An Efficient Methodology for Fracture Characterization and Prediction of DP980 Steels for Crash Application

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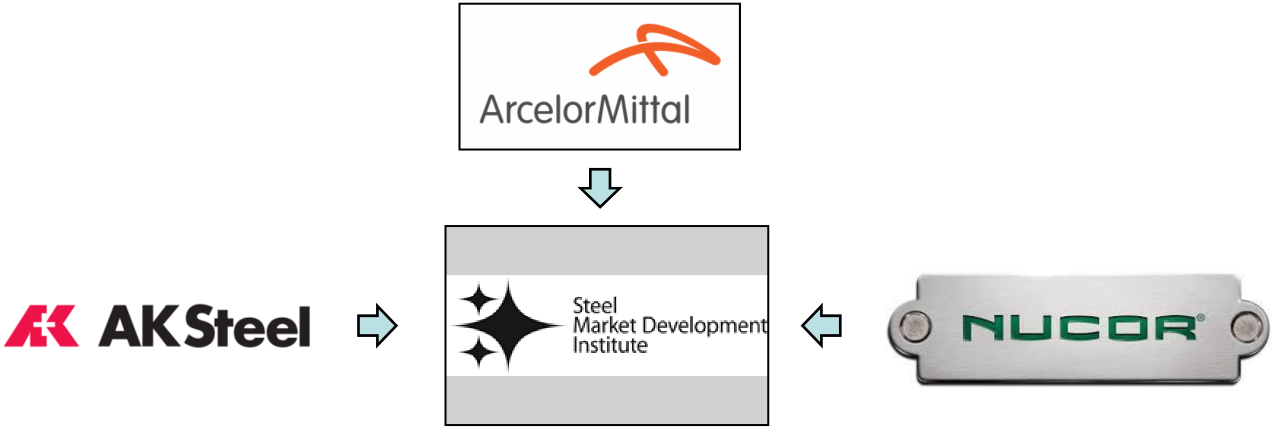
Project Structure

1. Each Supplier Submits One DP980 to SMDI Sample Bank



2. Material identification removed:

Sent to UW and Honda for Fracture Characterization from Coupons to Crash

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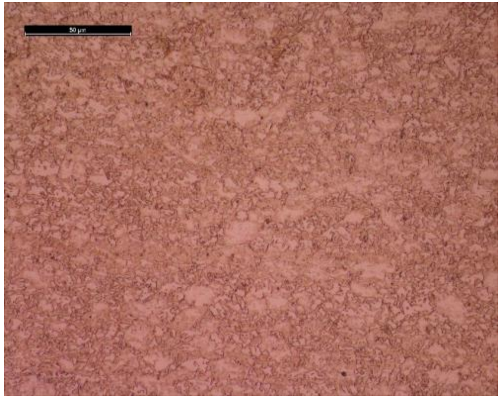
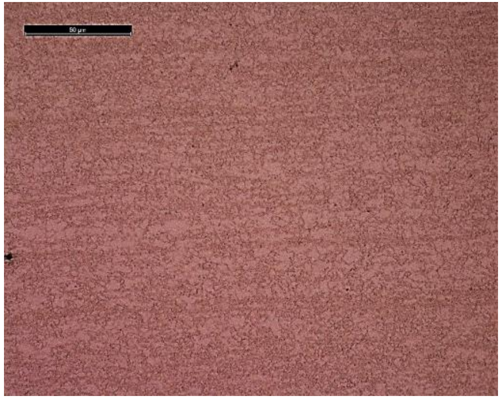
HONDA
The Power of Dreams

Study Materials: Composition

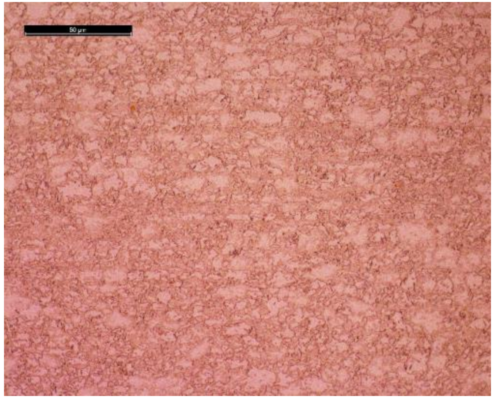
980 #1



980 #2



980 #3

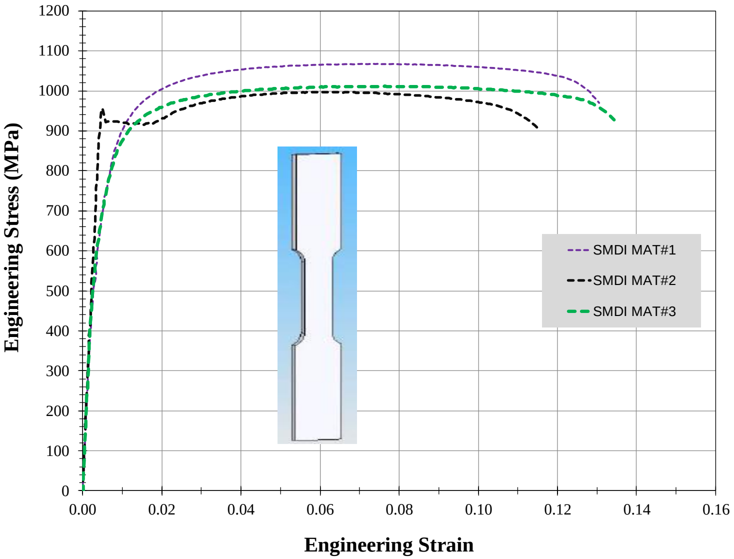


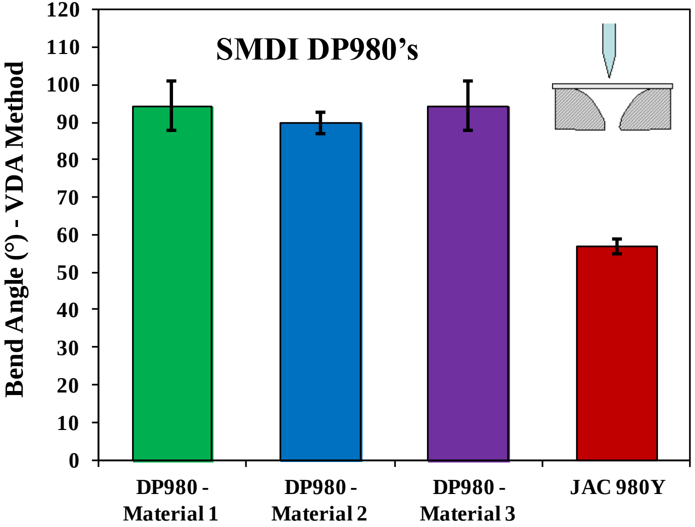
SMDI Grades	Thickness (mm)	Type	General Composition	Coating
980 Mat#1	1.2	Dual Phase	C-Mn-Si	Bare
980 Mat#1	1.6	Dual Phase	C-Mn-Cr-Mo-Nb	Zinc
980 Mat#3	1.4	Dual Phase	C-Mn-Si	Zinc

Materials can generally be described as DP with fine, uniform microstructure.

Grades represent recent optimization in processing / chemistry *(but are not Gen 3 level)*

DP980 Material Properties: Tensile & VDA Bend Performance





- Performance of these grades is consistent with or above current commercial products
- Better local formability relative to other DP980's

Project Goals

1. Characterize properties of various Dual Phase 980 grades selected by Steel Marketing Development Institute (*Blind Study*)

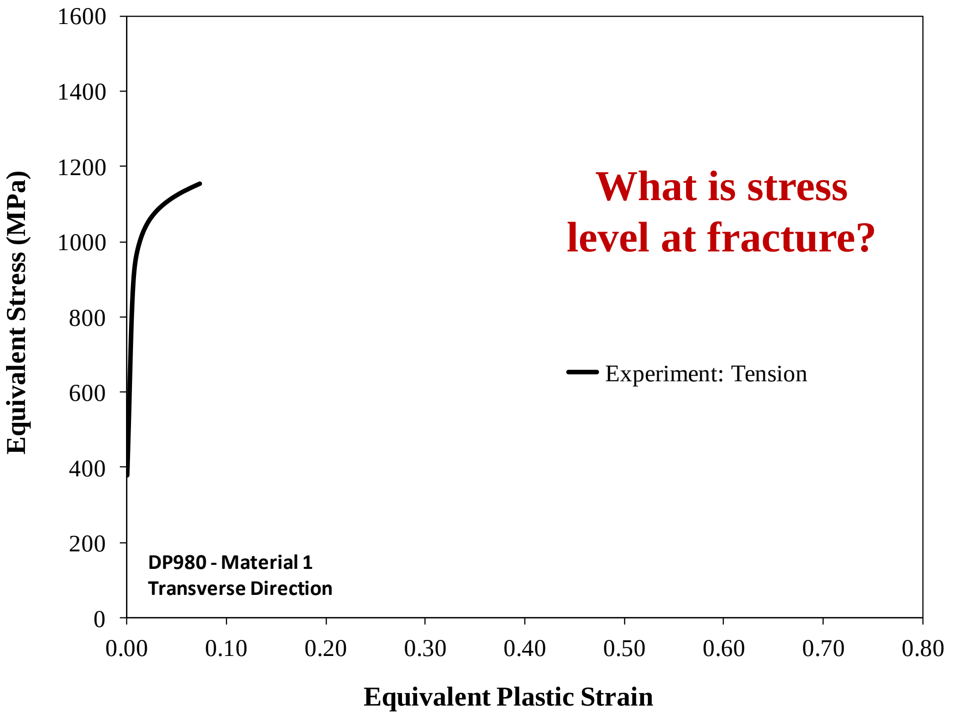
2. Investigate optimized fracture testing methodology for Advanced High Strength Steel → ***Industrial Friendly and Efficient Methods Required*** (GDIS 2017)

3. Perform experimental axial and bend crush experiments and assess fracture performance (GDIS 2017)

4. Numerical characterization for CAE ➔ application to dynamic tests (GDIS 2018)
   → ***Efficient methods needed to transition from coupons to crash simulations***

Recap: Material Characterization at Large Strains

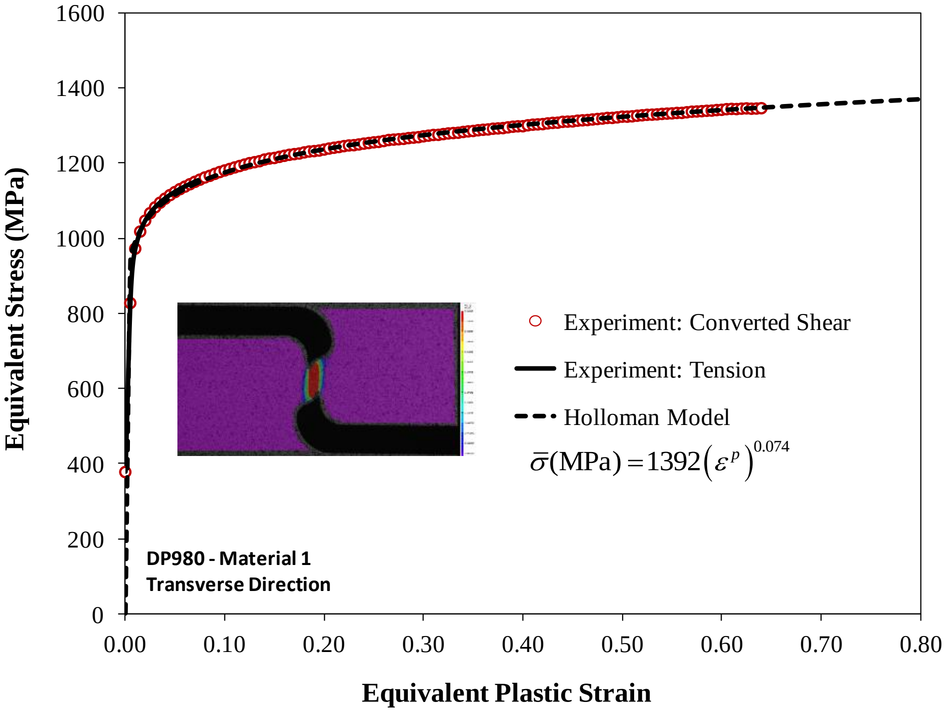
- Limited hardening data available in tensile tests
- Inverse FE modeling used to identify hardening at large strains for fracture
- Hardening data becomes a function of numerical model assumptions…



Recap: Material Characterization at Large Strains

- UW developed simple method to use tensile & shear test data to obtain hardening to large strain levels
- DP980 data to 60% strain!
- **Not related to FE model**

Methodology in Rahmaan, T., et al., *Int. J. Impact. Eng.*, 2017 (in-press)



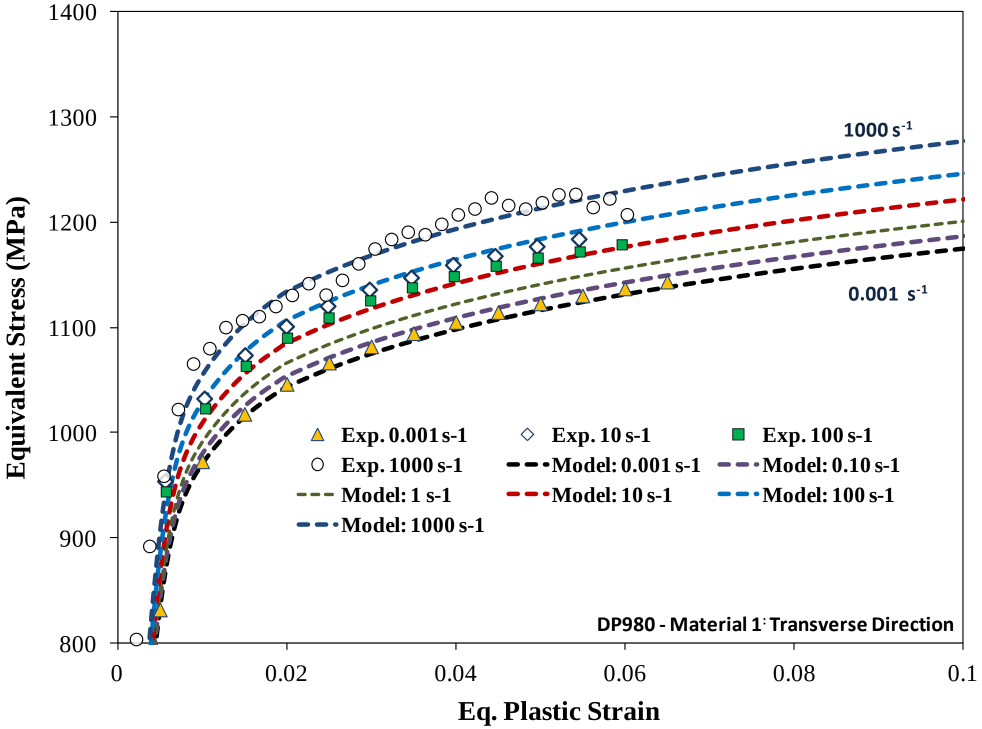
Material Characterization at Large Strains *and Strain Rates*

- Tensile characterization from 0.001 to 1000 s-1

- Scale quasi-static data obtained to large strains for strain rates

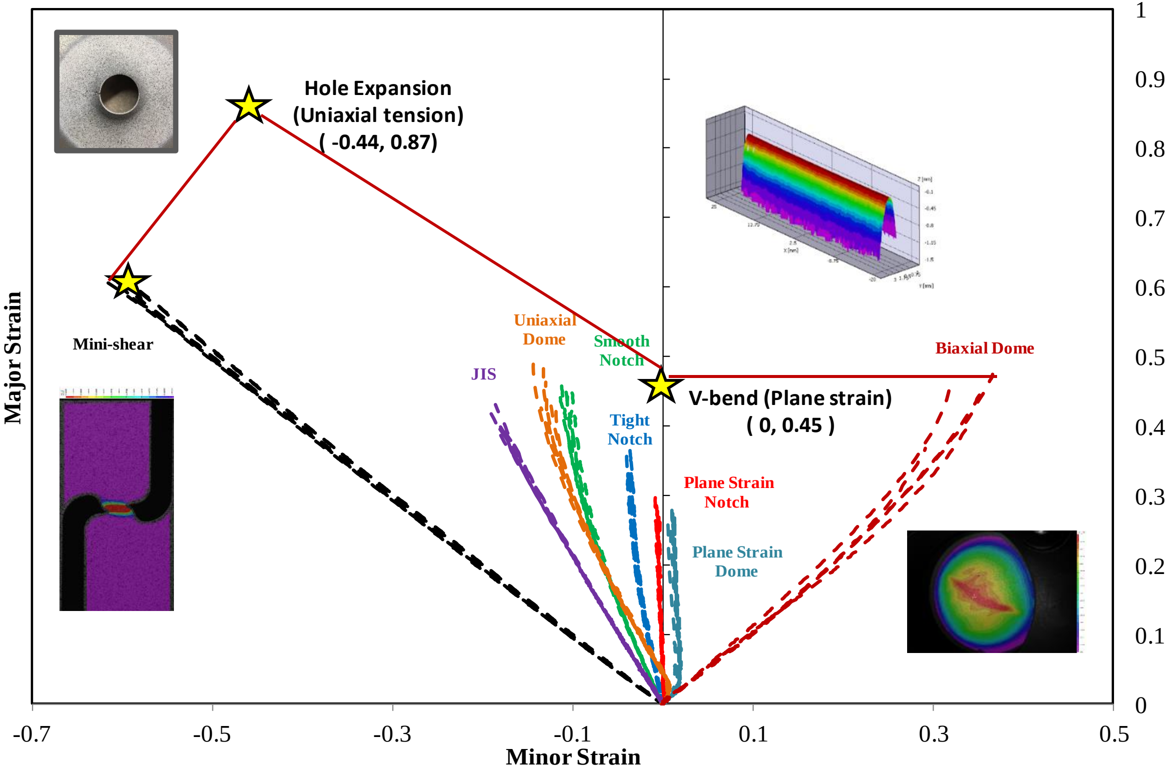
$$\bar{\sigma}\left(\varepsilon^{p},\dot{\varepsilon}^{p}\right)=\bar{\sigma}^{QS}\cdot F\left(\dot{\varepsilon}^{p}\right)$$

- **Efficient experimental method for constitutive characterization**



Fracture Characterization Results

- Conflicting limits provided by different specimen types if thinning correction not applied



Min. of 4 Tests can describe the fracture locus

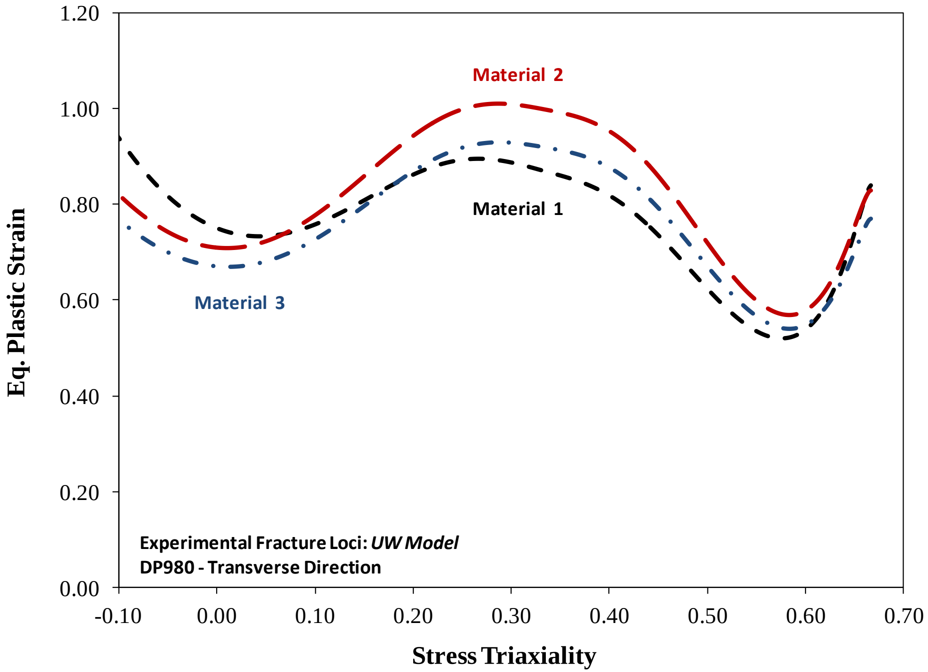
Four Relatively Simple Tests:

1. Mini-shear
2. Hole expansion (reamed)
3. V-Bend
4. Biaxial/Bulge

Experimental Fracture Loci: 3 DP980's

Four tests can be used to generate physically-meaningful fracture loci

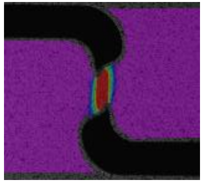
Not the product of a simulation exercise – Real material performance can be assessed



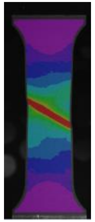
- **Relatively comparable fracture loci**
- **Mat 2 had the *lowest hardening rate*, *highest hole expansion* and *v-bend***
- ***How do we use this for CAE?***

Hybrid Experimental-Numerical Approach to Fracture

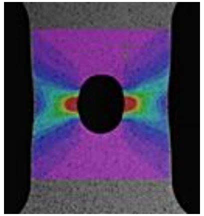
1. Perform set of characterization tests



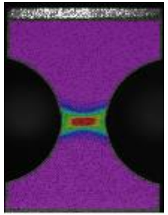
Shear



Tensile

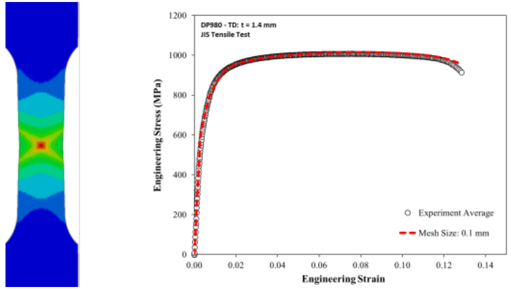


Central Hole

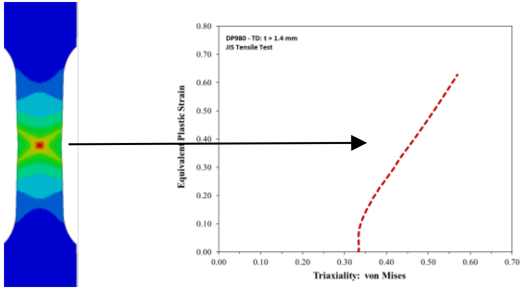


Notch Tension

2. FE modelling of characterization tests



3. Extract Local Stress Histories from models



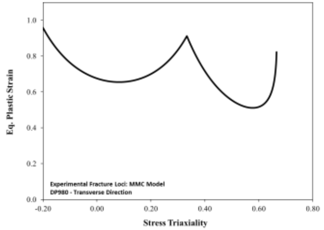
4. Damage Model for CAE

- Assume damage model, failure locus form & optimize

$$D = \frac{d\varepsilon^p}{\varepsilon_f(T)}$$

✚ $\varepsilon_f = \varepsilon^{MMC}(T, a_i)$

✚ *Optimization* →



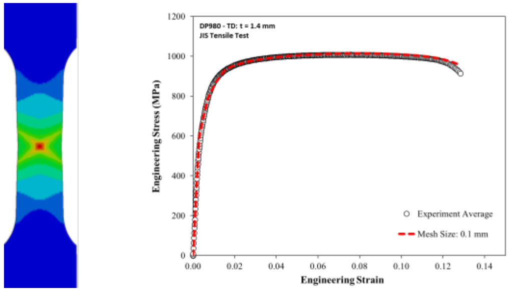
For industry, there are more steps remaining…

**Repeat Steps 2-4 for
Every Mesh Size of Interest***

Eventually…apply to a practical application not used in the calibration to see if it works

***Solid element regularization will be different than shell for shells**

2. FE modelling of characterization tests



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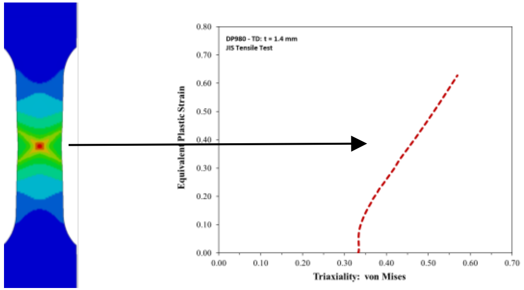

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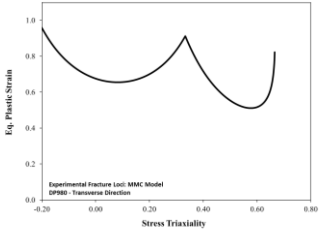
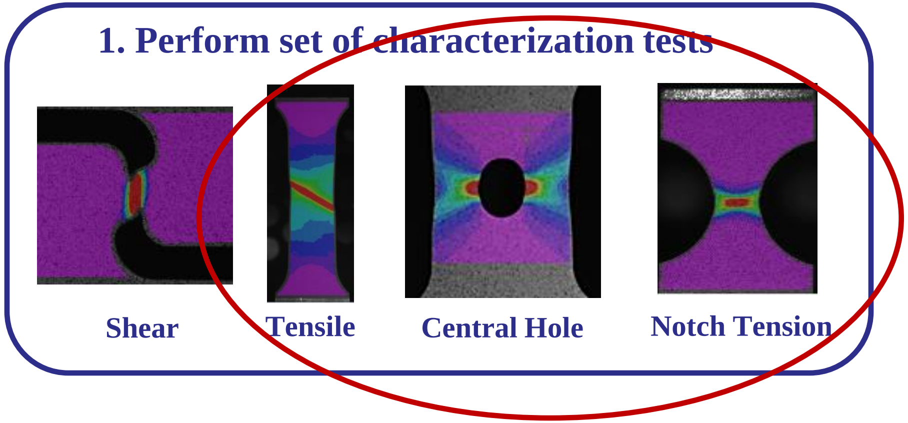
✚ *Optimization* →



Only works for 1 mesh size

Choice of CAE Characterization Tests



1. Perform set of characterization tests

Shear Tensile Central Hole Notch Tension

<u>Tensile-Based Characterization Tests are Employed</u>

- X – Strong localization
- X – Through-Thickness Strain Gradients
- X – Fractures at mid-thickness
  - ➔ No DIC strain measurement
- X – Requires 3-D solid elements
- X – Requires fine mesh: ~ 0.10 mm
- X – Non-linear 3-D stress state develops

Solid element models are great for academic research but less so for industry

CAE models for forming & crash use plane stress shell elements from 0.5 – 7.0 mm

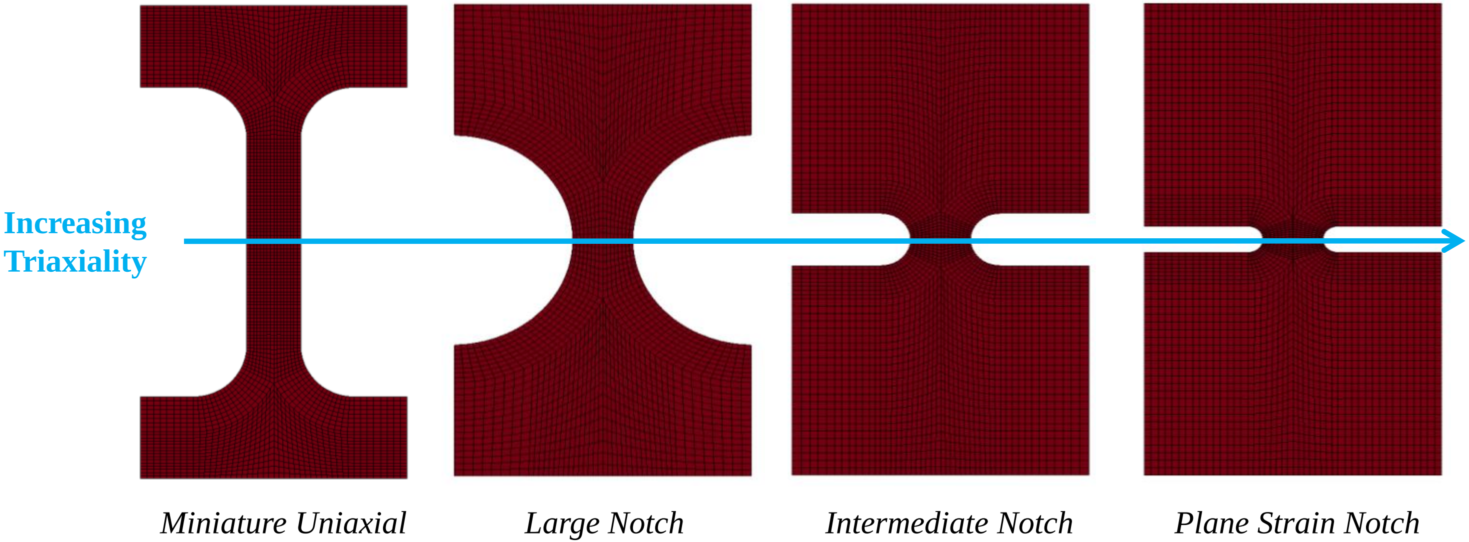
Extracting the plane stress fracture locus from a calibrated 3-D solid model works in theory…in practice the element mechanics are different

Tensile-Based Fracture Characterization

Relatively simple tests that most labs can perform and are comfortable with

Since sheet is thin, the logic is that these samples are plane stress….

Deformation rapidly localizes, violating plane stress assumption but creating a desired change in the stress state



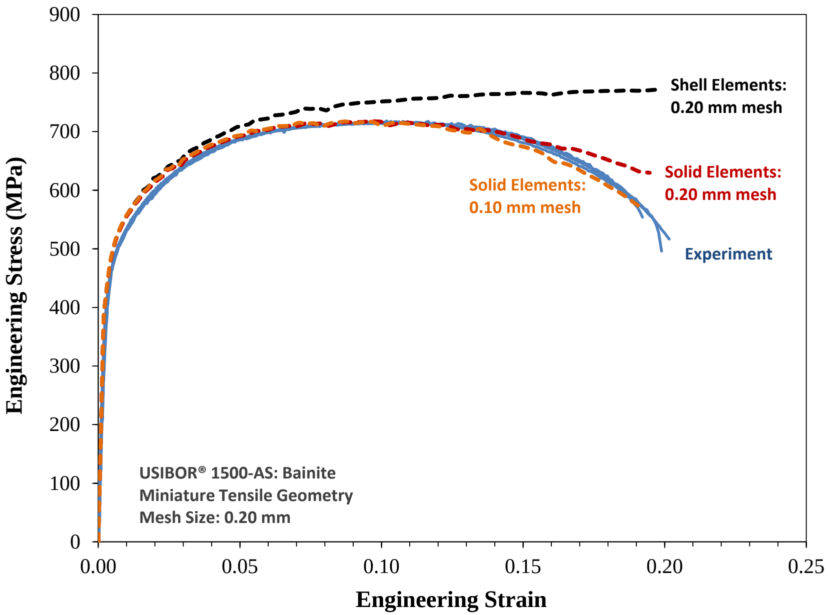
Representative Types of Tensile-Based Fracture Coupons

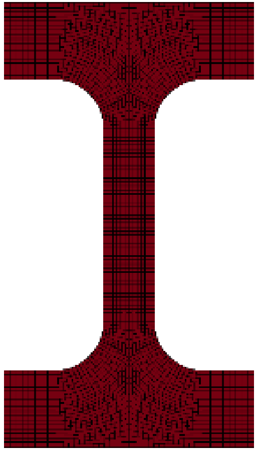
Comparison of Solid & Shell Models for Tensile CAE Coupons

Shell models cannot resolve strong local thinning and localization → Overestimate the stress response, underestimates strain

Methods exist to add *damage-induced softening* to improve the shell solutions. Not a damage issue but element type.

Can create problems for cases when shells are appropriate

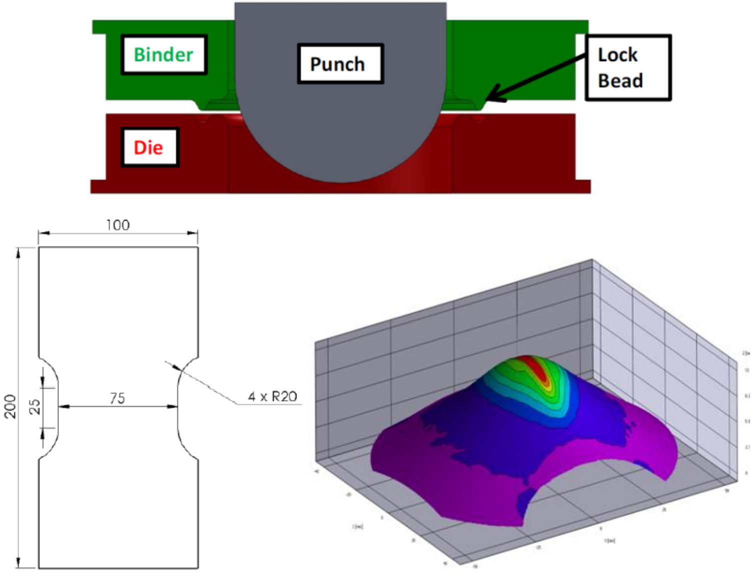




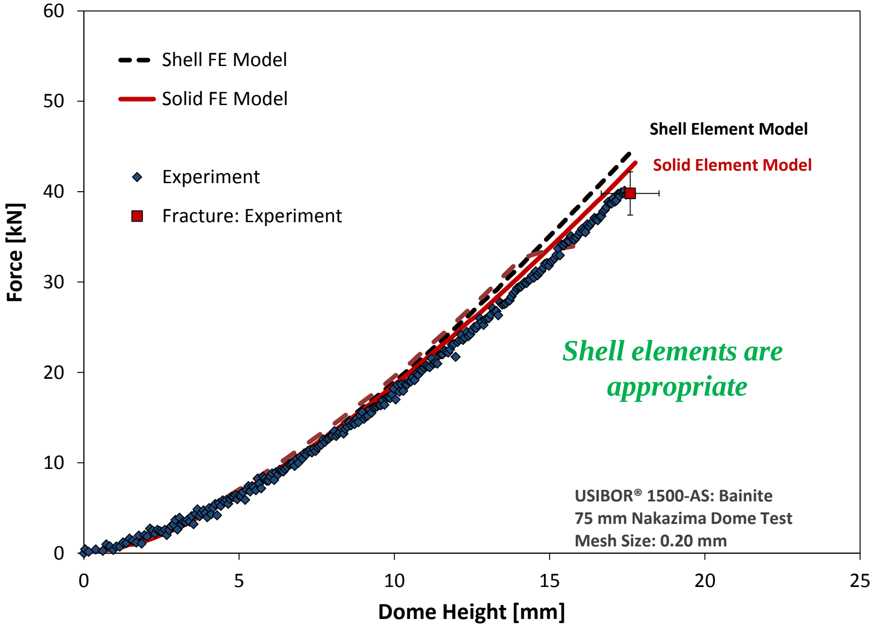
“Plane Stress Friendly” Characterization

Shell element models for sheet metal forming and structural component models can be very accurate

Use of Nakazima dome tests for CAE characterization is more consistent with the end-use applications



Plane Strain Nakazima Dome Test



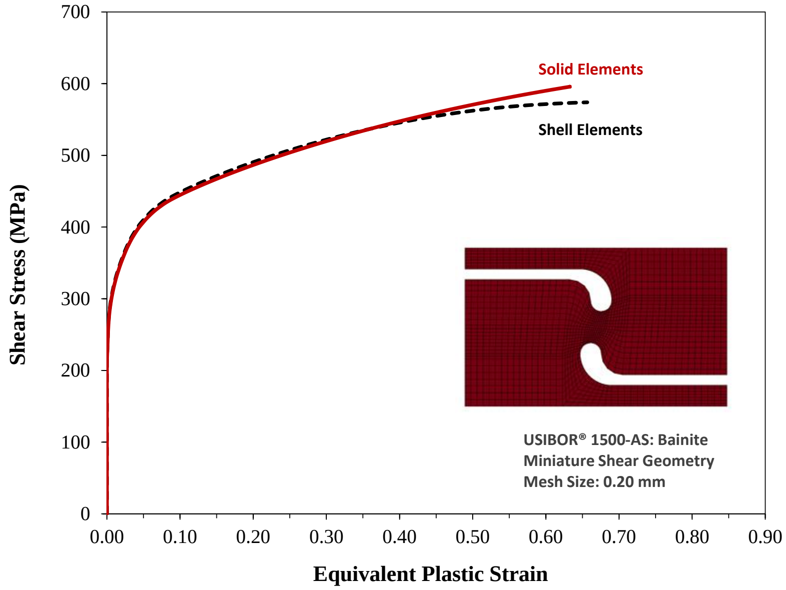
Shell elements are appropriate

USIBOR® 1500-AS: Bainite
75 mm Nakazima Dome Test
Mesh Size: 0.20 mm

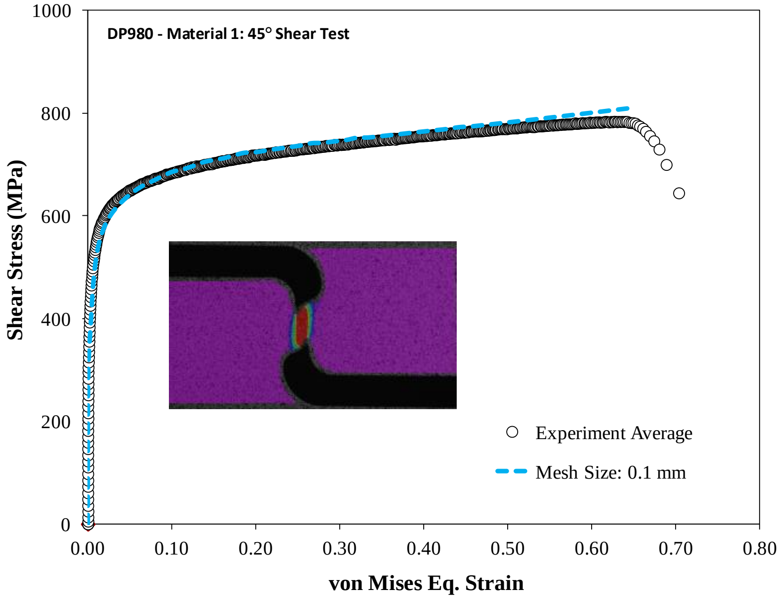
Plane Stress Representation of the Shear Test

Mechanics of shear deformation creates a Plane Stress-Plane Strain loading condition

Shell elements provide an accurate description

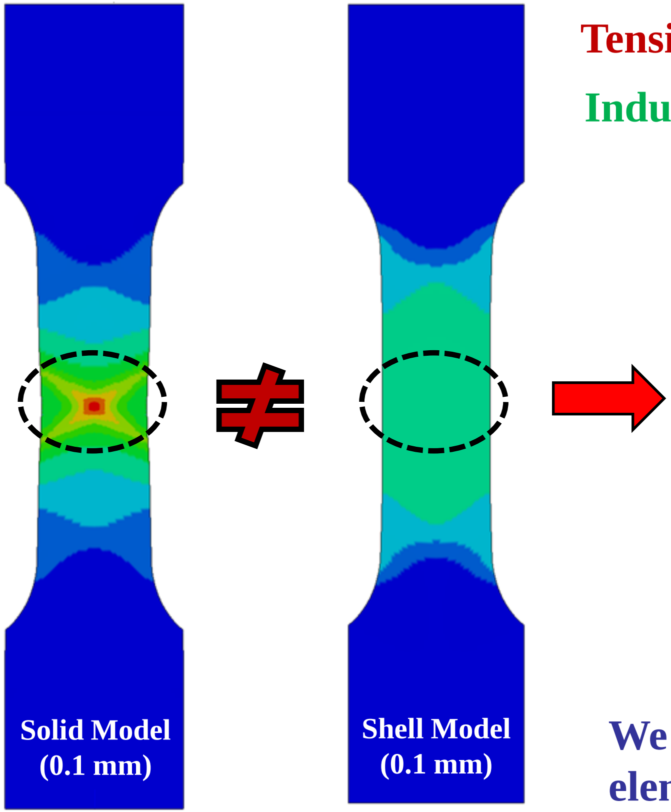


Comparison of FE models for a tailor hot stamped steel



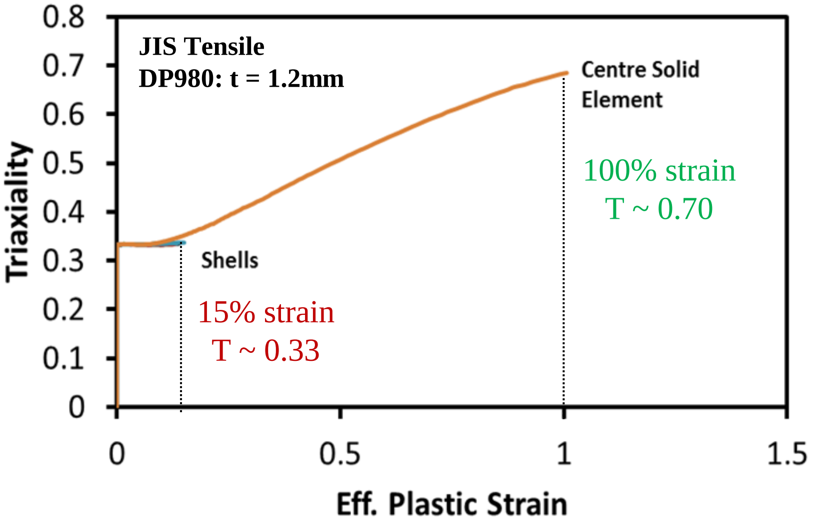
Exp. & FE comparison of shear test for a DP980 steel

An Industrial-Focused CAE Strategy is Required



Tensile-based strategy requires solid models: Academic-focused

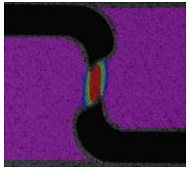
Industrial-focused strategy must be tailored for shell elements



We have identified exp. tests with minimal necking where shell elements can be used → *Consistent with CAE applications*

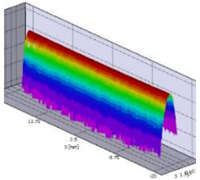
Industrial Strategy for Plane Stress Fracture Characterization

1. Perform 4 Plane Stress Characterization Tests

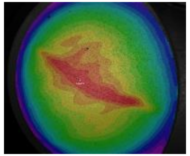


Shear

Hole Expansion



V-Bend

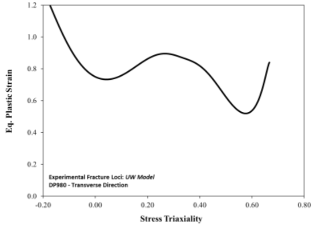


Biaxial Dome

2. Experimental Fracture Locus

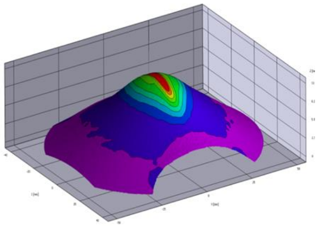
- Assume failure locus form & calibrate with 4 points

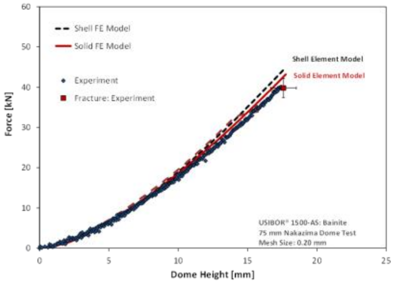
$$\varepsilon_f^{\exp} = \varepsilon^{UW}\left(T, a_{1-4}\right) \longrightarrow$$



Physically meaningful fracture locus: Not an FE construct

3. Plane Stress Models with Various Mesh Sizes





Knowledge Gap

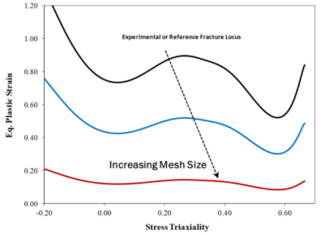
Efficient Length Scale Transition

4. Regularize Exp. Fracture Locus for CAE

- Assume damage model & scale locus with mesh size, R:

$$D = \frac{d\varepsilon^p}{\varepsilon_f\left(T\right)} \quad + \quad \longrightarrow$$

$$\varepsilon_f^{CAE}\left(R, \varepsilon_f^{\exp}\right) = R \cdot \varepsilon^{\exp}\left(T, a_i\right)$$

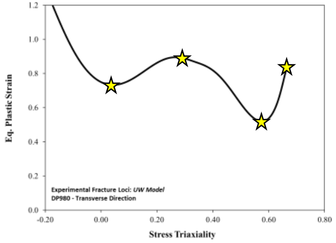


“Direct” Strategy for Numerical Fracture Characterization

1. Start with the Experimental Fracture Locus

- Assume failure locus form & calibrate with 4 points

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

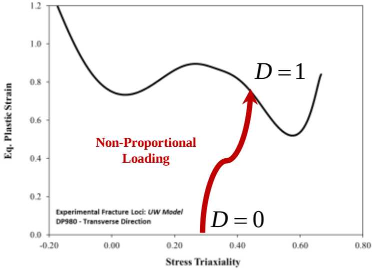


2. Assume a damage form for nonlinear loading

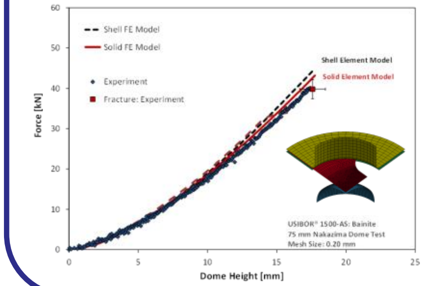
Examples:

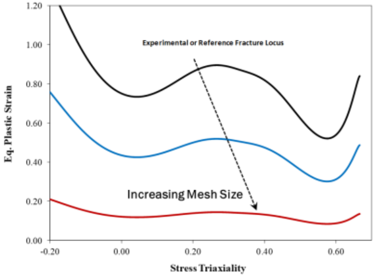
$$\Delta D^{JC} = \frac{\Delta\varepsilon^p}{\varepsilon_f^{\exp}(T)}$$

$$\Delta D^{GISSMO} = \left[\frac{n}{\varepsilon_f^{\exp}(T)} D^{\left(1-\frac{1}{n}\right)}\right]\Delta\varepsilon^p$$



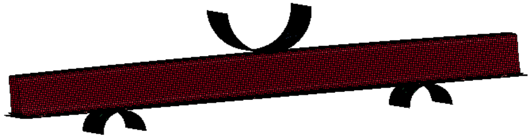
3. Plane Stress Models & Regularization





4. Apply to Structural Components

Static & Dynamic Conditions



3-Point Bend & Axial Crush of a 600 mm Rail:

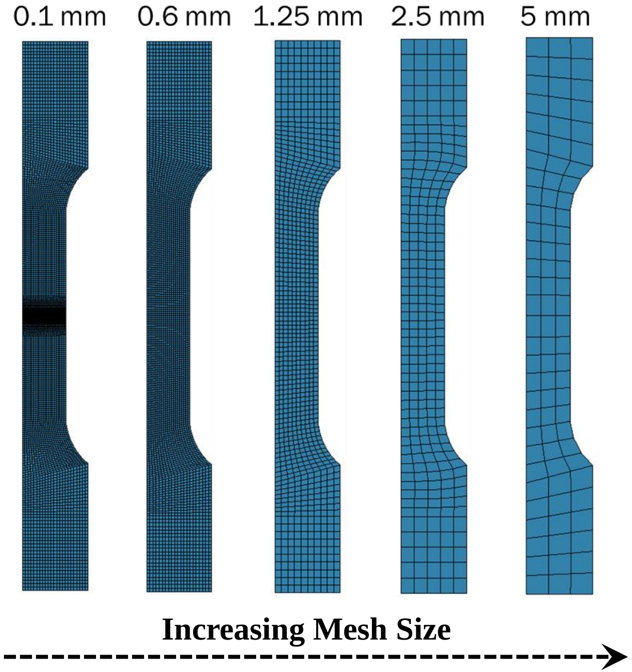
2.5 mm element mesh

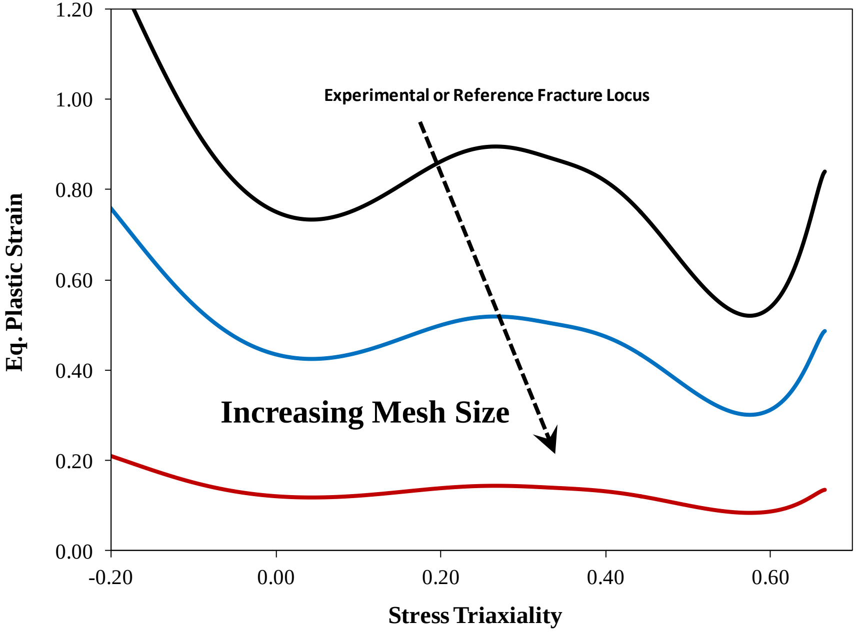
What is most efficient method to regularize for components?

Length-Scale Transition from Coupons to Components: *Regularization*

Large elements cannot resolve the stress and strain as accurately

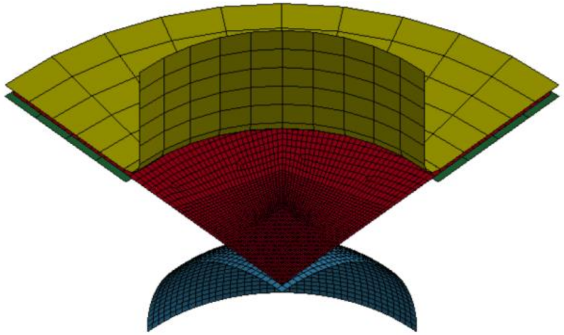
Local strain at fracture generally decreases with element size



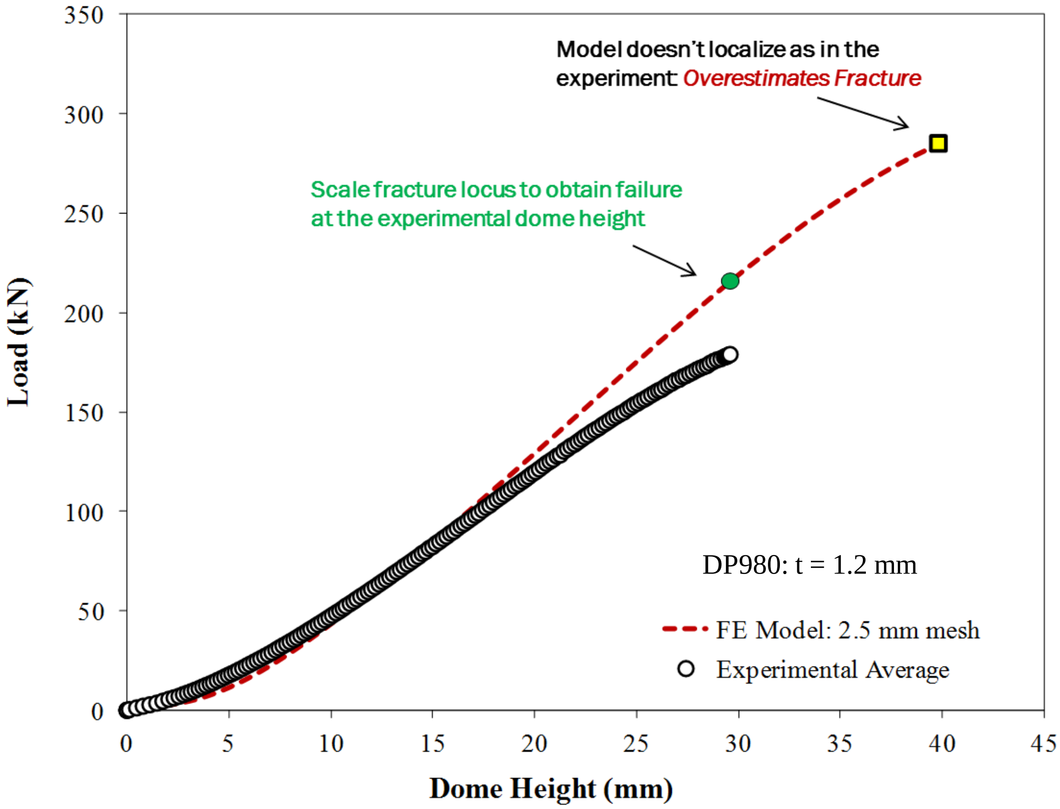


Regularization Example: Biaxial Dome Test with 2.5 mm mesh

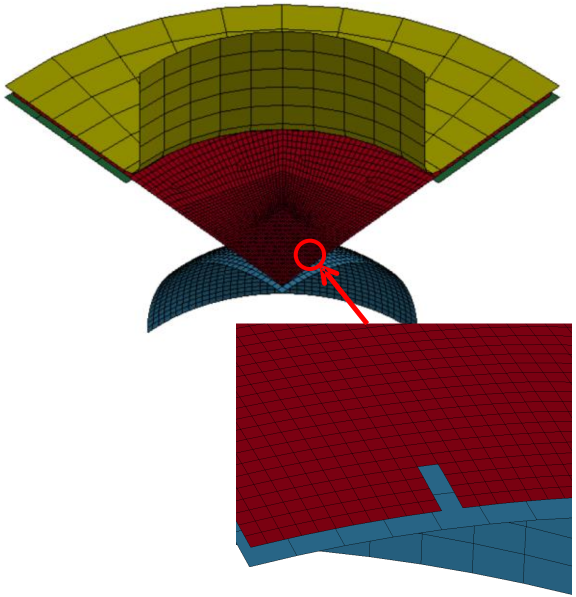
Decent load-displacement agreement for isotropic plasticity model



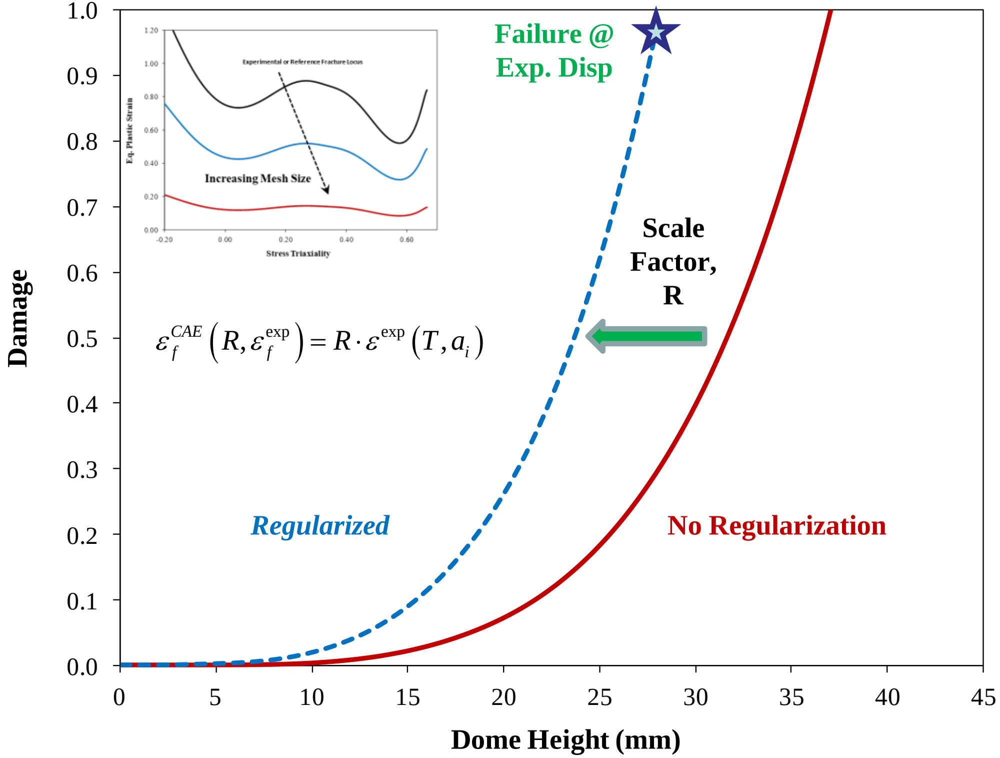
¼ FE Model of Biaxial Dome Test



Regularization Effectively Alters the "Damage" Accumulation Rate to Trigger Fracture at the Exp. Dome Height



Element deletion



$$\varepsilon_f^{CAE}\left(R,\varepsilon_f^{\exp}\right)=R\cdot\varepsilon^{\exp}\left(T,a_i\right)$$

However, Regularization is Not That Simple…

Regularization factor depends upon:

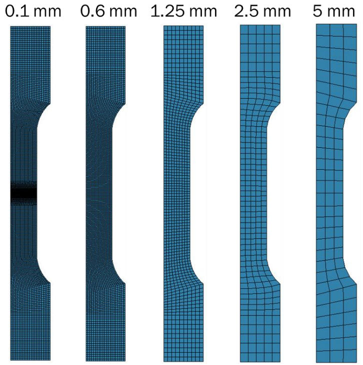
1. Coupon geometry
2. Element type: some geometries are poorly described by shells
3. *Deformation mode*: Bending mode is not well described by large elements relative to stretching mode
4. Stress State: Uniaxial tension is different than biaxial tension

Regularization atones for any experimental and modelling sins

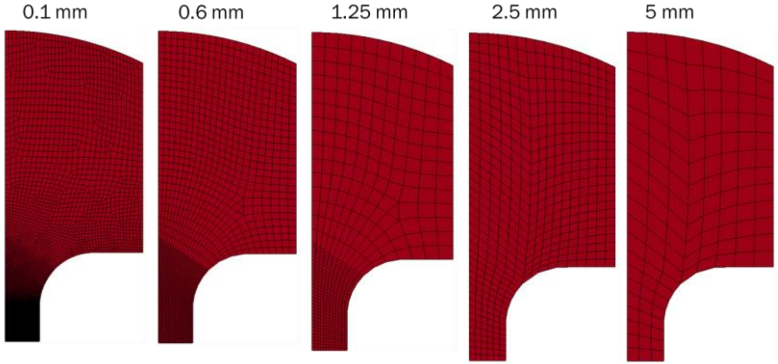
Issues of modelling taste → Different fracture methodologies can lead to similar results in component tests after each is regularized…

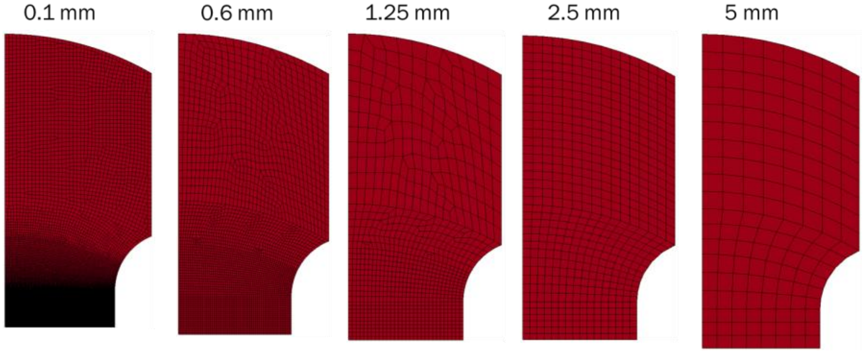
4 Geometries for Regularization: 0.1 to 5 mm mesh

1. JIS Tensile (T = 0.33)

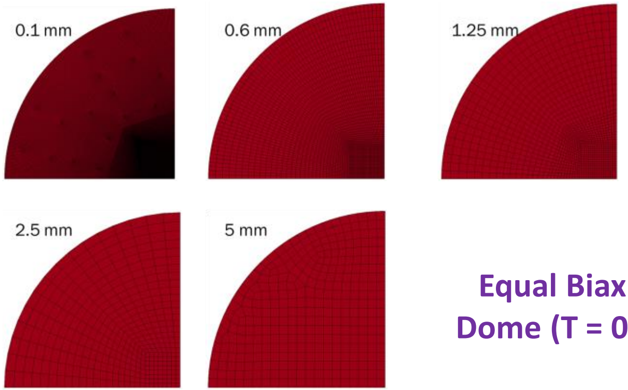


2. Uniaxial Dome (T = 0.33)





Plane Strain Dome (T = 0.58)



Equal Biaxial Dome (T = 0.66)

Mesh Regularization for DP980: t = 1.2 mm

Scale factors vary with element size

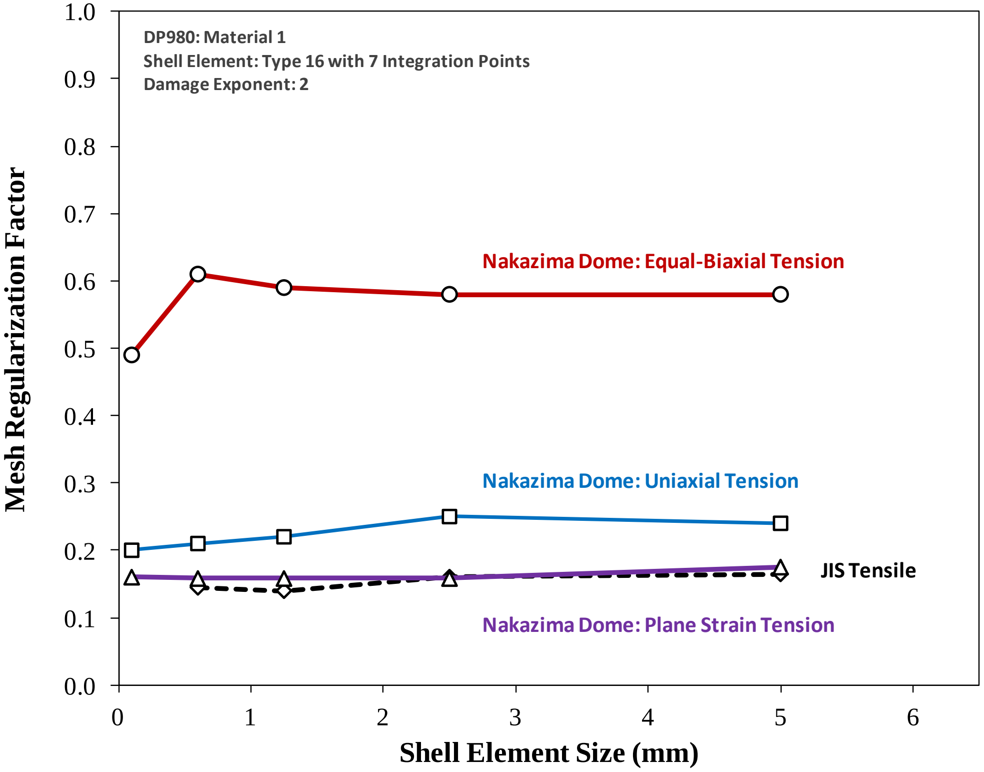
as the local stress state and strain also change

Relatively constant factors for elements larger than thickness

Regularization ranking:

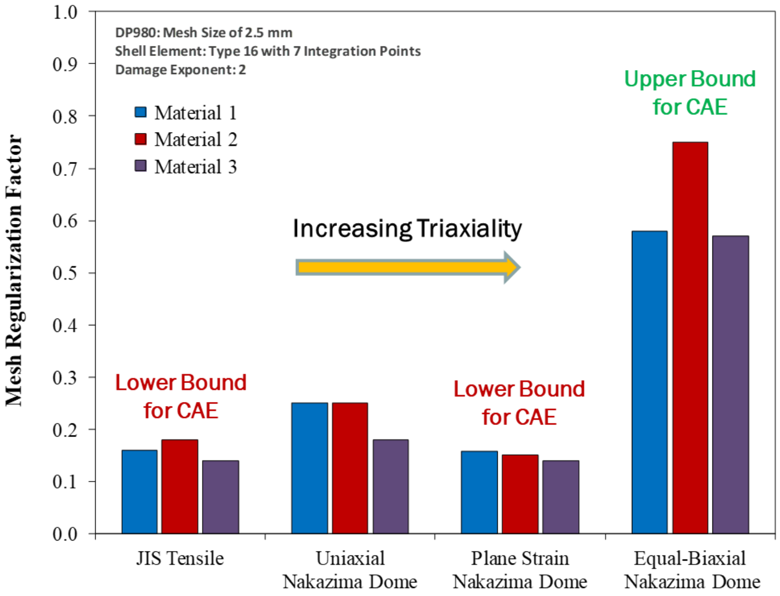
1. Biaxial requires least regularization
2. Uniaxial dome
3. JIS & PS Dome are similar & lowest

Same trends for other 2 DP980's



Regularization Results: 2.5 mm Mesh*

1. Plane Strain Dome ≈ JIS Tensile (severe regularization – lower bound for CAE)
2. Equal Biaxial Dome – Least amount of regularization (upper bound for CAE)
3. Uniaxial Dome – Similar but a bit higher than PS Dome and JIS

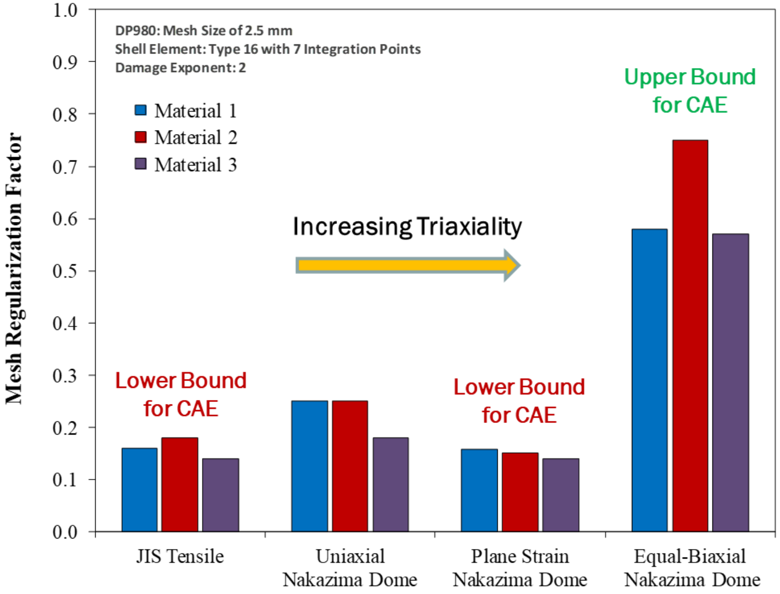


***Component models built with a 2.5 mm mesh size**

Regularization Results: 2.5 mm Mesh*

Expect Choice of Regularization Factor to be Application Dependent

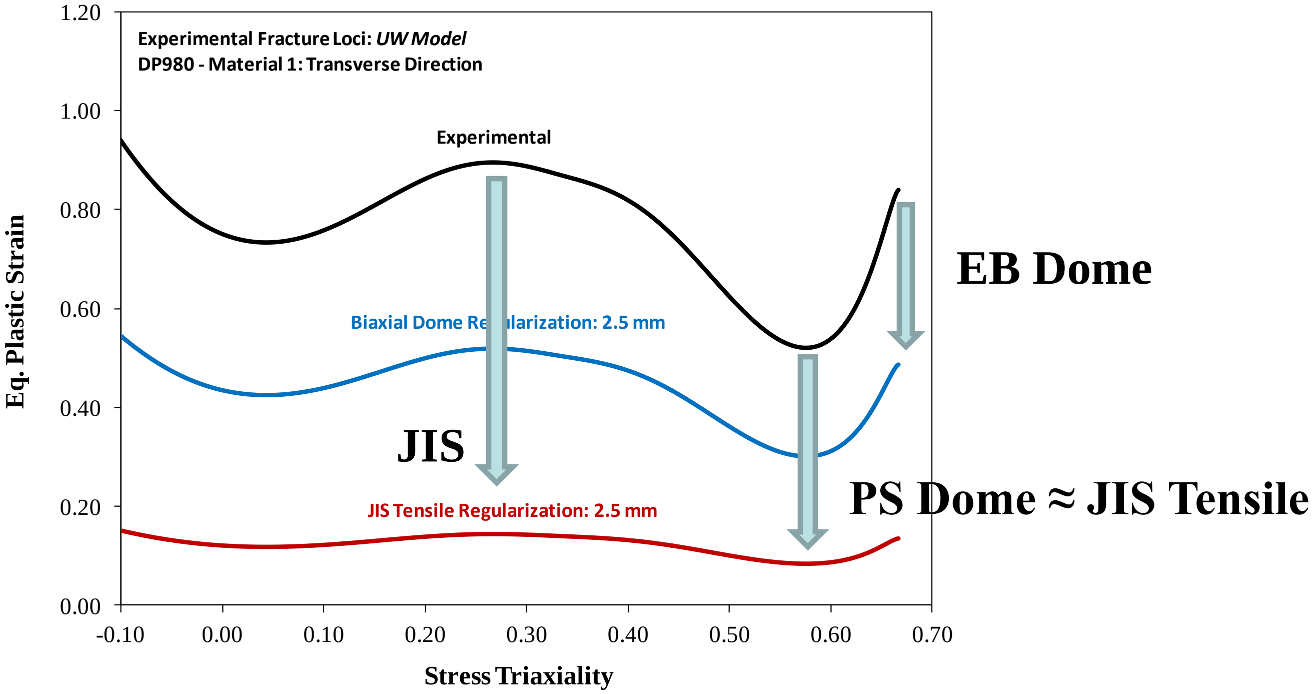
1. For Moderately Uniform Sheet Stretching → PS Dome/JIS/UT Dome
2. For Bending, Folding, Crash → Nakazima Biaxial Dome



***Component models built with a 2.5 mm mesh size**

Stress-State Dependence: Create a Regularization Locus

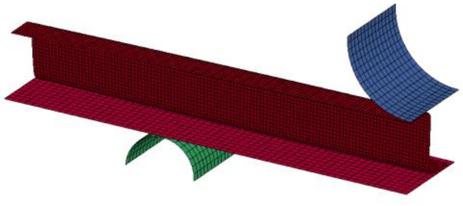
Calibrate a new failure locus with stress-state regularized values to obtain a *regularization locus*



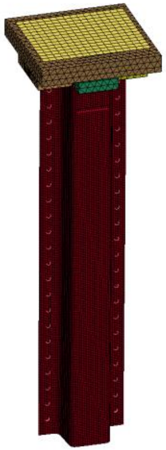
Regularized Fracture Loci for Component Tests

3 Strategies for Component Simulations

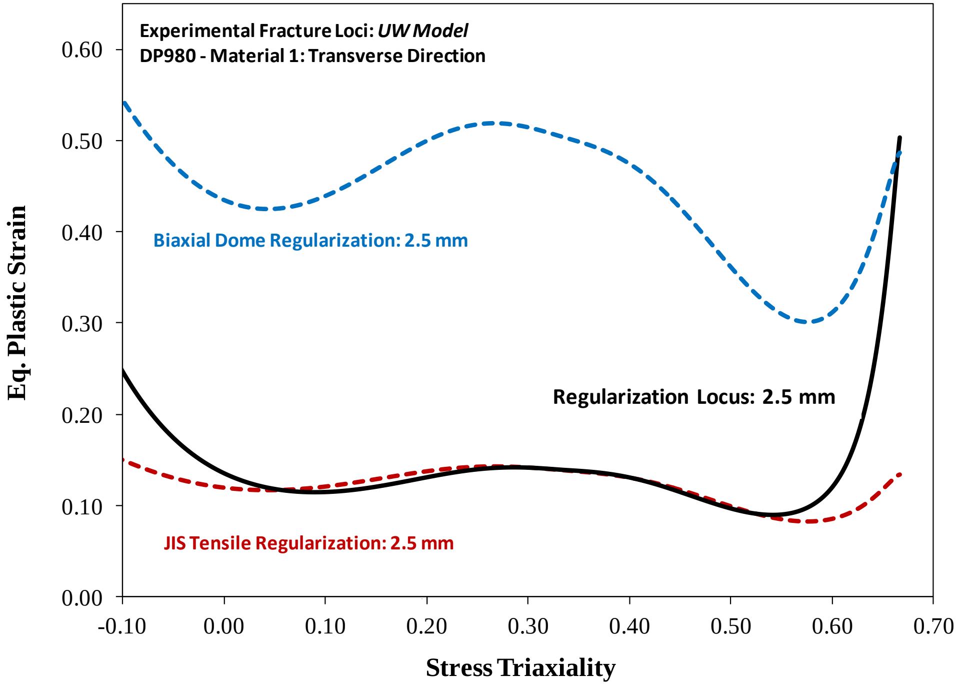
1. *JIS/PS Dome Regularization*
2. *Biaxial Dome Regularization*
3. *Regularization Locus*



3-pt Bend Model (half symmetry)



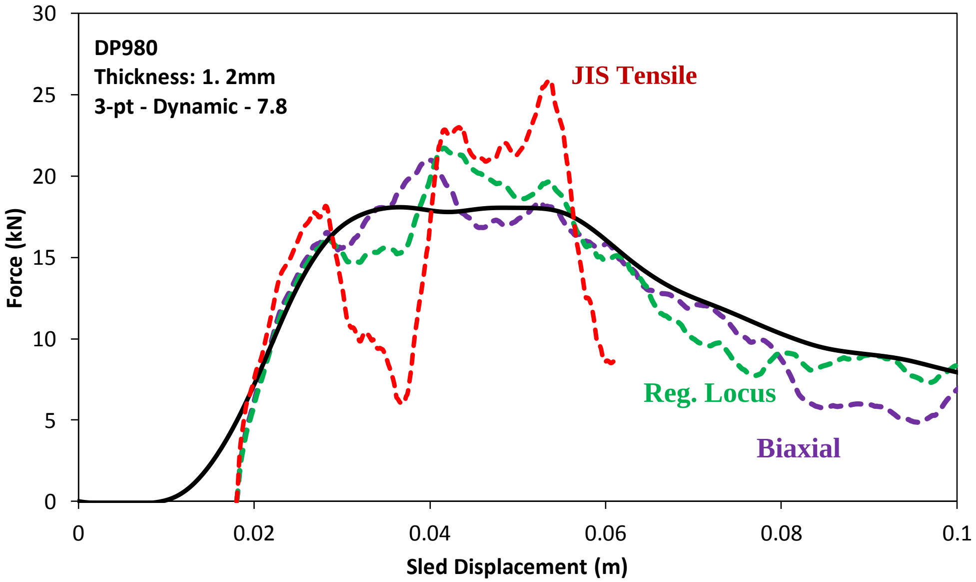
Axial Crush Model
(full symmetry)



Dynamic 3pt Bend of DP980: *Force-Disp.*

JIS/PS Dome Regularization is too aggressive: Premature failure

EB Dome and Reg. Locus performed well: Local bending & folding



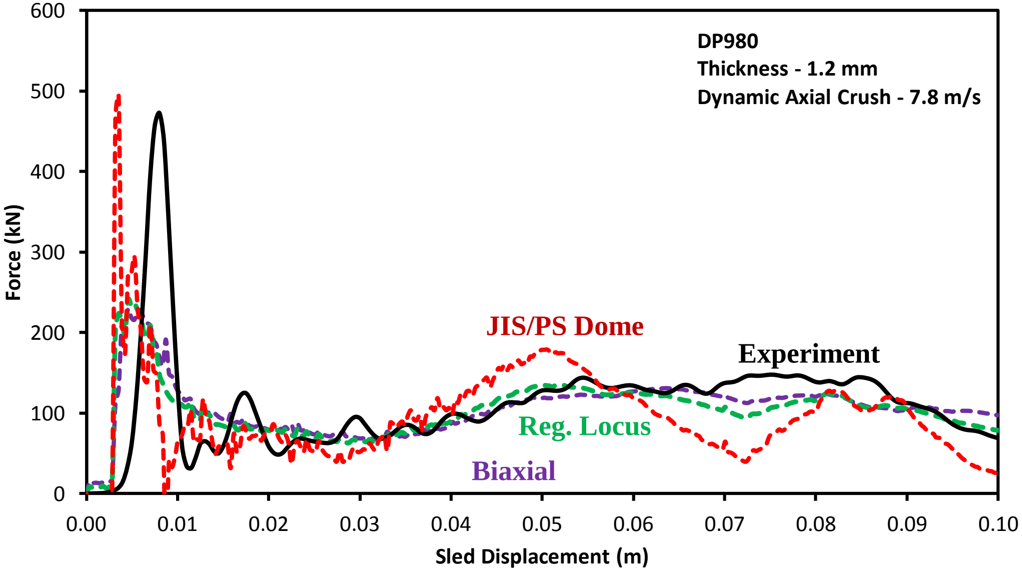
980 #1

Dynamic Axial Crush of DP980: *Force-Disp.*

JIS/PS Dome Regularization is too aggressive:

Near Instant failure that changes folding mode and leads to the high peak force

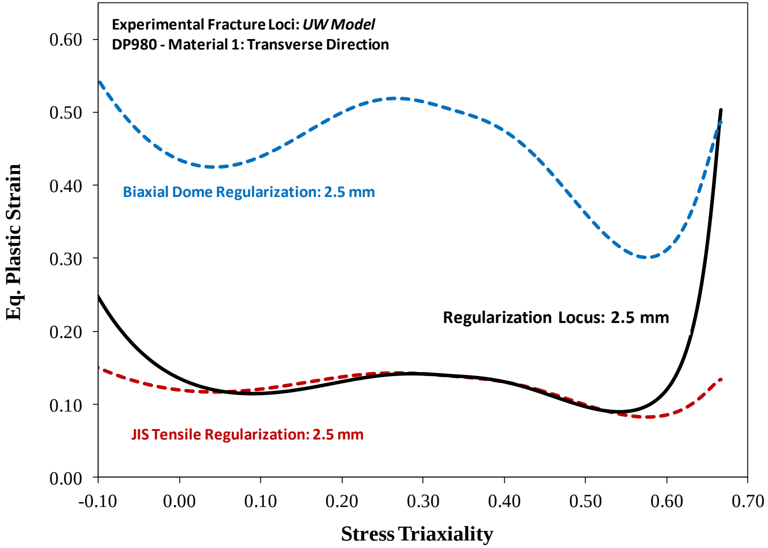
EB Dome and Reg. Locus perform well: Local bending & folding



Regularization for CAE Summary

Biaxial dome regularization can rapidly convert the exp. fracture locus to a CAE model for components

- shells are valid for biaxial dome simulation
- can use large mesh sizes
- simple test & model



Regularization locus will give best performance in both coupon and component simulations

- much more effort required to develop

Select biaxial dome regularization & apply to other component simulations

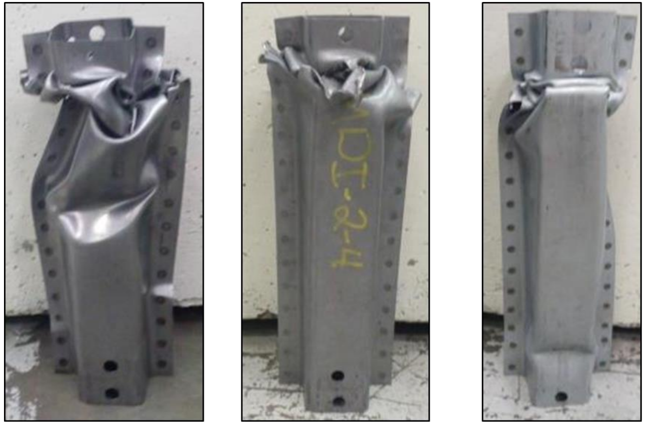
Selected Component Simulations

Quasi-Static & Dynamic Loading Cases:

1. No Damage Model
2. Damage Model without Regularization
3. Damage Model with Biaxial Regularization

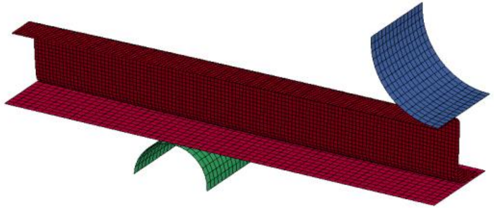
Dynamic 3-Point Bend

Dynamic Axial Crush



Material #1: $t = 1.2$ mm   Material #2: $t = 1.6$ mm   Material #3: $t = 1.4$ mm

Axial Crush Model

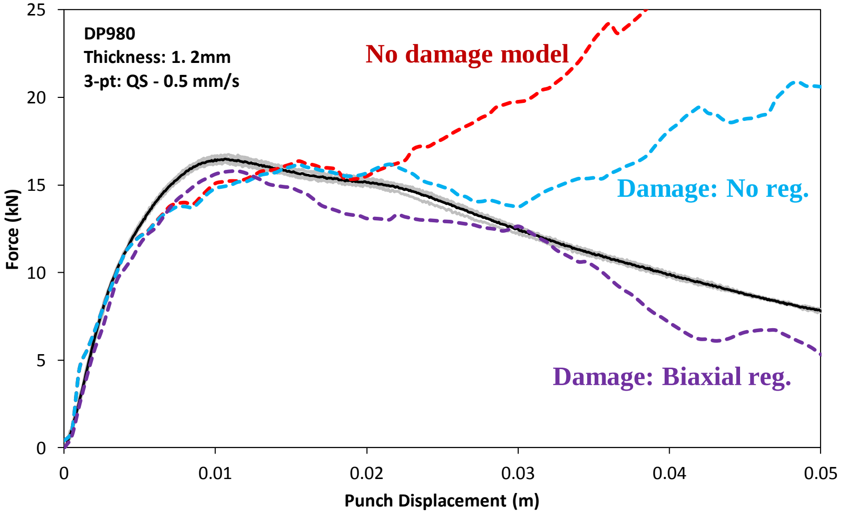


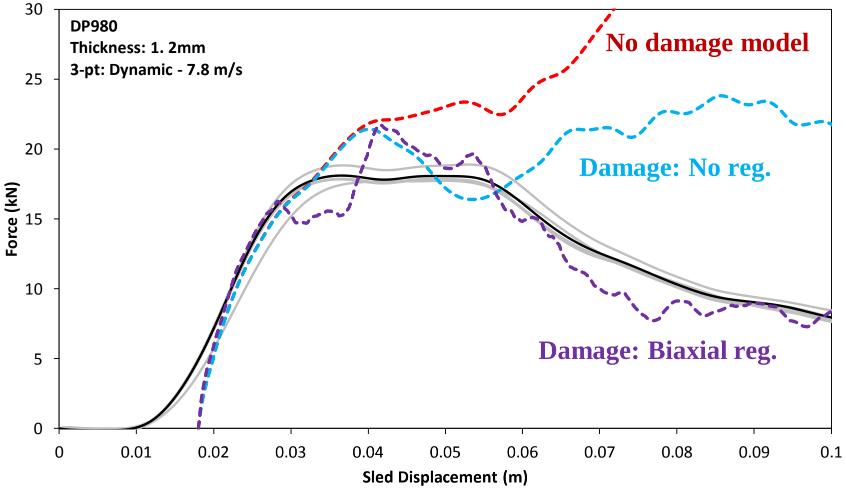
3-pt Bend Model (half symmetry)

3-Pt Bend: Quasi-static & Dynamic: Material 1 (1.2 mm)

Force vs. Displacement Results

Experimental Fracture Locus + Biaxial Regularization can give good CAE predictions in 3-Pt Bend





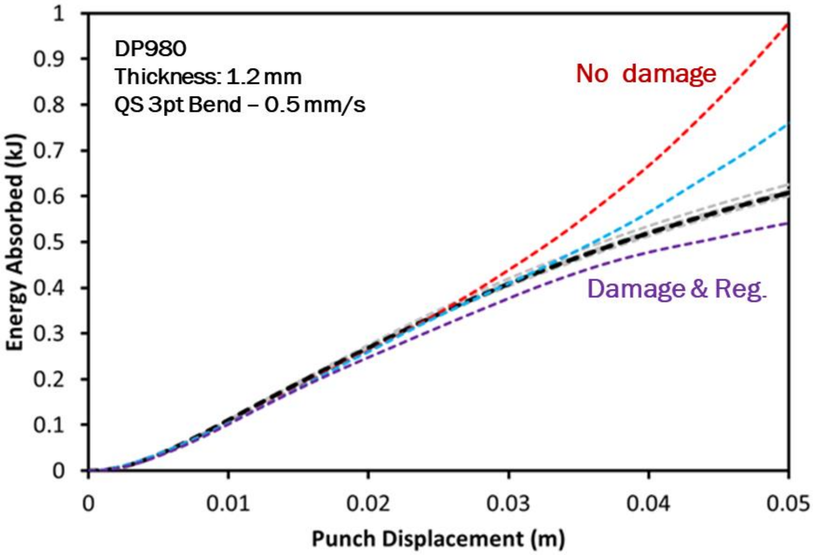
Quasi-static 3pt Bend – 0.5 mm/s

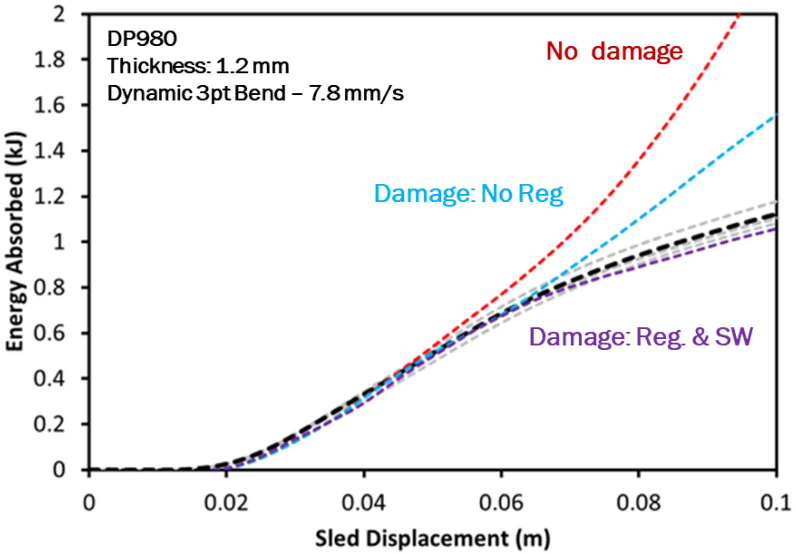
Dynamic 3pt Bend – 7.8 mm/s

3-Pt Bend: Quasi-static & Dynamic: Material 1 (1.2 mm)

Energy Absorption

Experimental Fracture Locus + Biaxial Regularization can give good CAE predictions in 3-Pt Bend



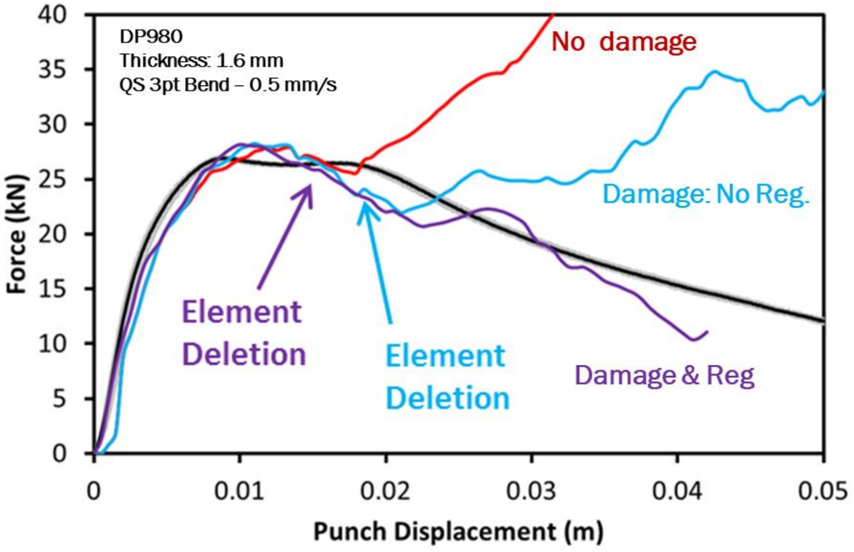


Quasi-static 3pt Bend – 0.5 mm/s

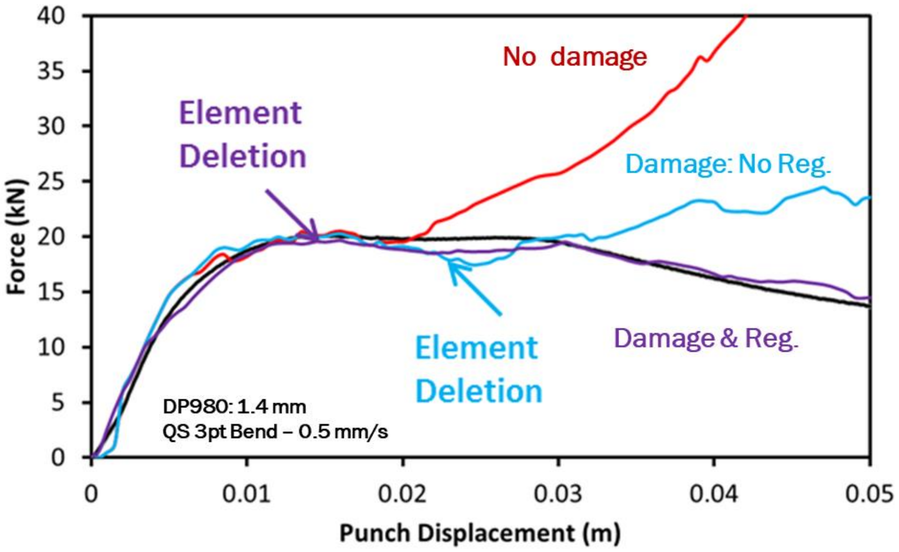
Dynamic 3pt Bend – 7.8 mm/s

Similar Results for Other DP980's

Quasi-static 3pt Bend – 0.5 mm/s



DP980 – Material 2

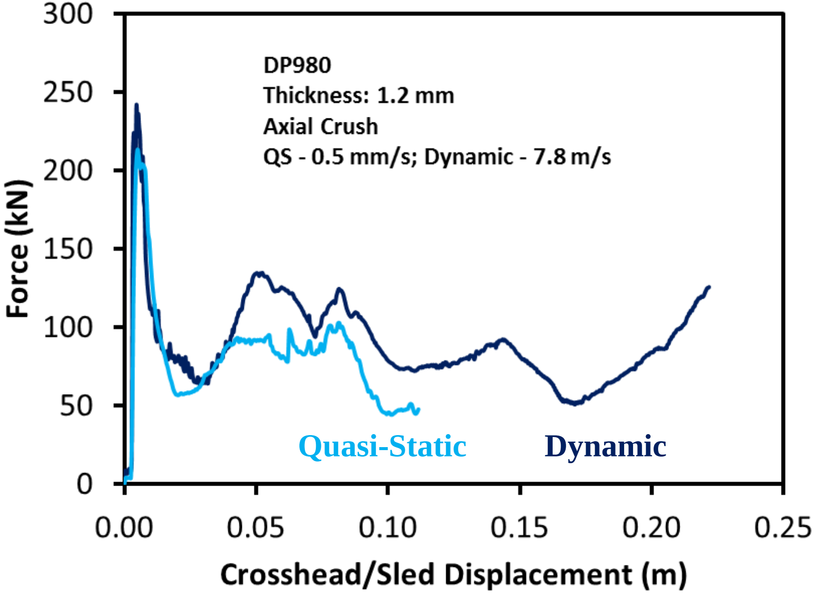


DP980 – Material 3

Comparison of Quasi-Static (QS) and Dynamic Axial Crush

Numerical deformation modes are markedly different in QS and Dynamic crush: ***Strain-rate & inertial effects***

Added a force-based spot weld failure criterion

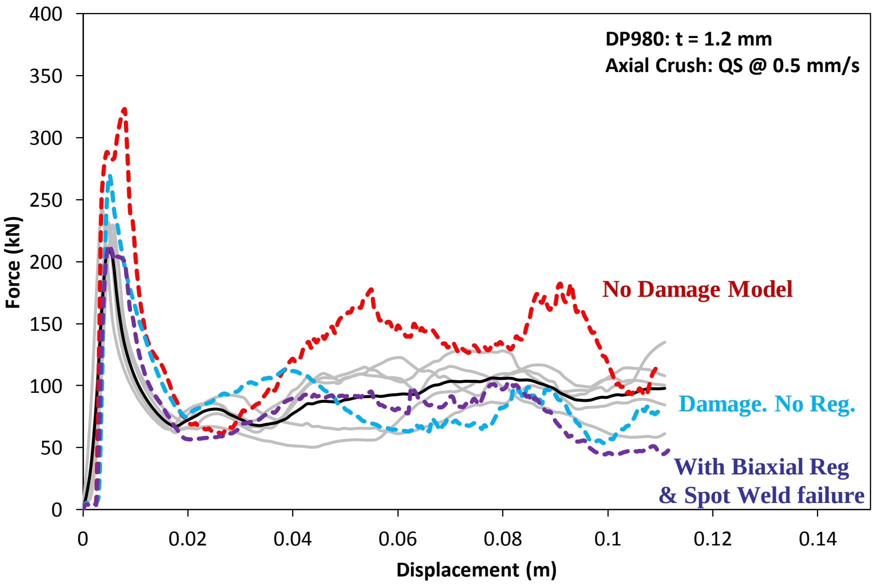


Quasi-Static

Dynamic

QS Axial Crush: Material 1

Force-Displacement



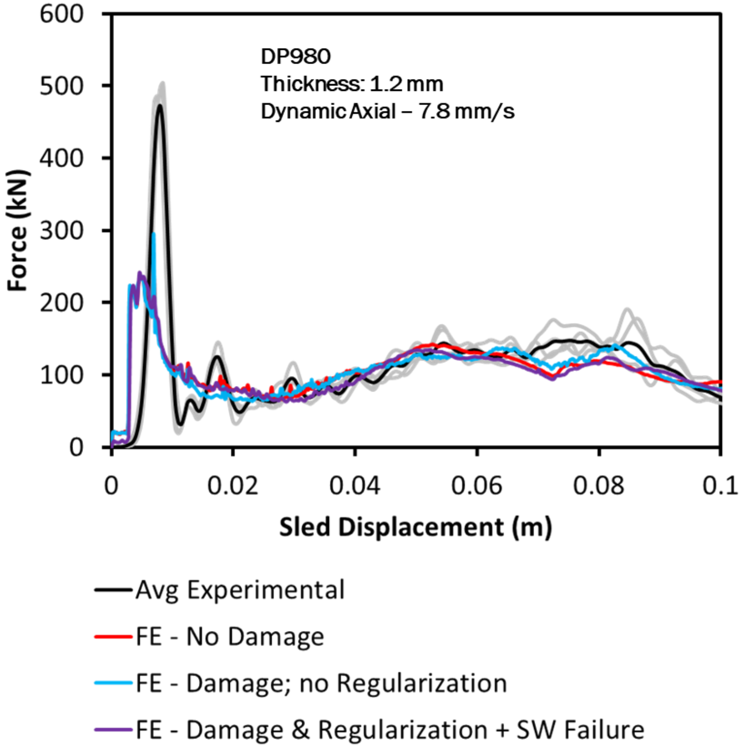
Progressive Folding
(No Damage Model)

Progressive Folding
(Damage without Reg.)

Progressive Folding:
3 SW failures
(Damage + Reg. + SW Failure

Dynamic Axial Crush: Material 1

Force-Displacement



Mixed Buckling/
Folding
(No Damage Model)

Mixed Buckling/Folding
(Damage without Reg.)

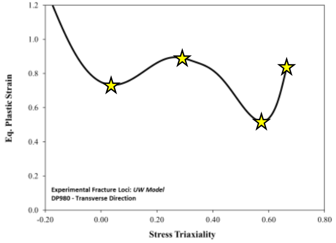
Progressive Folding:
1 SW failure
(Damage + Reg. + SW Failure)

Conclusion: “Direct” Strategy for Numerical Fracture Characterization Established

1. Start with the Experimental Fracture Locus

- Assume failure locus form & calibrate with 4 points

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

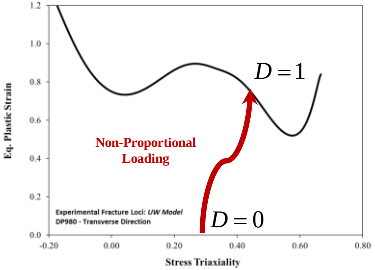


2. Assume a damage form for nonlinear loading

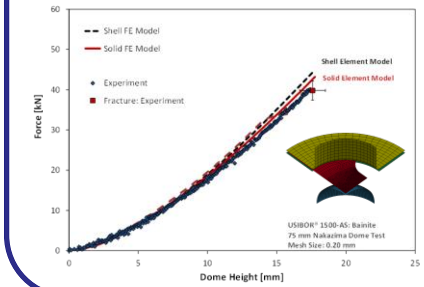
Examples:

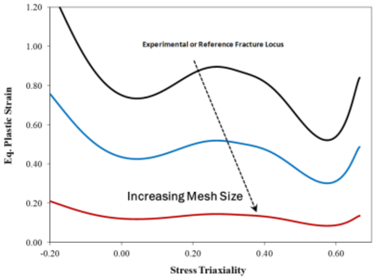
$$\Delta D^{JC} = \frac{\Delta\varepsilon^{p}}{\varepsilon_f^{exp}\left(T\right)}$$

$$\Delta D^{GISSMO} = \left[\frac{n}{\varepsilon_f^{exp}\left(T\right)} D^{\left(1-\frac{1}{n}\right)}\right]\Delta\varepsilon^{p}$$



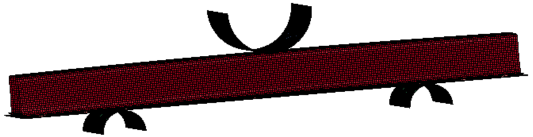
3. Plane Stress Models & Regularization





4. Apply to Structural Components

Static & Dynamic Conditions



3-Point Bend & Axial Crush of a 600 mm Rail:
2.5 mm element mesh

Outlook & Future Work

Have developed an industrially-focused methodology for efficient fracture characterization

The results are promising but much work remains:

- Application to sheet metal forming with severe non-proportional loading
- Application to sheet metal forming through to crash of an AHSS component
- Spot weld failure and potential un-zipping of weld groups
- Improve physics of damage model
- Need some physics to help guide regularization

Acknowledgements

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UNIVERSITY OF
WATERLOO

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