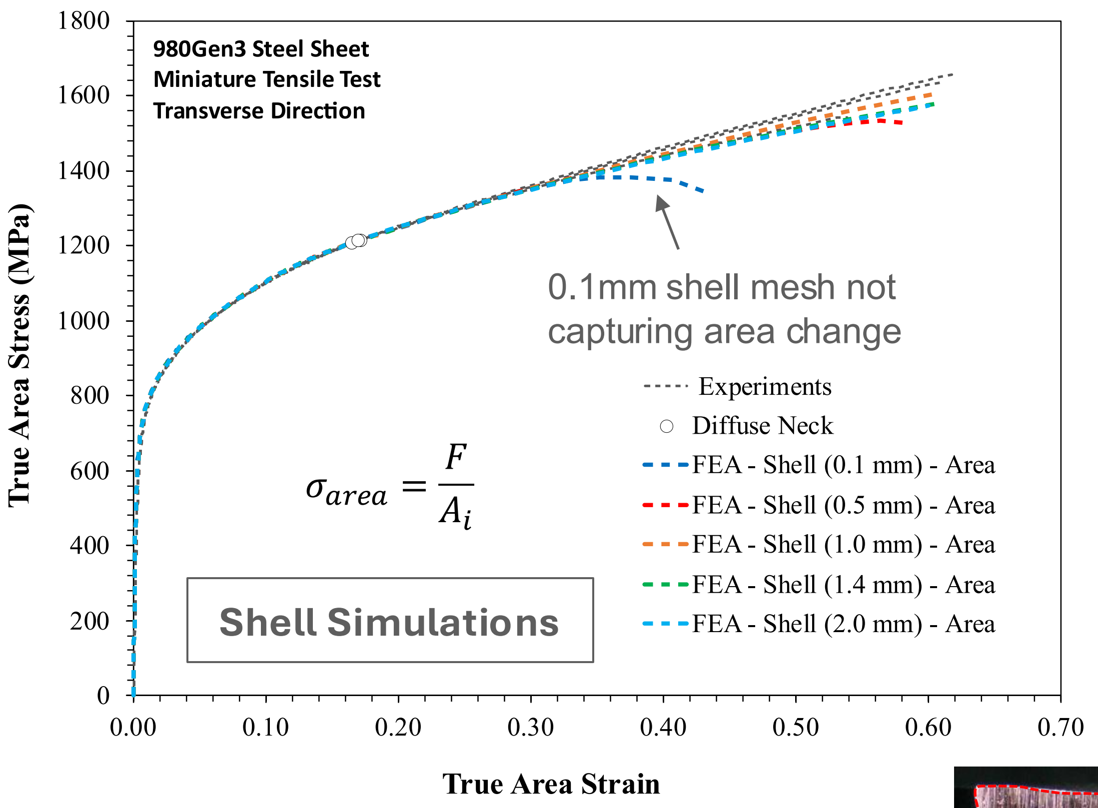


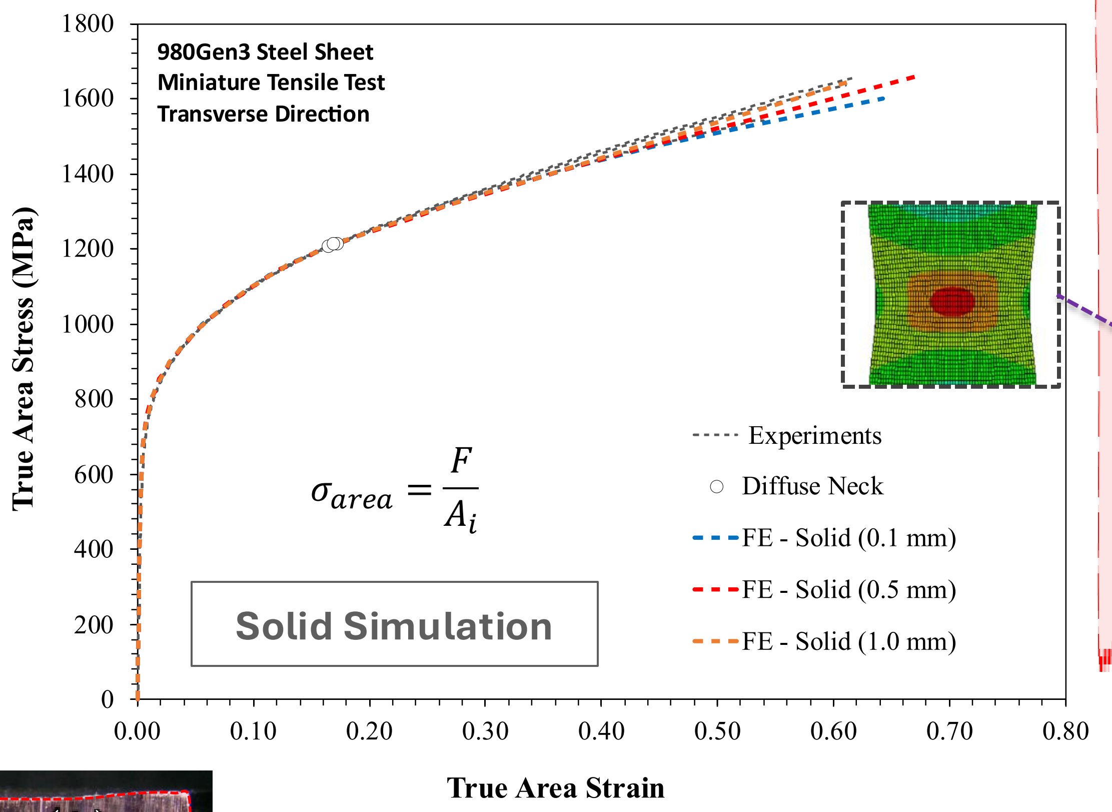


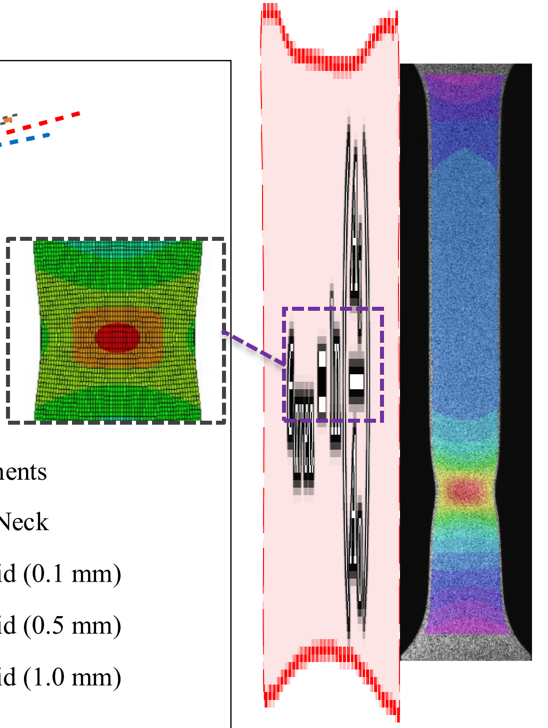
$$\epsilon_{true} = \ln(1 + \epsilon_{eng})$$

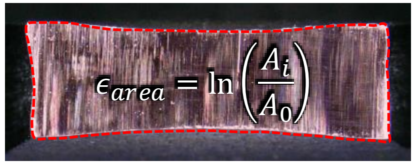
Uniaxial Tension: Advanced Model Correlation with DIC

- Instead, compare the local behaviour where fracture is occurring
- **True stress** (using instantaneous areas) versus **DIC area strain**
- More confidence in model → Correlates to experiments with forces ***and*** local strain







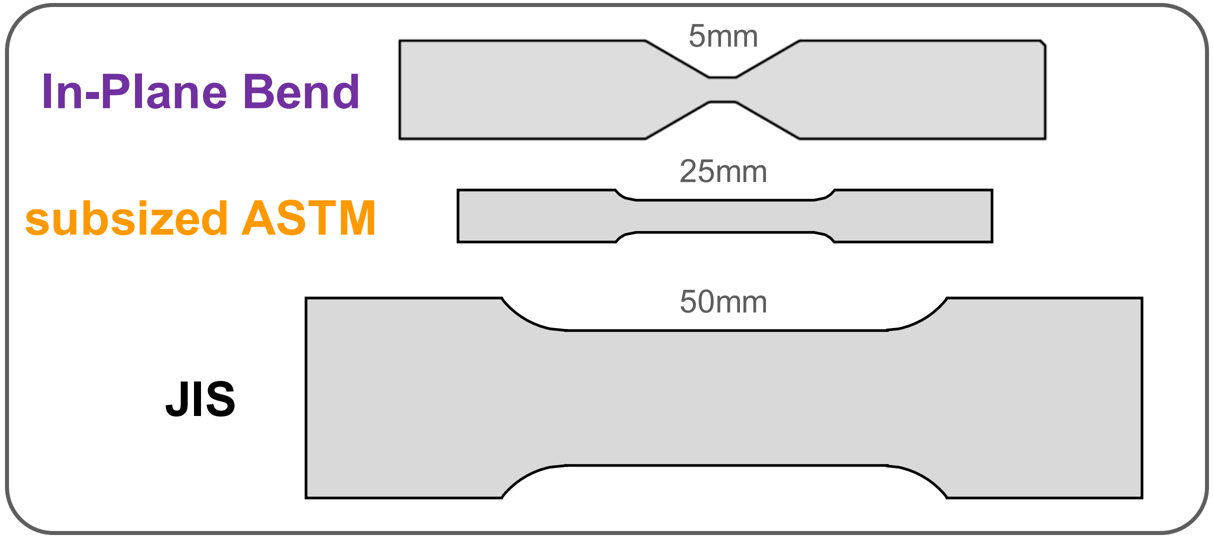


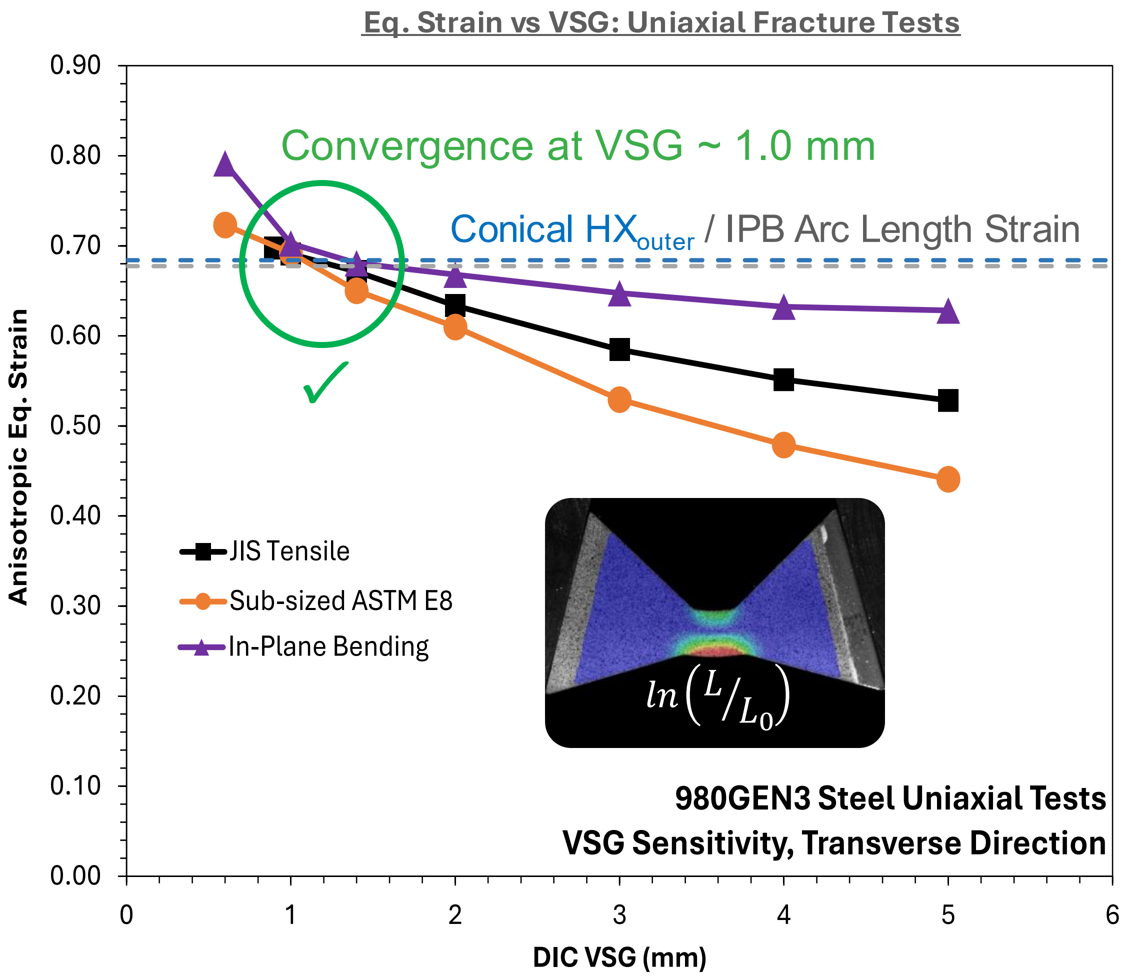
DIC Lengthscale Application: Uniaxial Fracture

- **DIC-Independent fracture strain methods**
  - In-plane bend test arc length measurement
  - Conical hole expansion ratio - *outer-diameter*

- **DIC fracture strain methods**
  - In-plane Bend test at convex edge
  - Uniaxial tension test (JIS & subASTM)

- JIS tensile & sub-sized ASTM E8 surface strains lower than IPB due to necking before fracture.

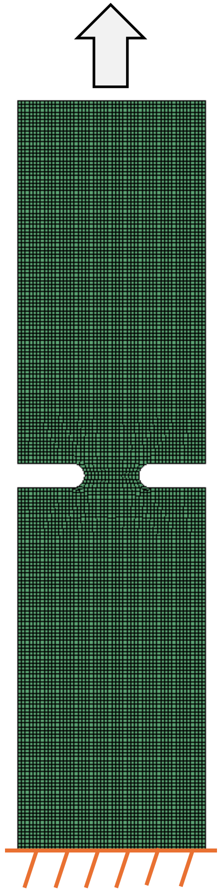


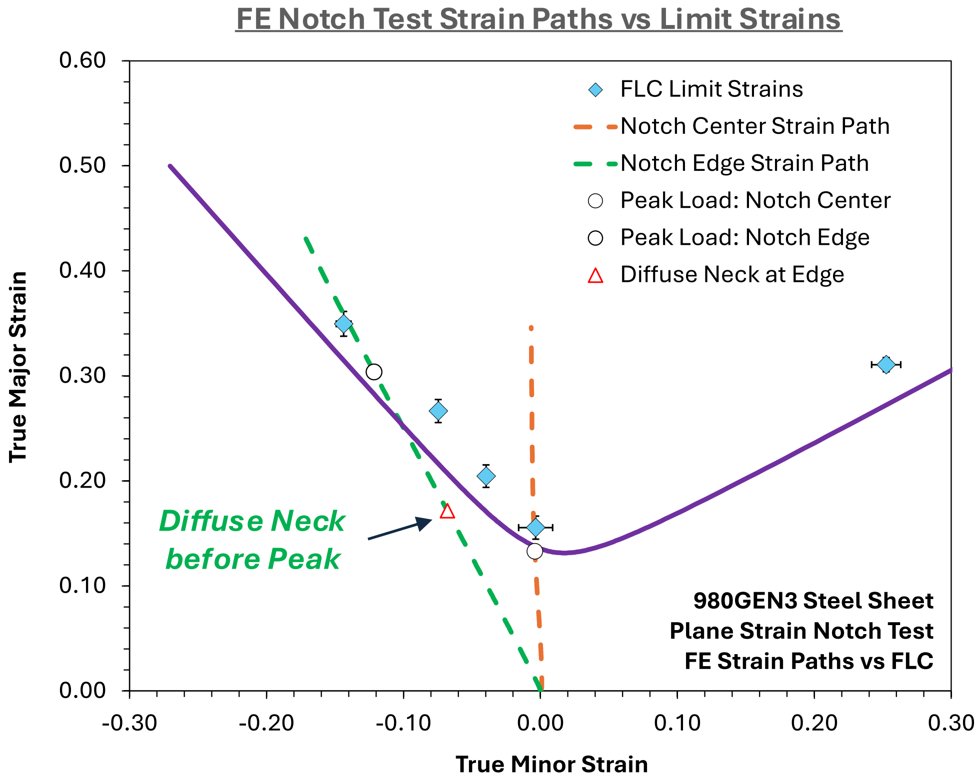


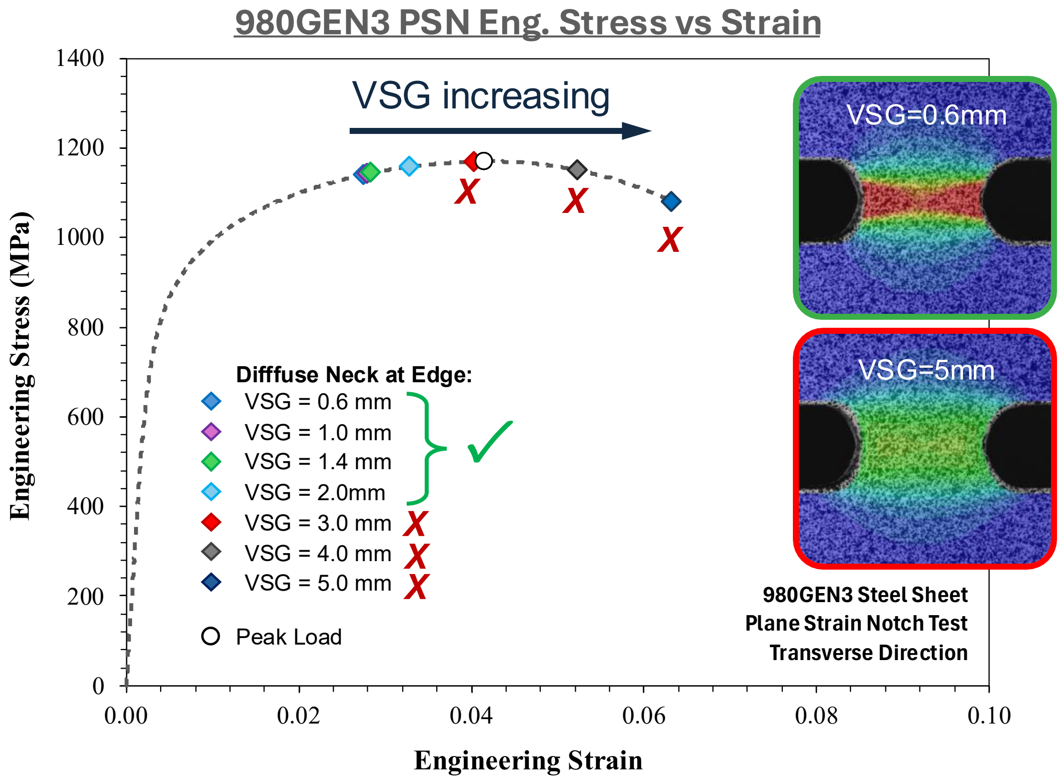
VSG(mm) = [(Filter-1)×Step (pixel) + Subset] × Image Scale (mm/pixel)

DIC Lengthscale Application: Plane Strain Notch

- Peak load correlates with acute necking start
- Diffuse neck at notch edge occurs at Uniform Elongation → Before peak load
- VSG's giving diffuse neck after the peak load are non-physical

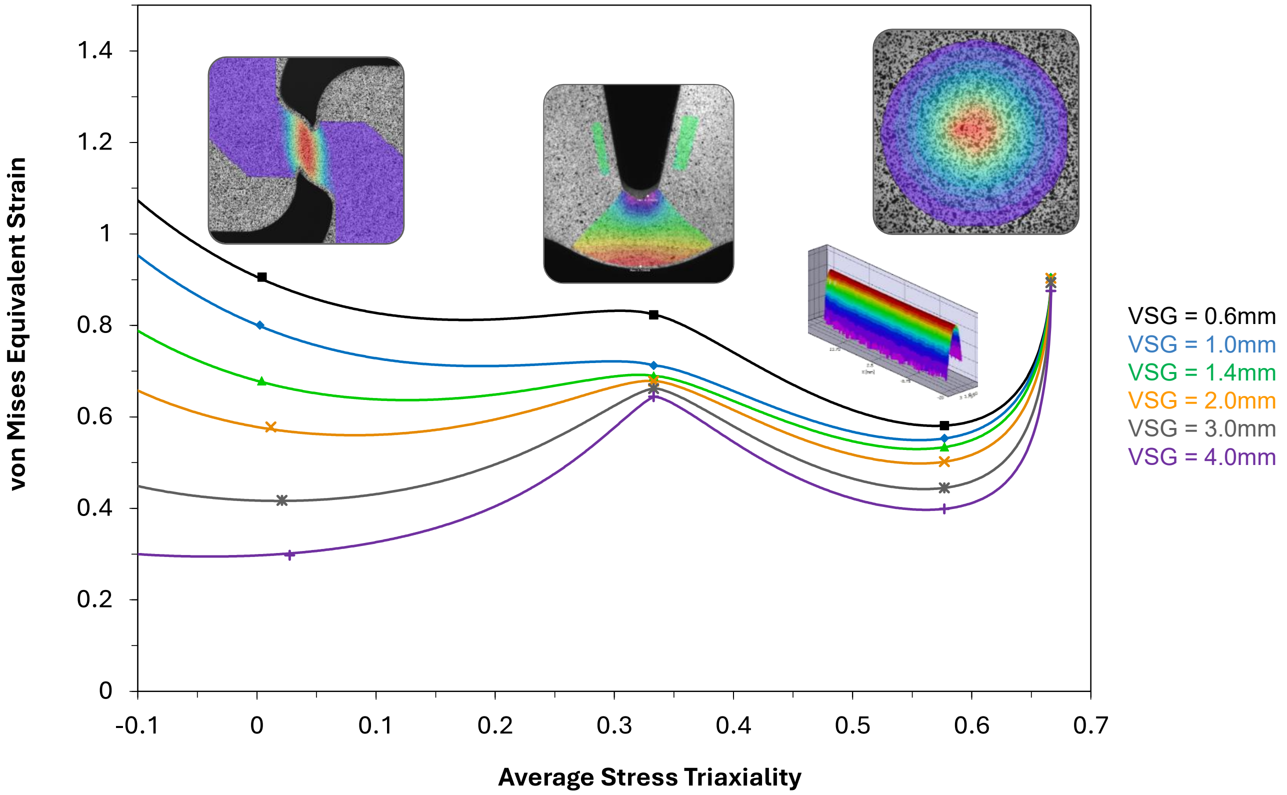






Variation of Fracture Loci with Test Coupons and VSG: 980-GEN3

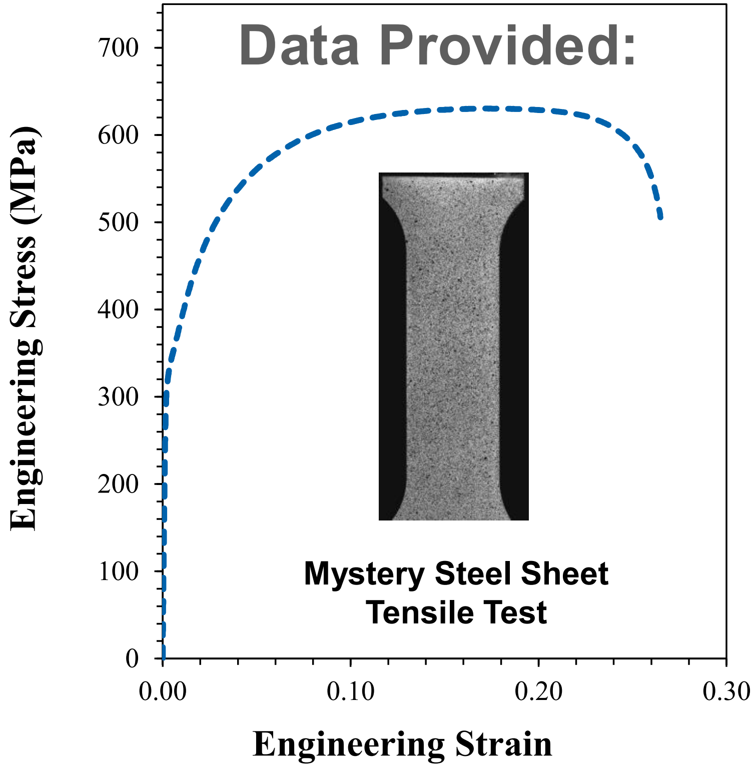
- Strong effect on fracture loci with VSG lengthscale selection
- More confidence in experimental fracture loci with ideal VSG selection
- Potentially coupon-dependent VSG
- More work to be done for direct DIC to CAE model!



Need for Consistency

Mystery steel tensile test analysis (Initiated by Dr. Danny Schaeffler, EQS Group)

- Performed by 15-20 independent testing facilities
- Tensile analysis defined with Internation Standards (ASTM, ISO, etc.)
- Does not consider experimental process variation, how would this look otherwise…?



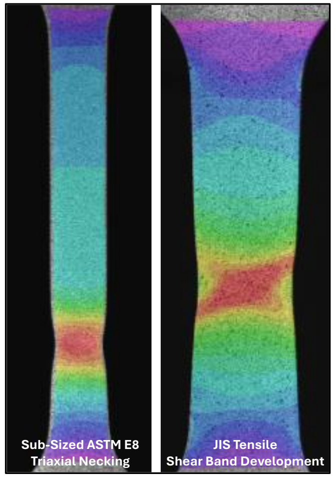
Metric	Units	# of respondents	Average	Standard Deviation (sample)	Min	Max
Elastic modulus	MPa	17	207545	9531	183000	218390
Yield Strength	MPa	19	331.8	12.18	300	367
Tensile Strength	MPa	19	630.2	2.02	623	634
Unif. Elongation	%	19	17.6	1.58	16.1	22.5
N value	0.1-unif	17	0.172	0.0134	0.144	0.207
Elongation	%	18	26.3	0.33	25.7	26.5

Coupons for DIC Analysis & Reporting

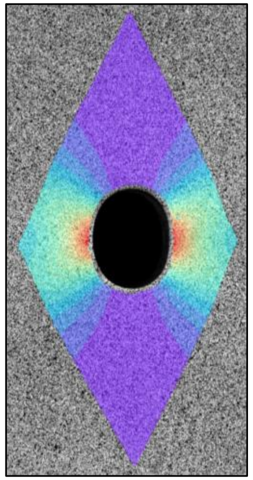
GDIS

- Tensile
- Hole tension
- Notch tension
- Shear
- Biaxial Punch
- Hydraulic Bulge
- Flat punch hole expansion
- V-bend (extra)

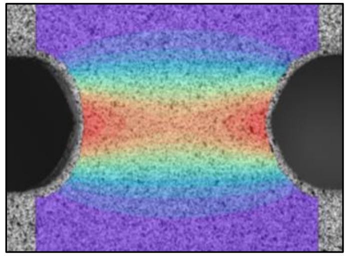
Uniaxial Tension



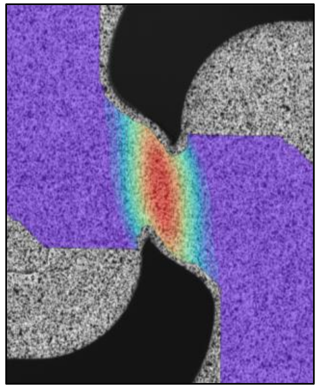
Hole Tension

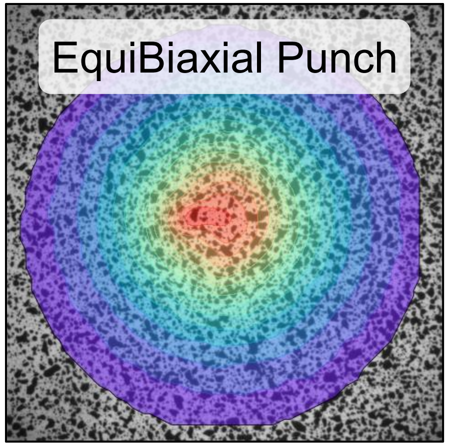


Notch Tension

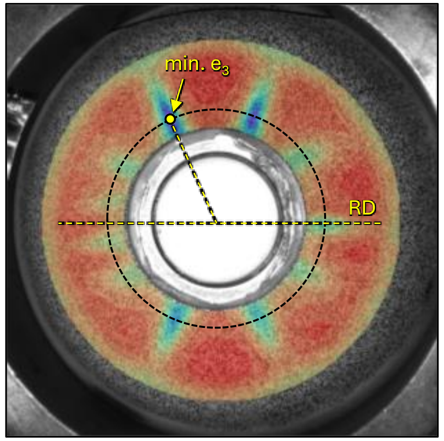


Simple Shear

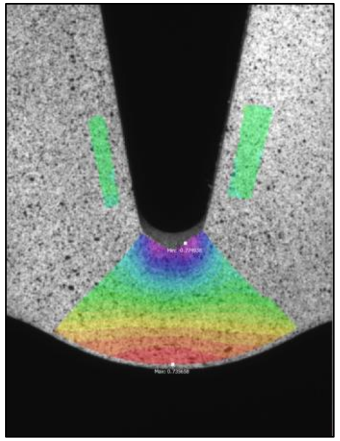




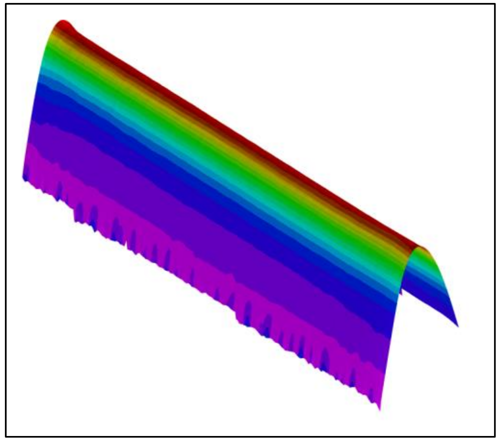
Flat Punch Hole Expansion



In-Plane Bend



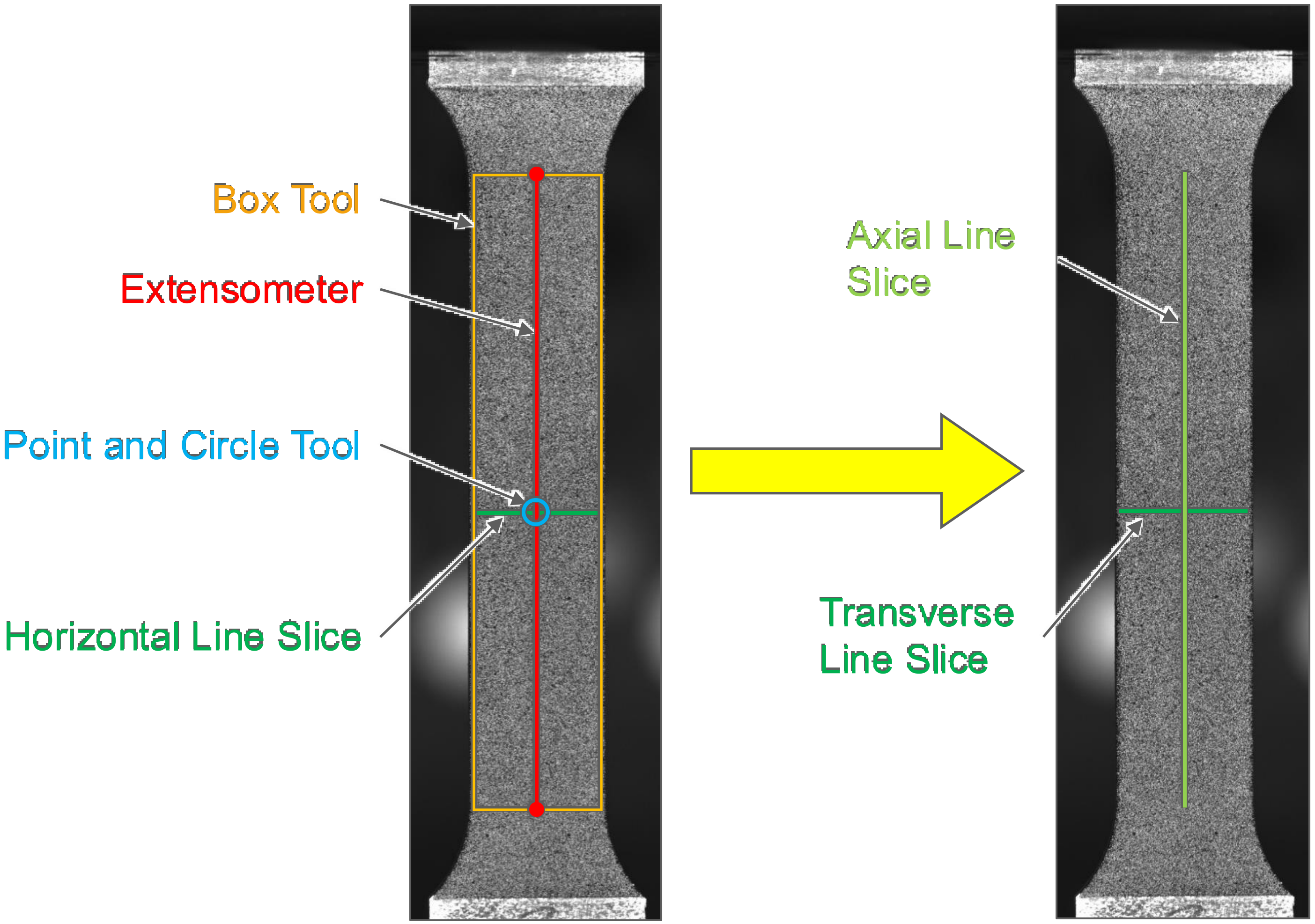
V-Bend



Proposed data extraction: Uniaxial Tension

GDIS

Current Method **Proposed 'Standard'**



- Axial line slice along gauge length
  - Passes through center of specimen
  - Any two points on the axial line can be used as extensometer
- Transverse line slice across gauge width
  - Passes through point of max major strain
  - Max strain location point for fracture strains
  - W-displacement on entire line used for instantaneous area calculations in A.R.M.

Notes:

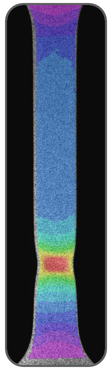
- Box tool optional for better R-value calculation

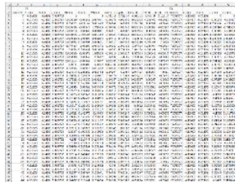
DIC Processing Toolbox: MatLab Analysis

- **Graphical User Interface**
- **A/SP Laboratory Procedure and Data Library**
- **Analysis Scripts for A/SP Members**
  - Uniaxial Tension
  - Notch Tension
  - Hole Tension
  - Shear
  - Biaxial Punch
  - VDA Bend

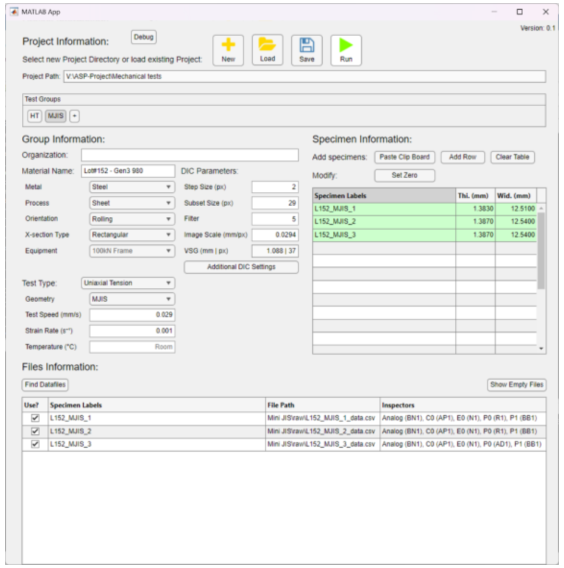
Development of good practices supported by NIST

Structured DIC Data export



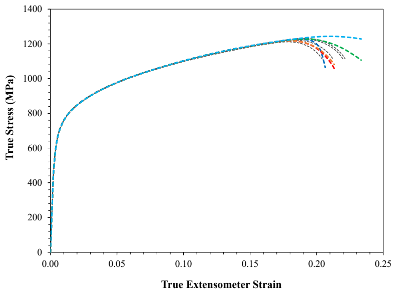


Automated Reporting



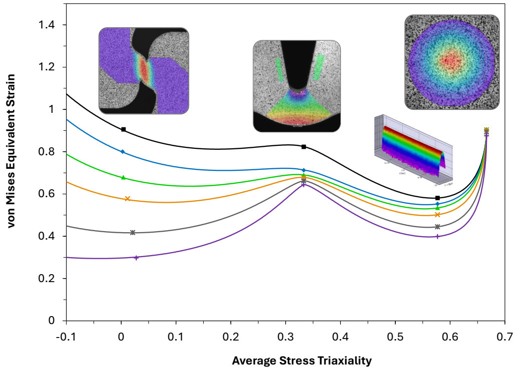
DIC Data	
Image/Index to Zero Load	16
Image/Index at Yield	39
Image/Index for Diffuse Neck	515
Image/Index for Acute Neck	602
Image/Index at Fracture (or last entry)	637
Angle in DIC to Reference Direction (deg)	90

Tensile Summary Data	
0.2% Yield Strength (MPa)	649.41
Ultimate Tensile Strength(MPa)	1022.67
Uniform Elongation UE (%)	17.91
Acute Neck Elongation (%)	21.9
Total Elongation (%)	
Plastic Work @ UE (MJ/m^3)	
Plastic strain @ UE	
Strength Coeff @ UE: K(MPa)	
Hard Exp. @ UE: n	
Major Limit Strain	
Minor Limit Strain	



Phase 2

- Data Summary
- Specimen results
- Chart generation



Summary and Project Outcomes

GDIS

- Adoption of a common DIC test methodology will promote greater consistency in material reporting
- Dependable sources of material cards will aid in material selection and predictive component/assembly modeling
- The suggested approach is useful for both formability modeling (important for making parts) and fracture modeling (important for part performance)
- The suggested approach considers the DIC test scale (VSG) and the modeling scale for greater correlation between predicted and actual performance

Thank You

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