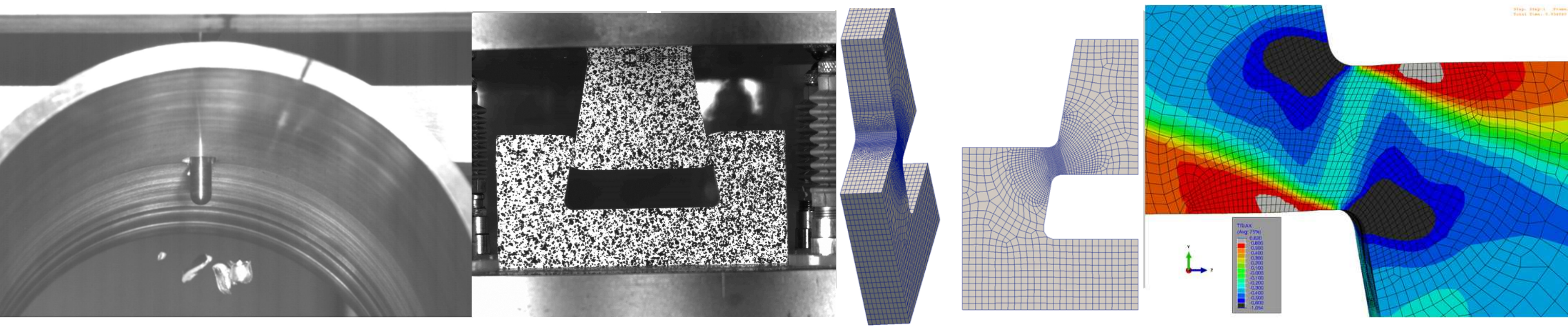
SAND2016-7972C

Exceptional service in the national interest

Sandia National Laboratories



Ductile Failure of Shear-Dominated "Hat" Specimens

Edmundo Corona

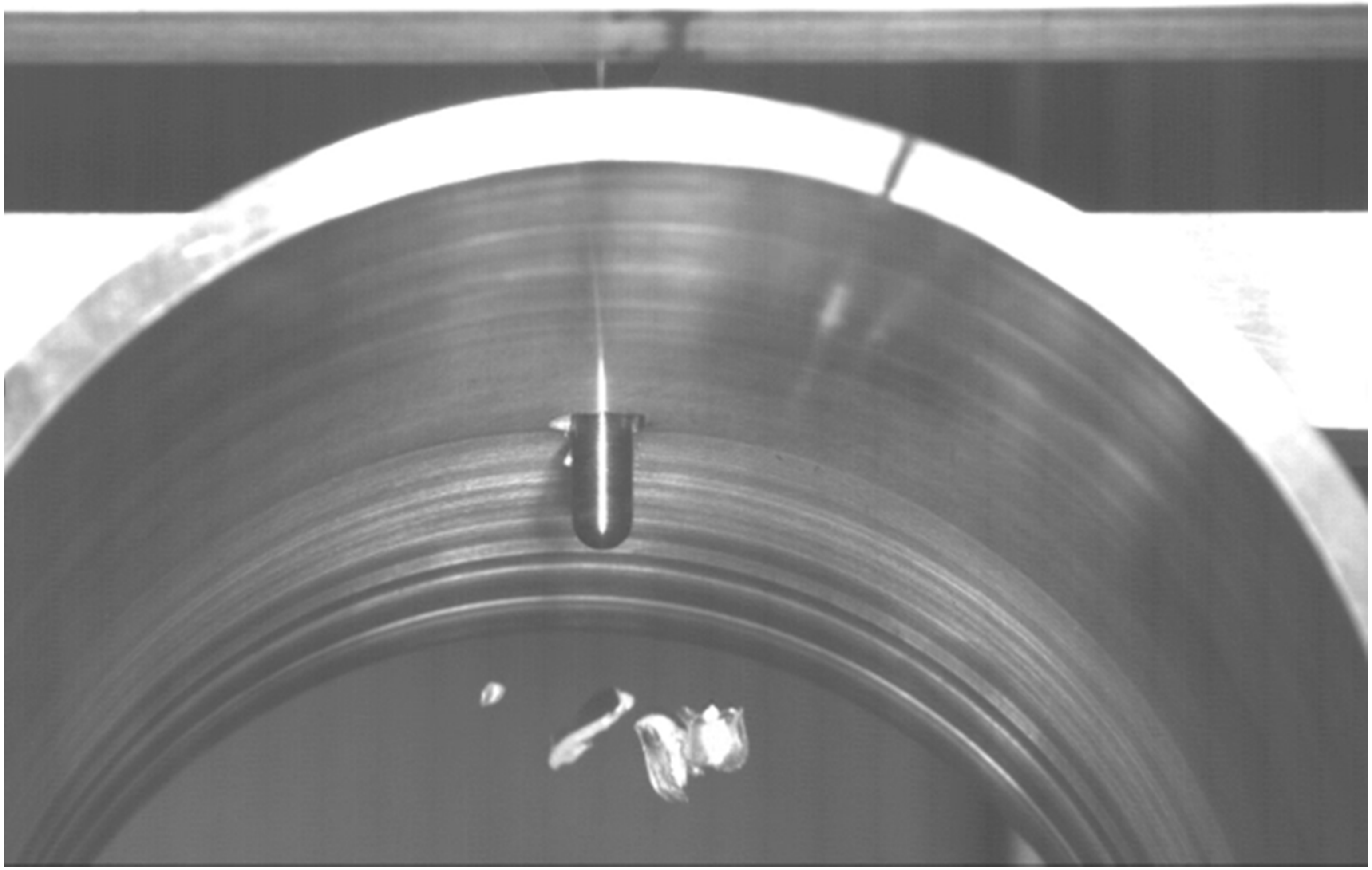
U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Acknowledgments

Brad Boyce: Specimen design
Theresa Cordova: Material testing
Lisa Deibler: Metallography and microscopy
Jack Heister: CAD
Mathew Ingraham: Hat specimen testing
Artis Jackson: Material testing
Darren Pendley: Material testing
Benjamin Reedlunn: Experimental data analysis, computational analysis
Brad Salzbrenner: Specimen Design, CAD
William Scherzinger: Constitutive and failure model implementation
Matthew Spletzer: Plate punch testing
Shelley Williams: Microscopy

Puncture of Al 7075 Tube by Cylindrical Punch



Objective/Outline

- Within the Johnson-Cook model, assess the dependence of material failure on stress triaxiality
- Conduct quasi-static tests and analysis to calibrate and evaluate the model
- Elastic-plastic response evaluated using J_2 flow rule with isotropic hardening
- Concentrate on a “hat” specimen geometry where failure is shear dominated
- Explore two materials: Al 7075-T651 and Steel A286

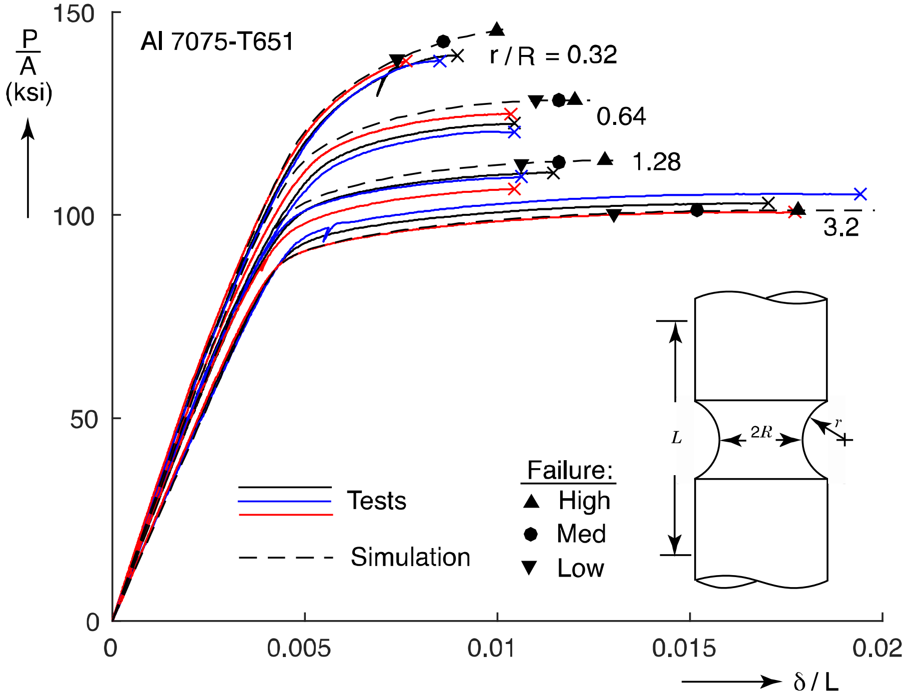
$$\varepsilon^p_{ef} = \left[d_1 + d_2 e^{d_3 \eta}\right] \left[1 + d_4 \ln\left(\frac{\dot{\varepsilon}^p_e}{\dot{\varepsilon}_o}\right)\right] \left[1 + d_5 \hat{T}\right]$$

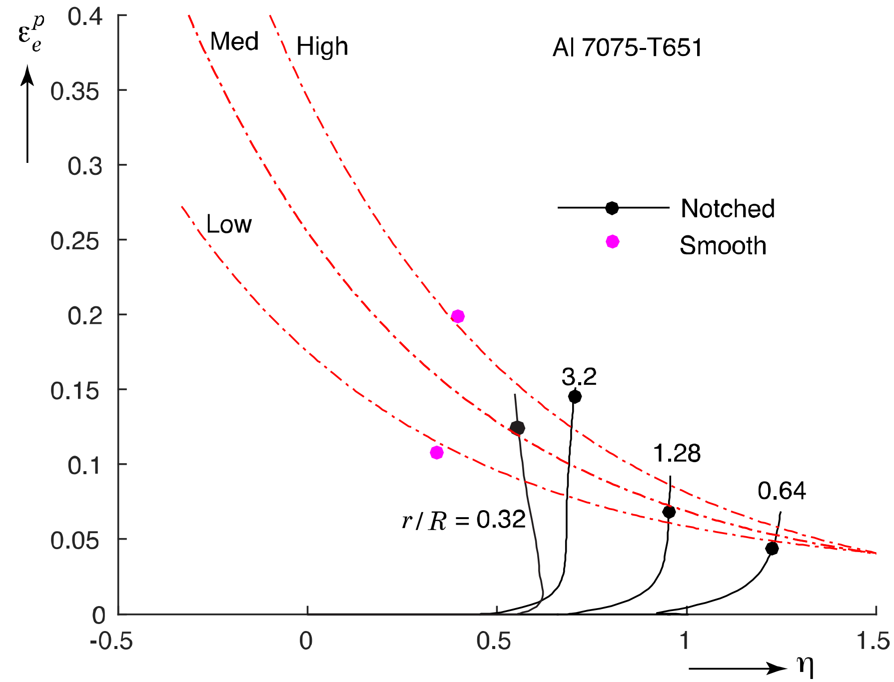
$$\bar{D} = \int \frac{d\hat{\varepsilon}^p_e}{\varepsilon^p_{ef}} \quad \text{and} \quad 0 \leq \bar{D} \leq 1$$

Al 7075-T651

Triaxiality Dependence (Al7075-T651)

$$\varepsilon^{p}_{ef} = d_1 + d_2 e^{d_3 \eta}$$

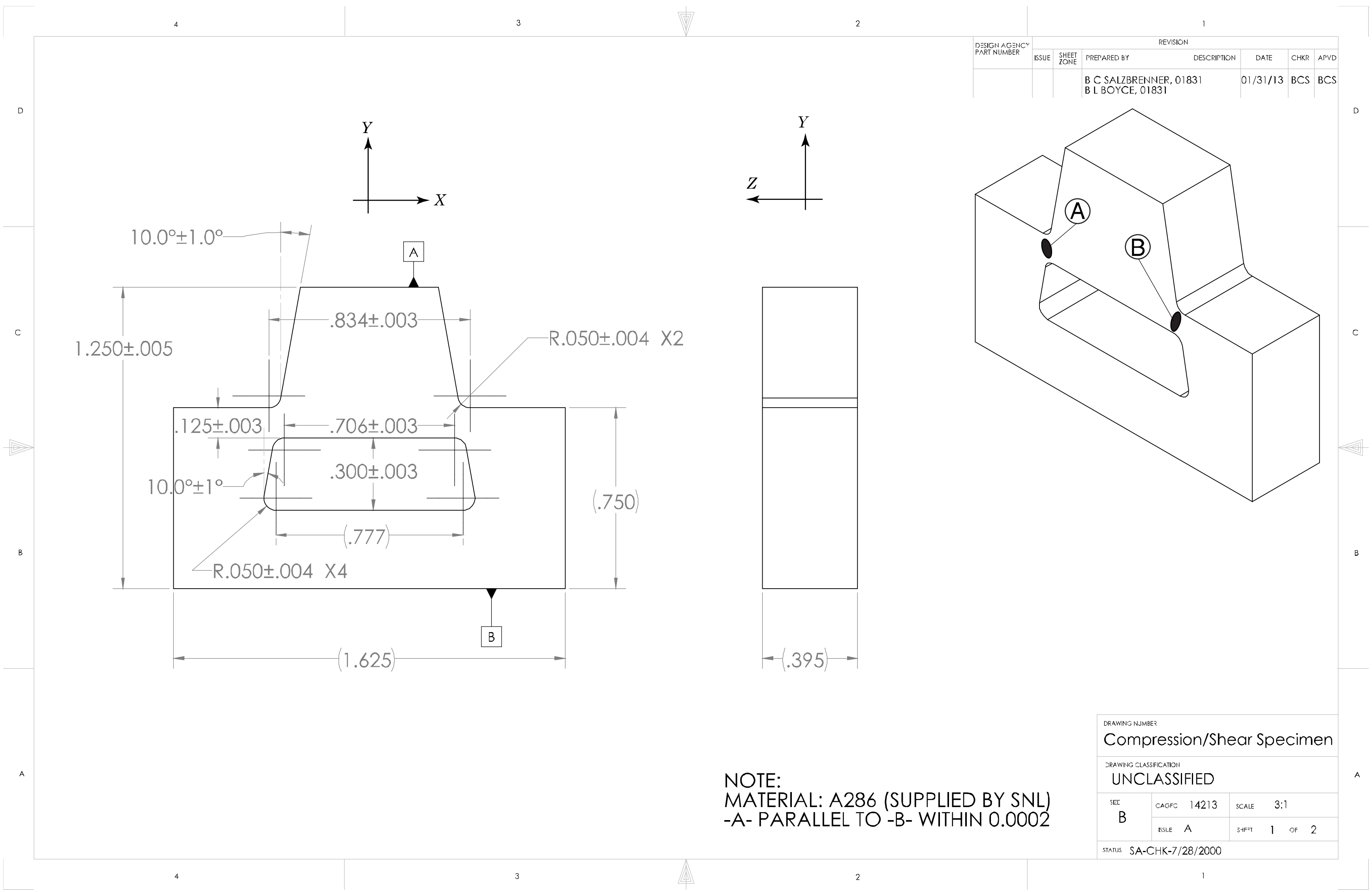




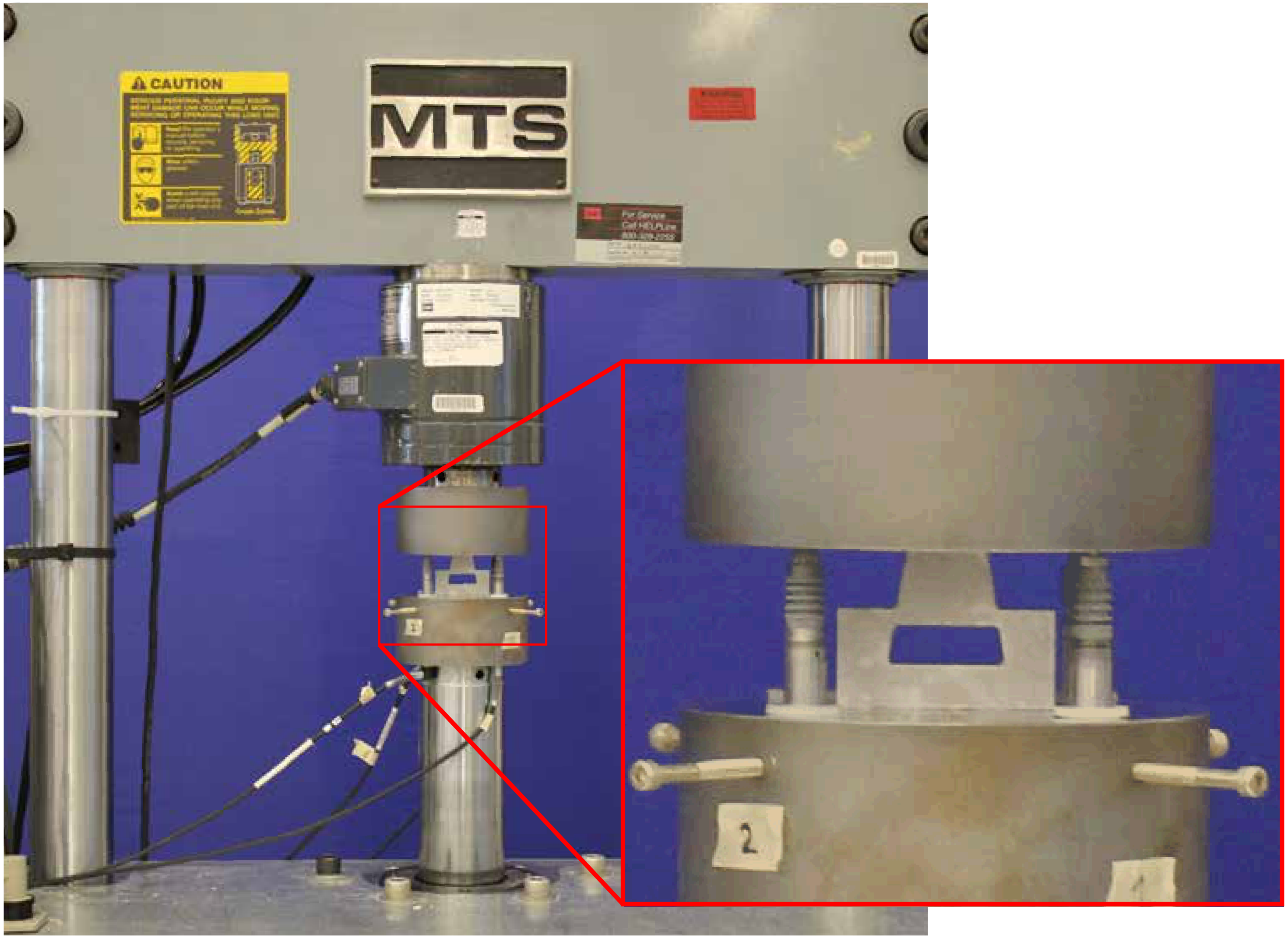
High:	(0.005, 0.34, -1.5)
Mid:	(0.015, 0.24, -1.5)
Low:	(0.000, 0.15, -1.5)

What about the region around η = 0?

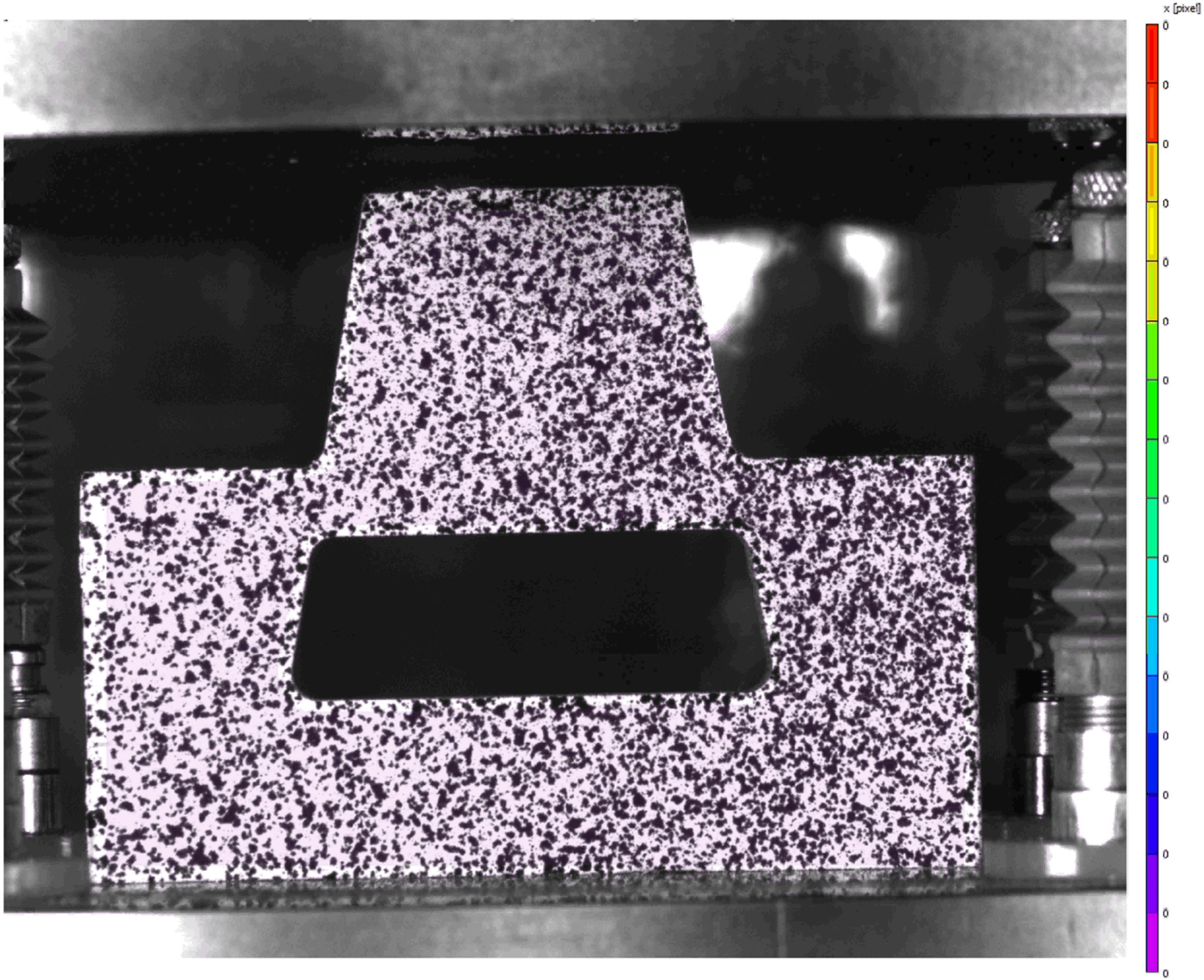
Hat Specimen Geometry



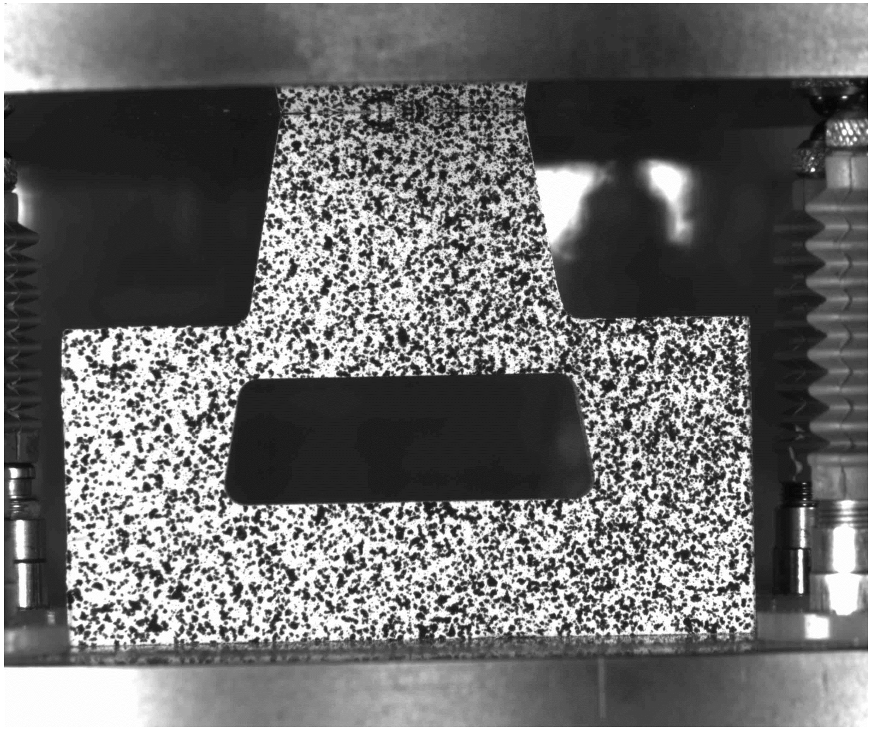
Test Configuration



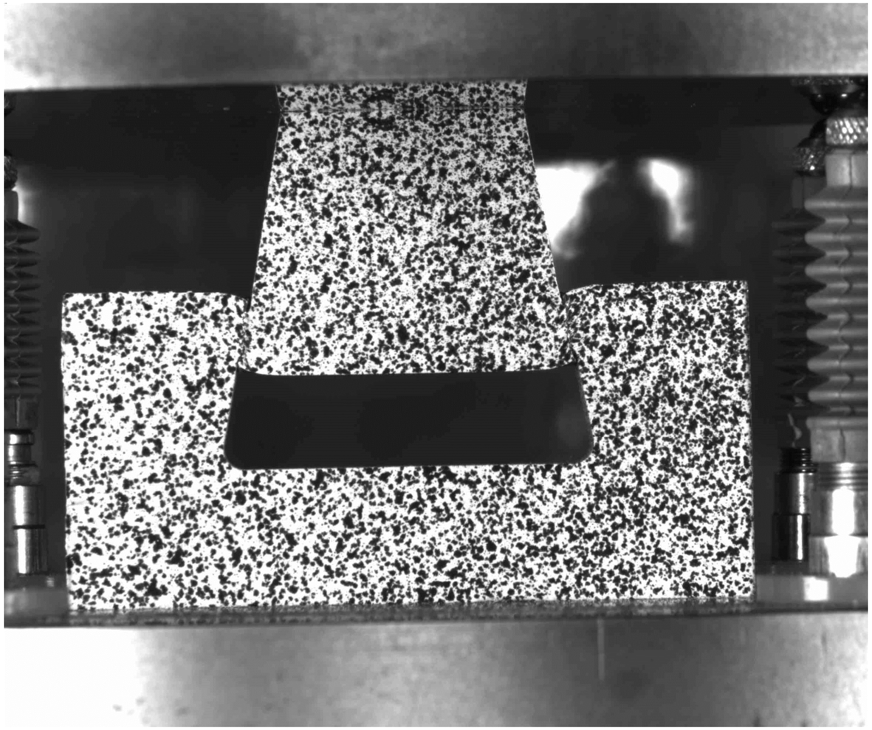
Test Results (Steel A286)



Test Results (Steel A286)

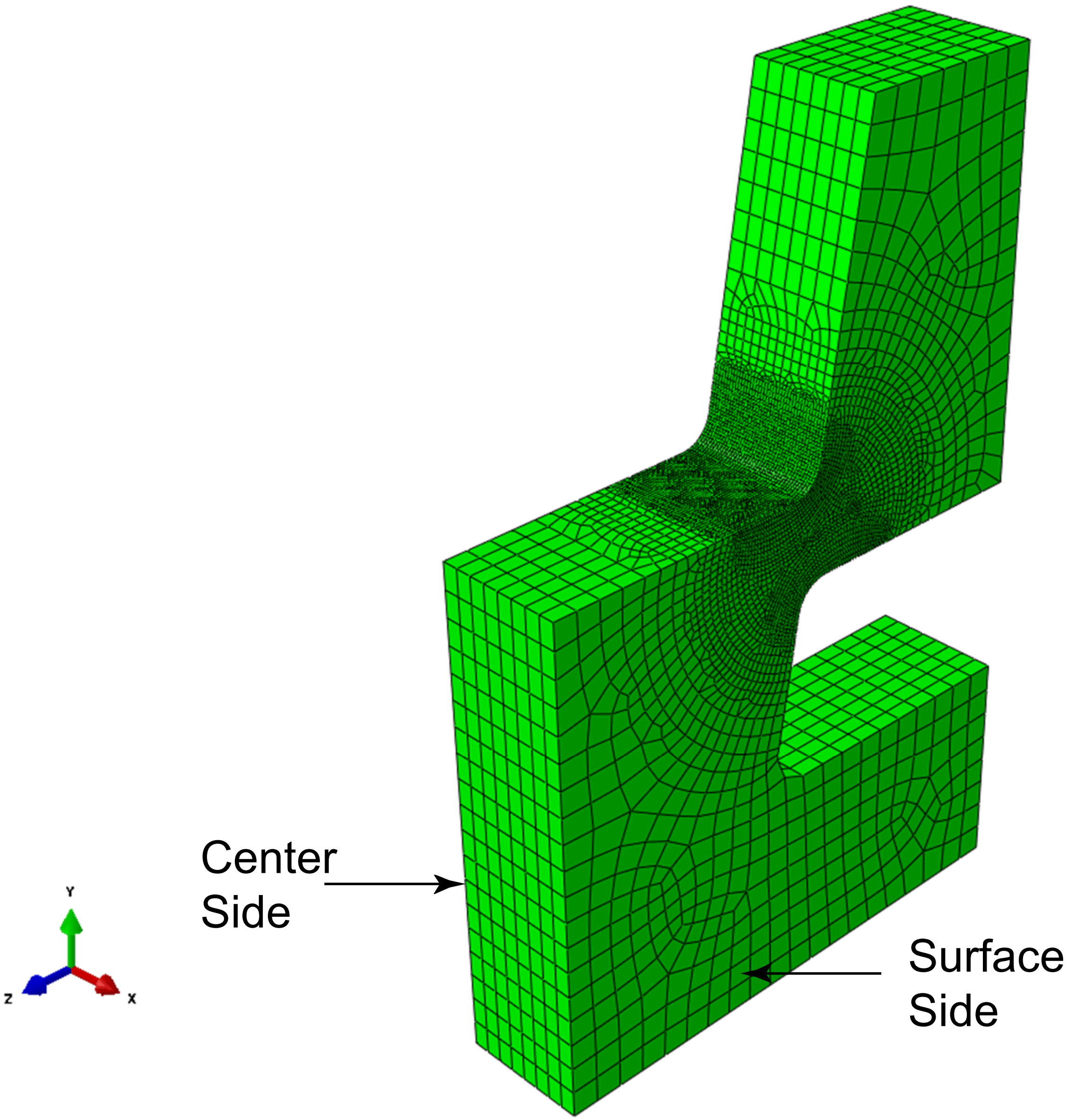


Test Start



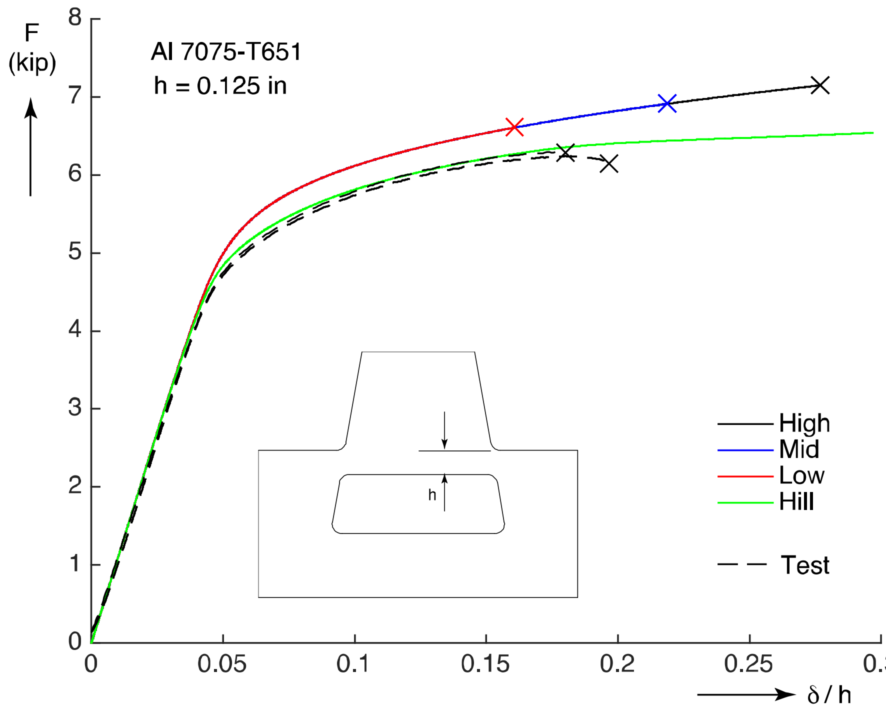
Just Before Failure

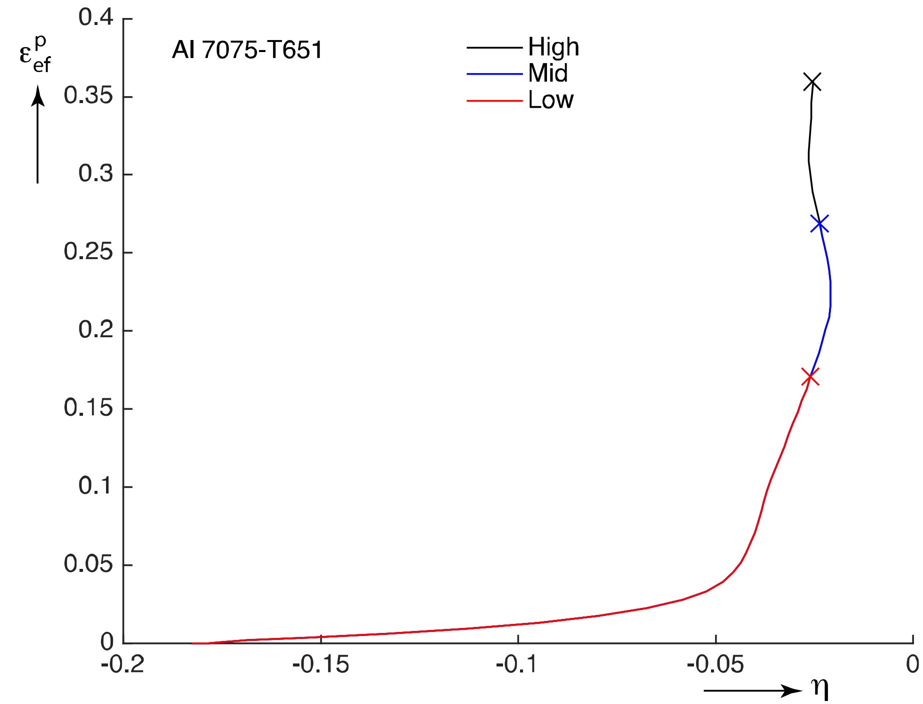
Finite Element Model



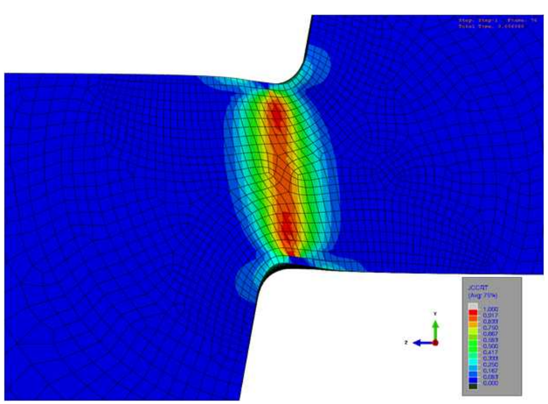
- Two planes of symmetry
- 8-node hexahedral elements
- Reduced integration elements
- Explicit dynamics formulation
- Smooth step loading
- Johnson-Cook material model
- Abaqus Code

Hat Specimen Results
Al 7075-T651

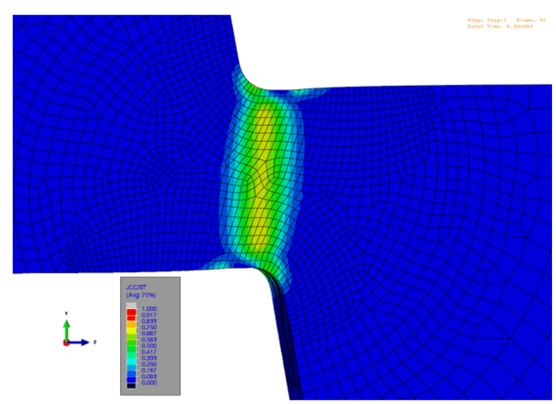




Surface

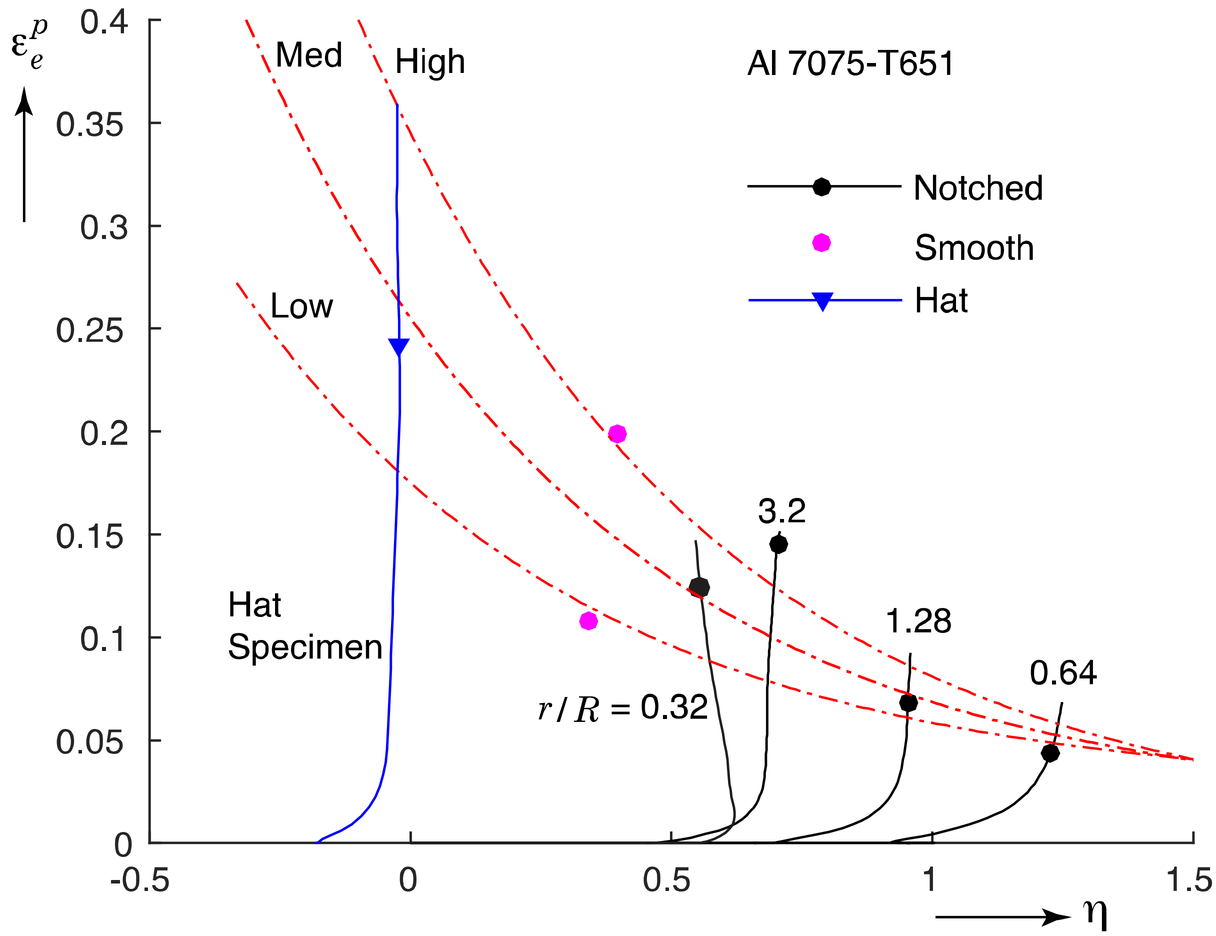


$\bar{D}$



Center

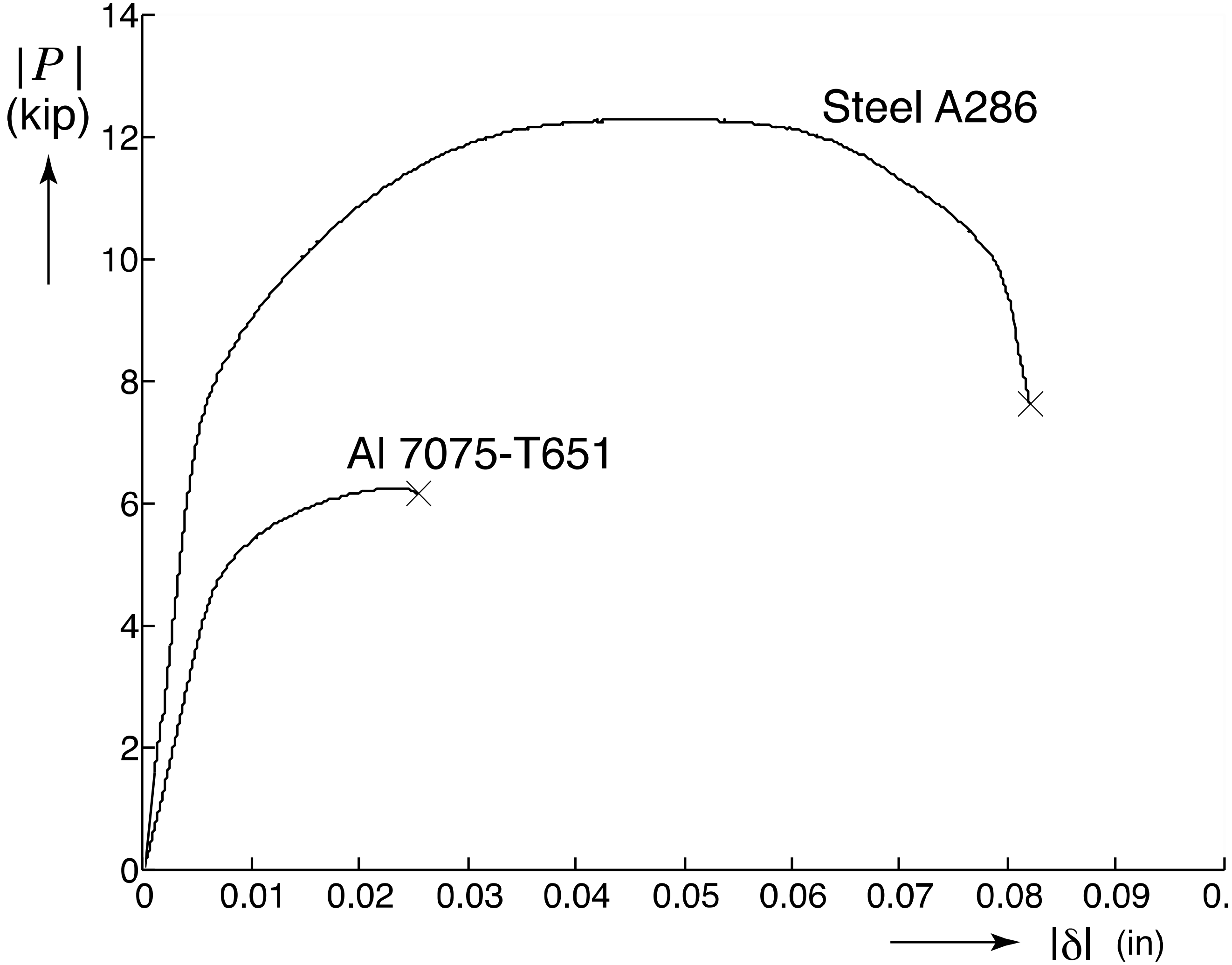
Triaxiality Dependence with Hat Specimen



- Johnson-Cook model fits data well
- Current results show preference for the “Med” fit.

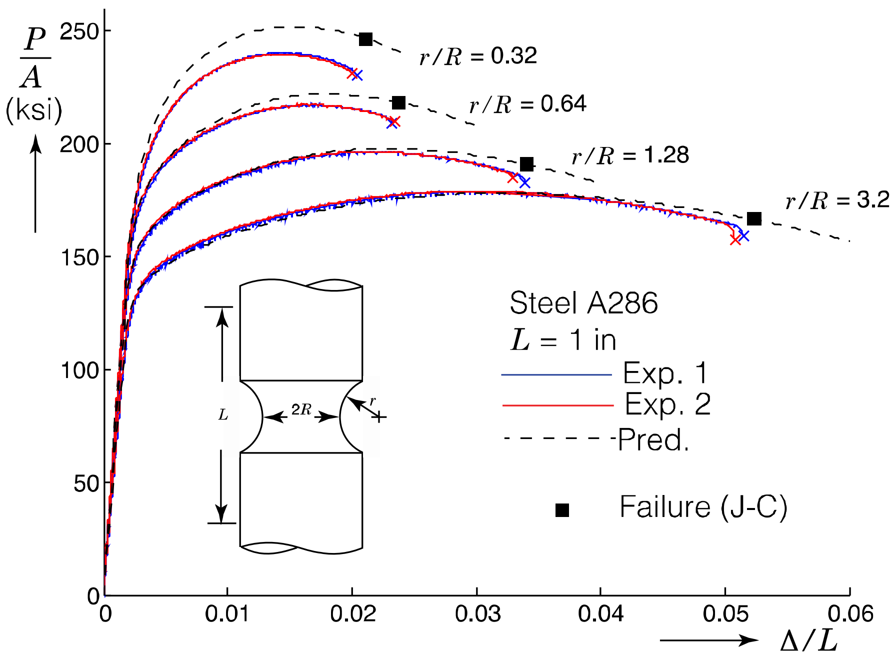
Steel A286

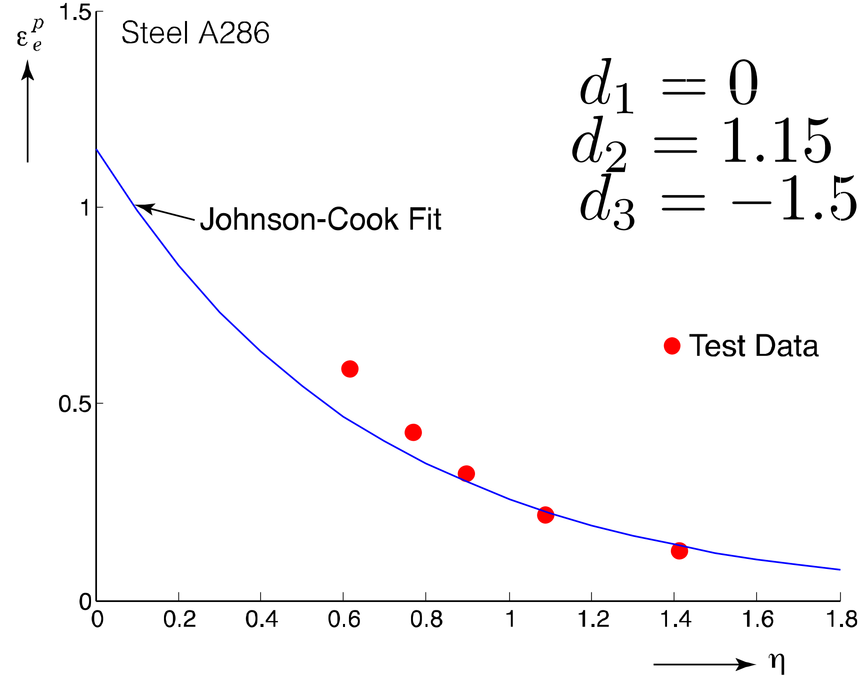
Load-Deflection Response



Johnson-Cook Failure Calibration for Steel A286

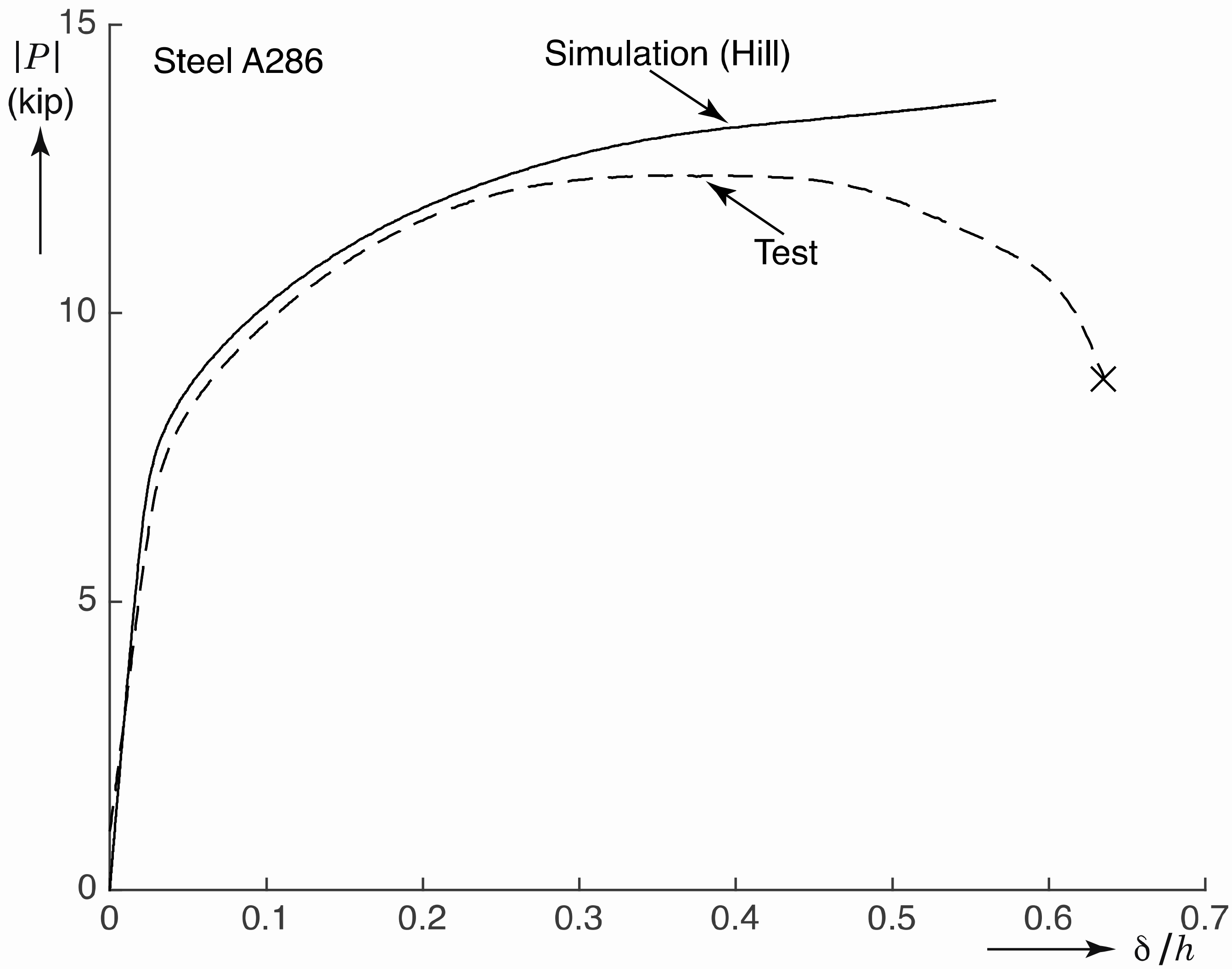
$$\varepsilon^p_{ef} = d_1 + d_2 e^{d_3 \eta}$$



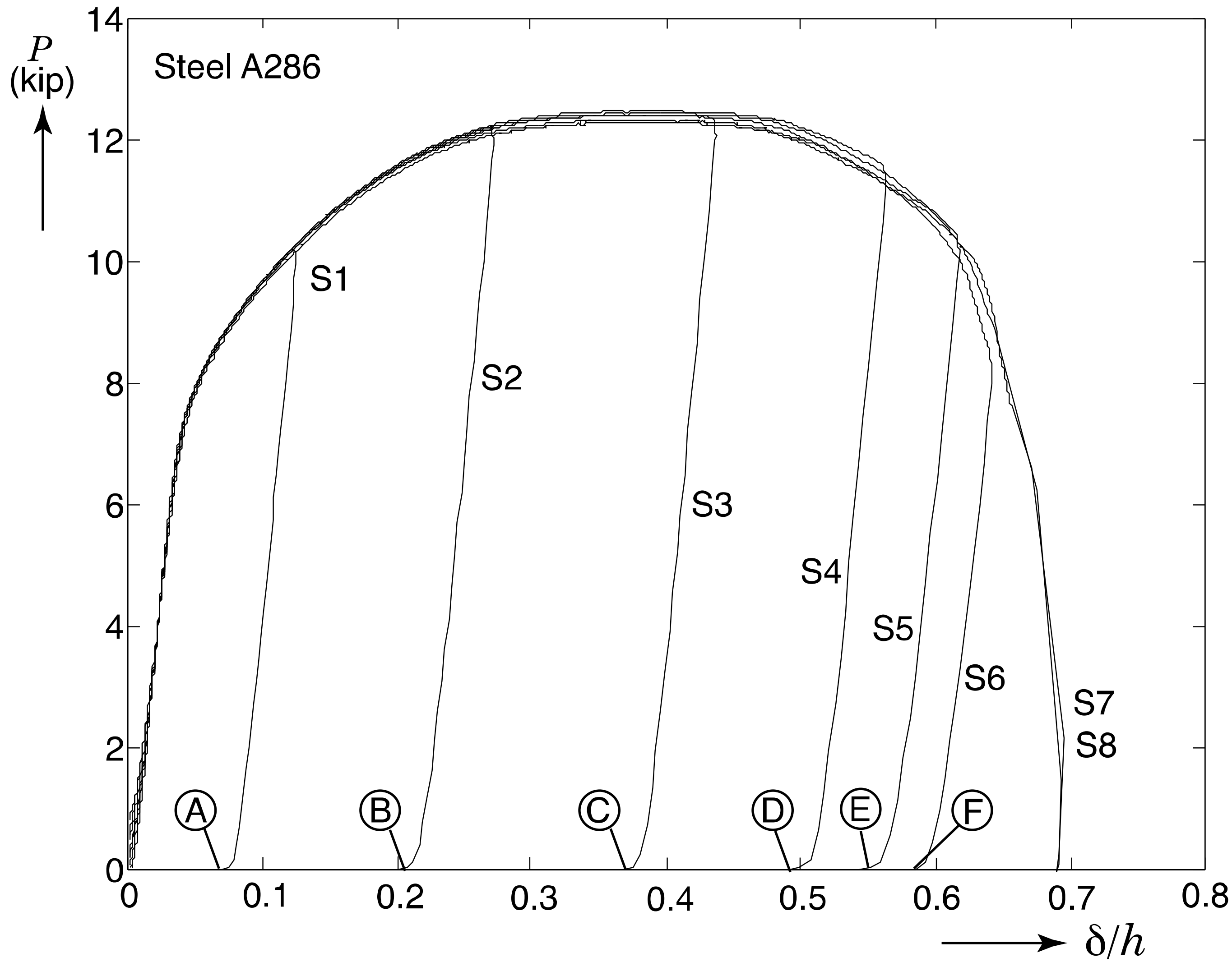


$$d_1 = 0$$
$$d_2 = 1.15$$
$$d_3 = -1.5$$

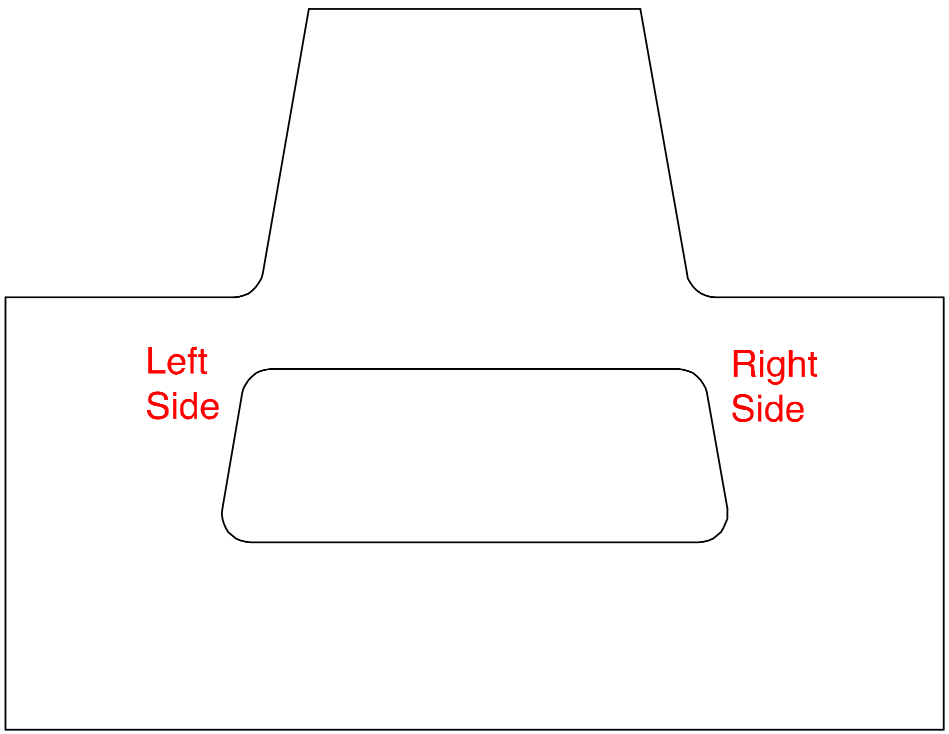
Measured and Predicted Response for Hat Specimen Steel A286

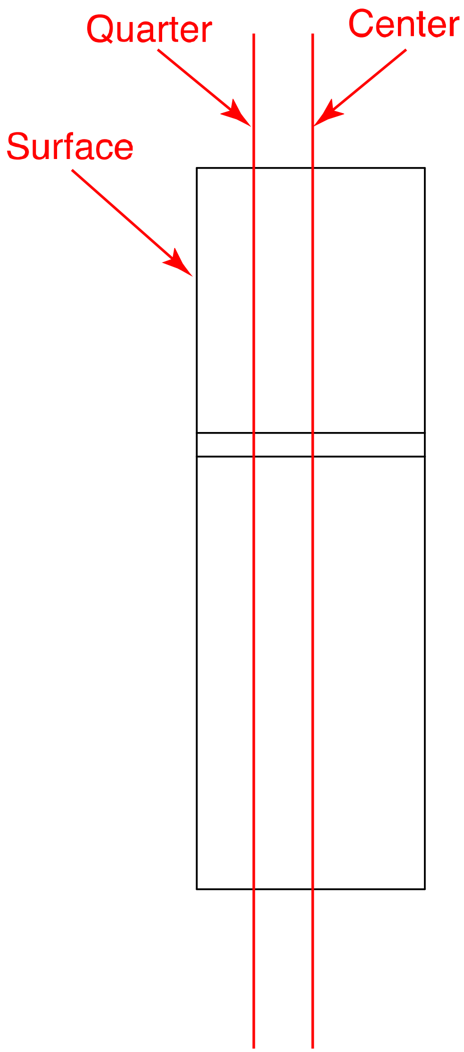


Load-Deflection Responses for All Steel A286 Specimens



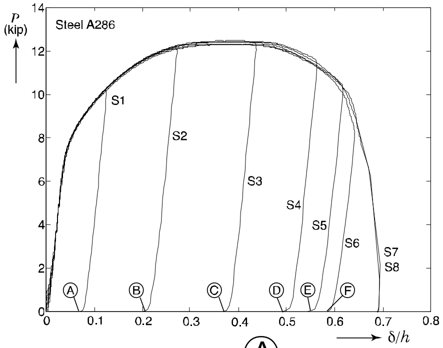
Specimen Sectioning

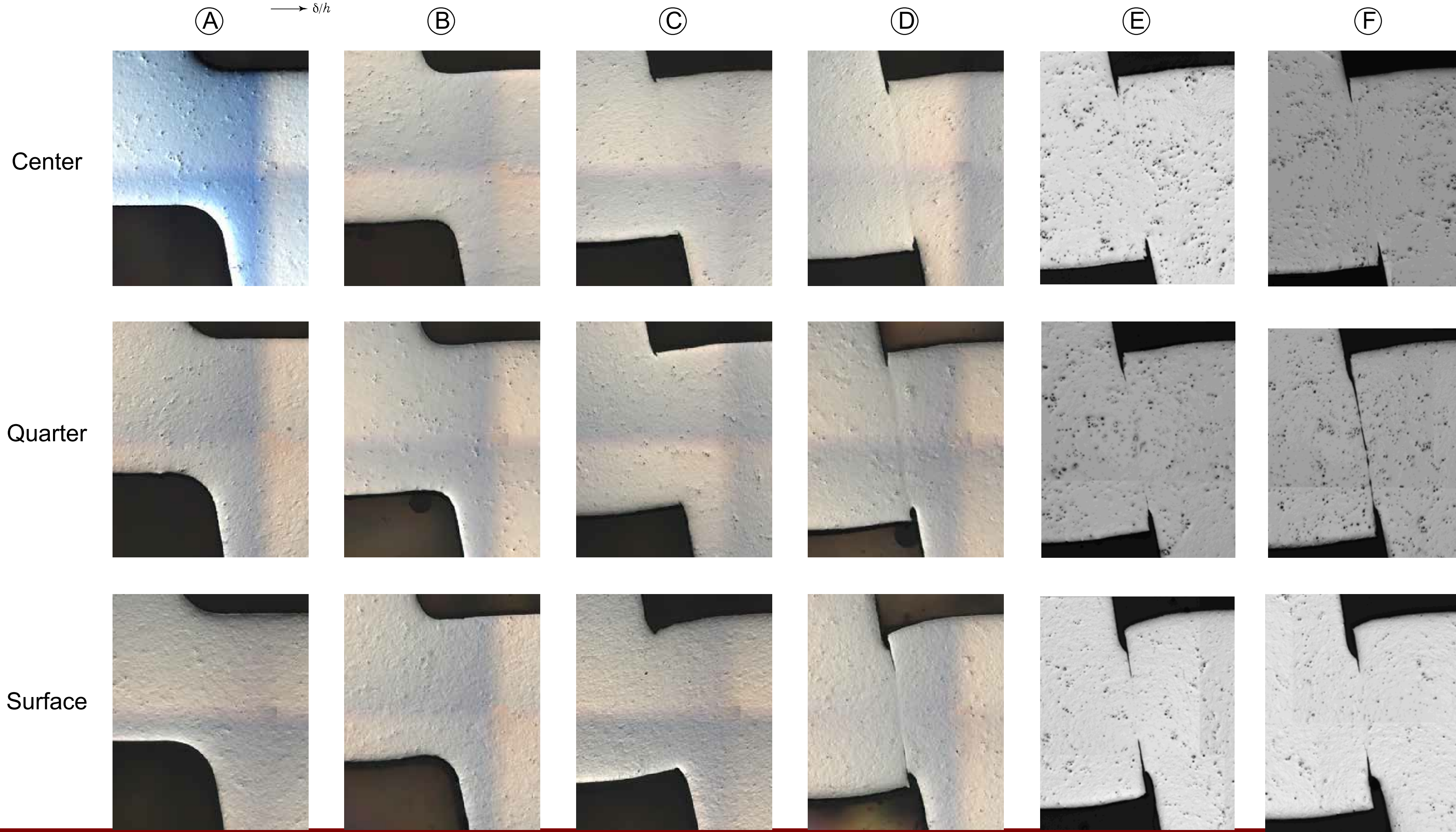




Micrographs for Steel A286 Specimens (Right Side)

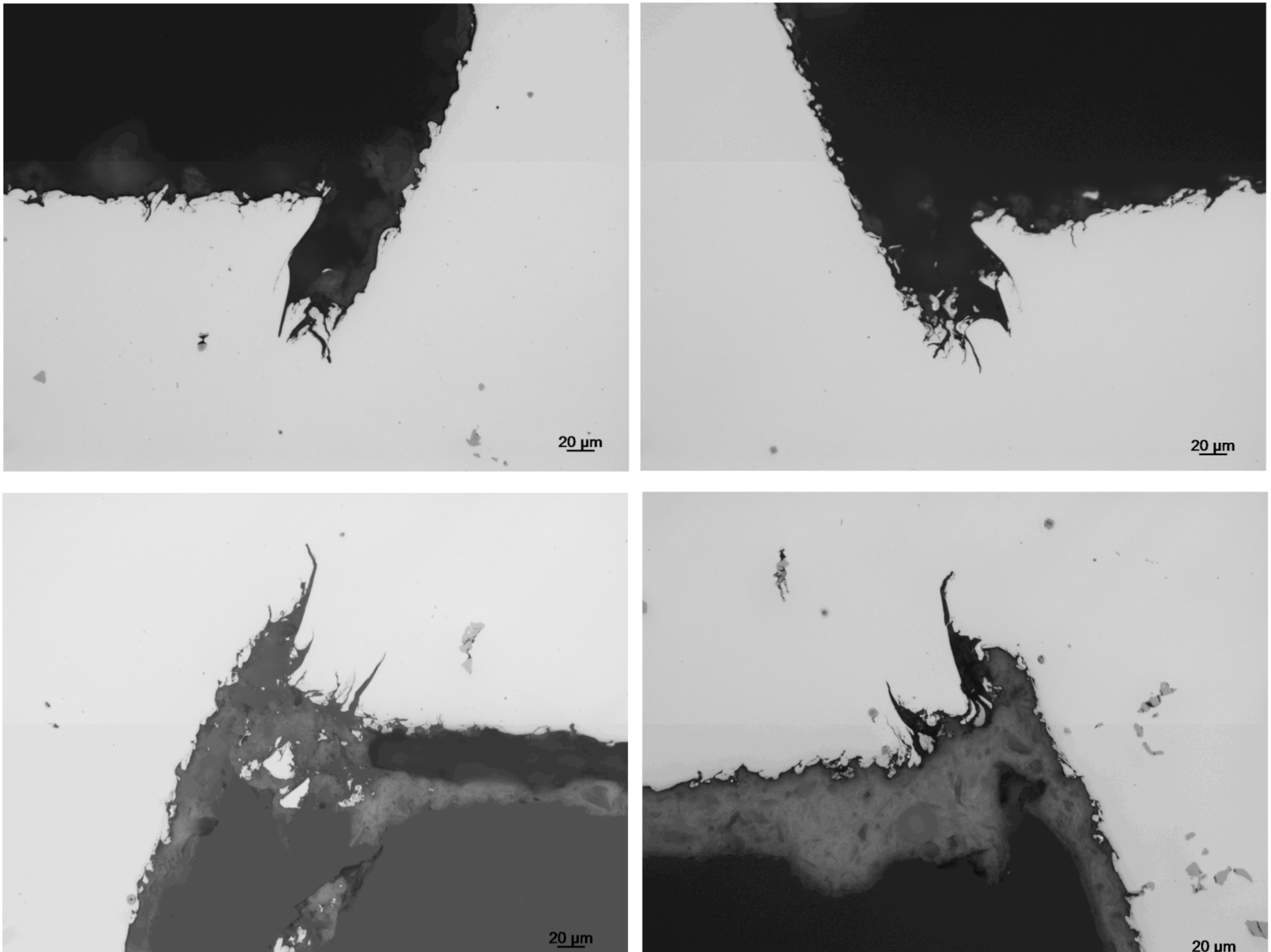
Sandia National Laboratories



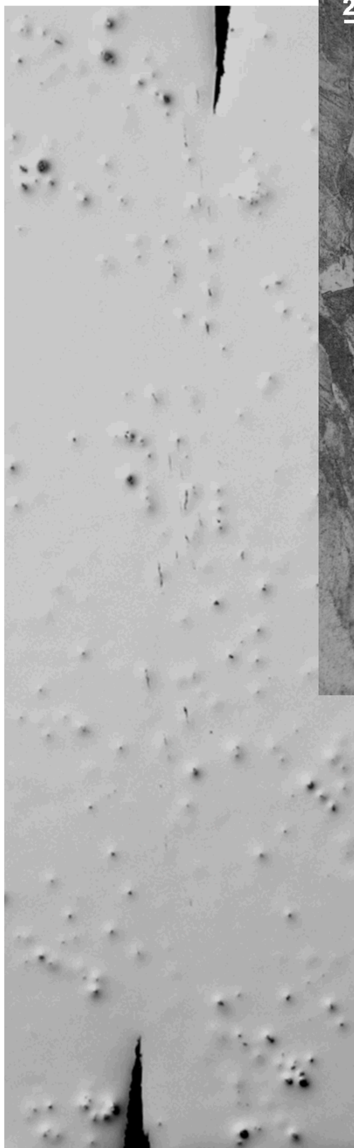


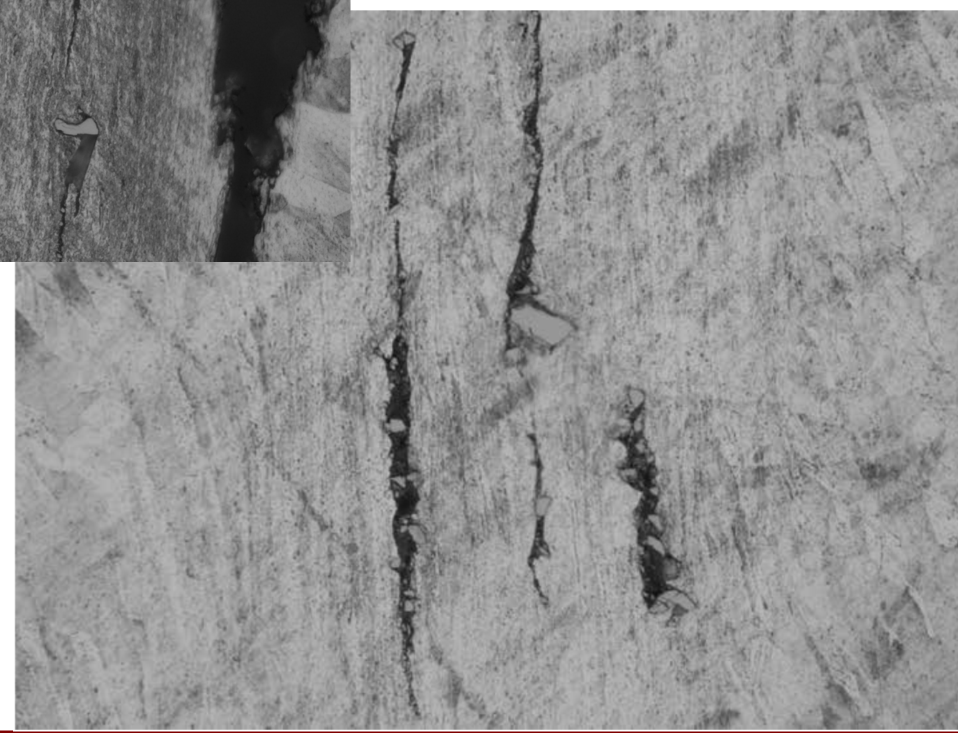
Four Critical Regions Center of S3 (Max Load)

Sandia National Laboratories

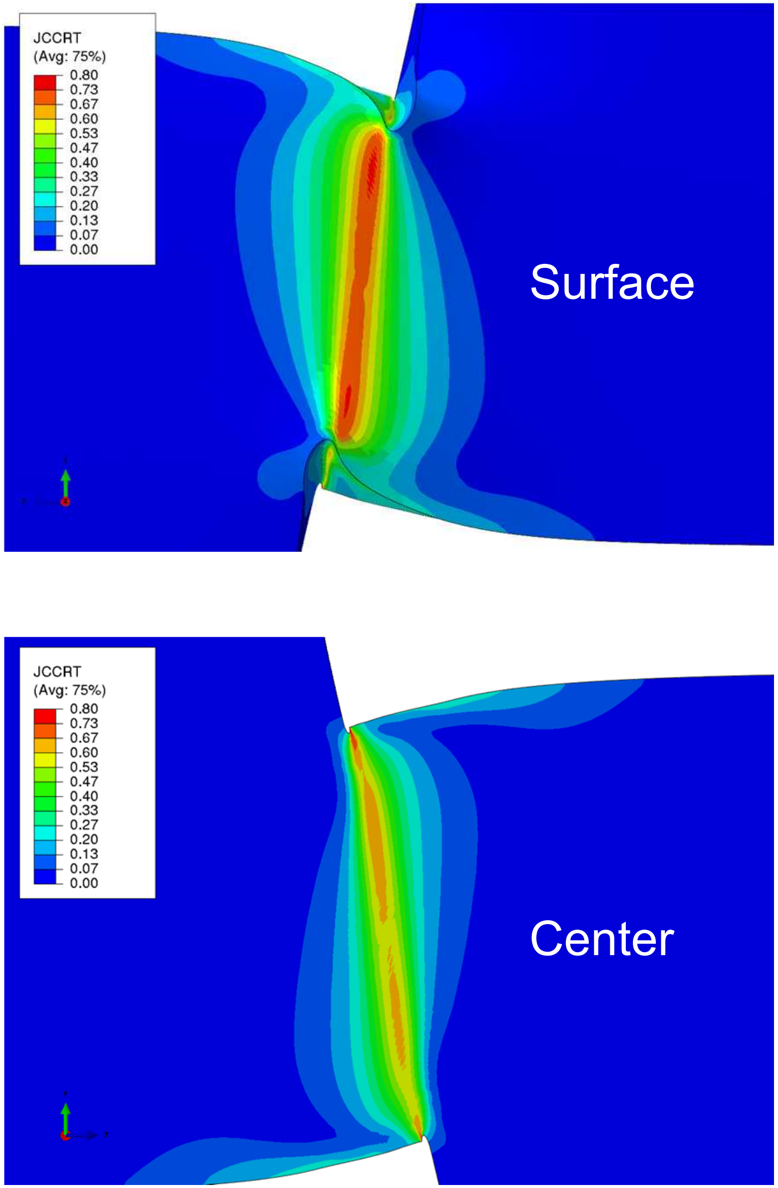


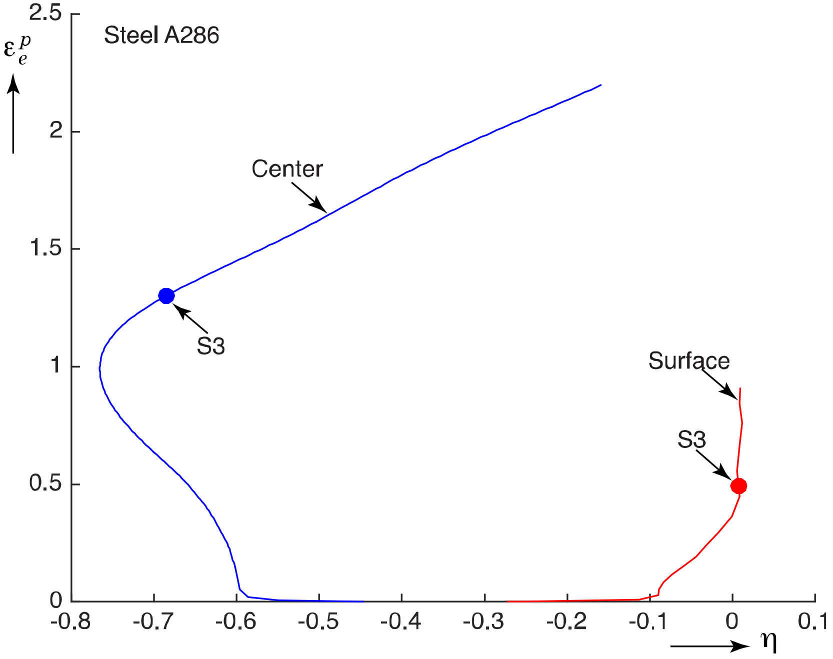
Examples of Higher Magnification Images Post Maximum Load





Progression of Johnson-Cook Damage

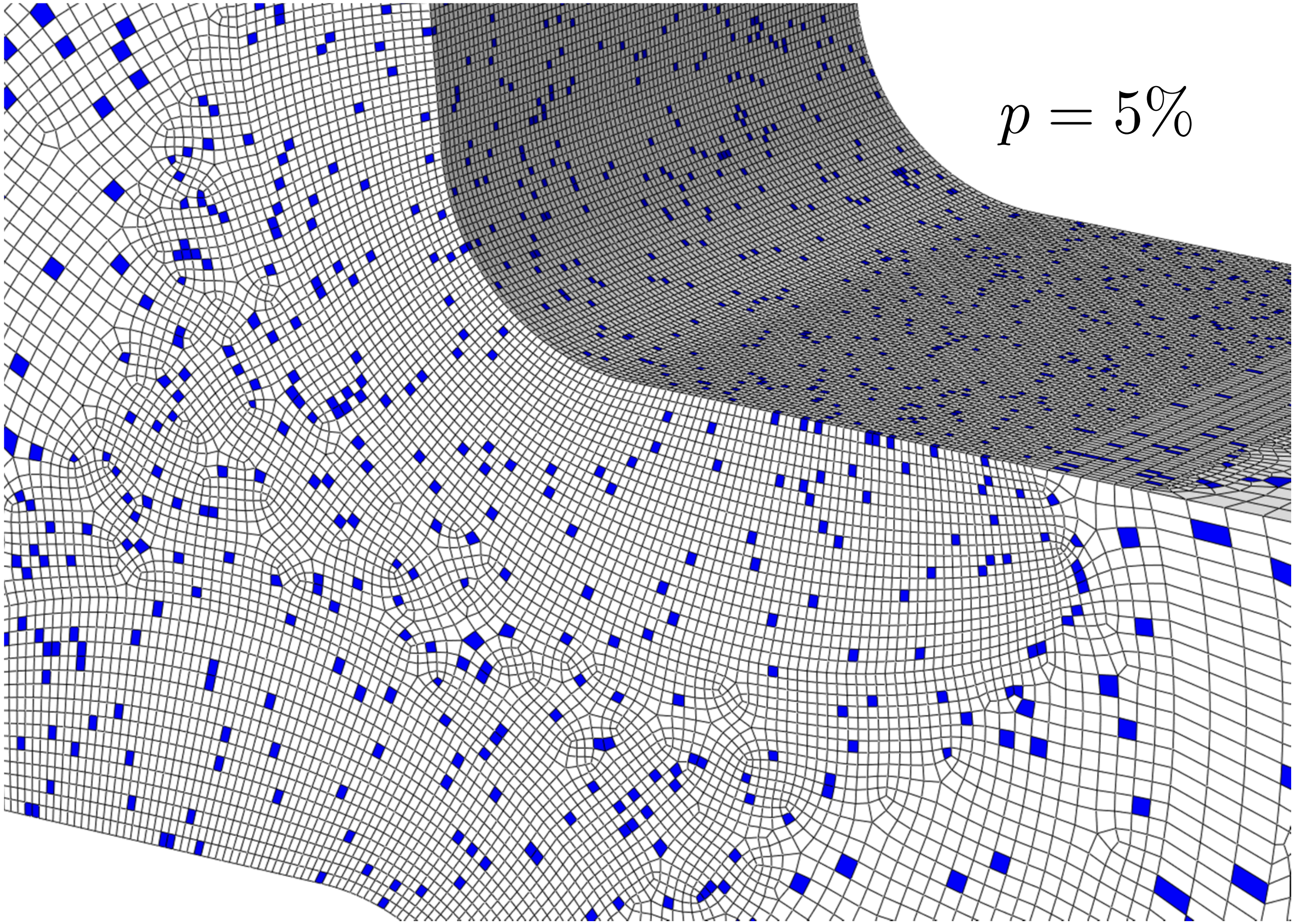




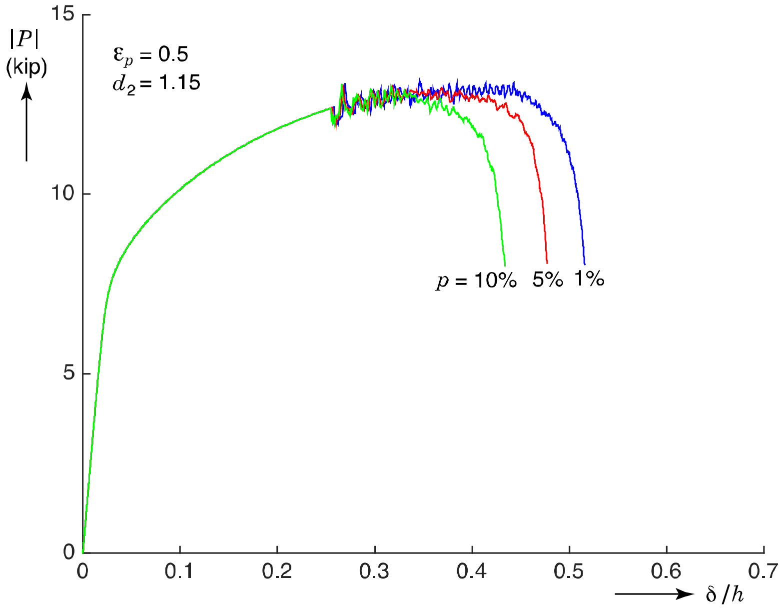
Two-Phase (Imperfect) Model

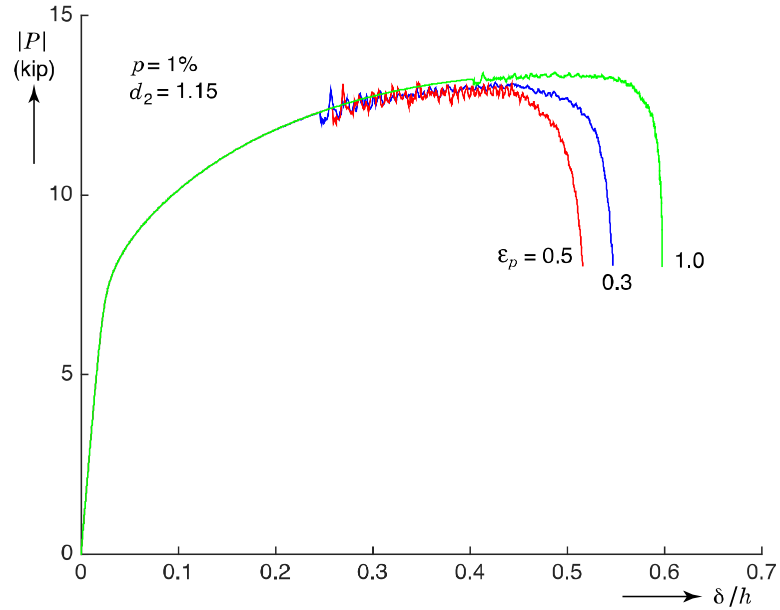
Phase 1 (Johnson-Cook)

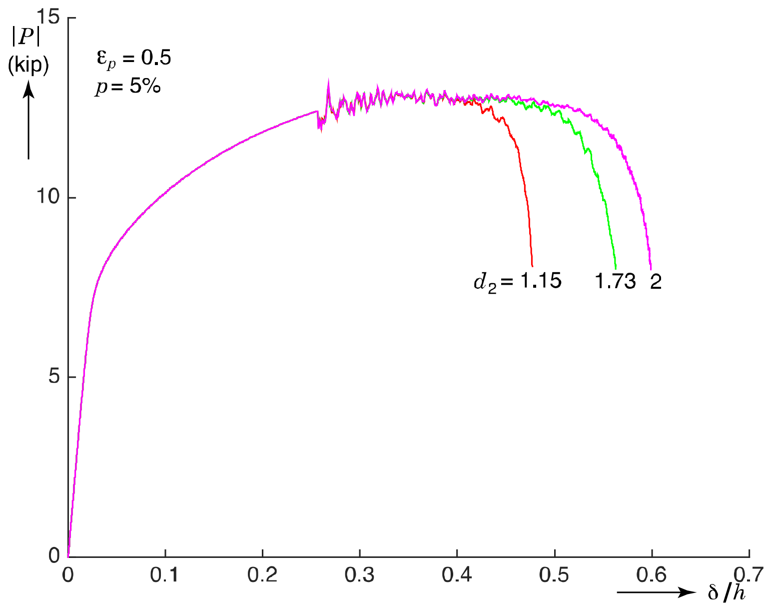
Phase 2 (Fail at low ε_e^p)



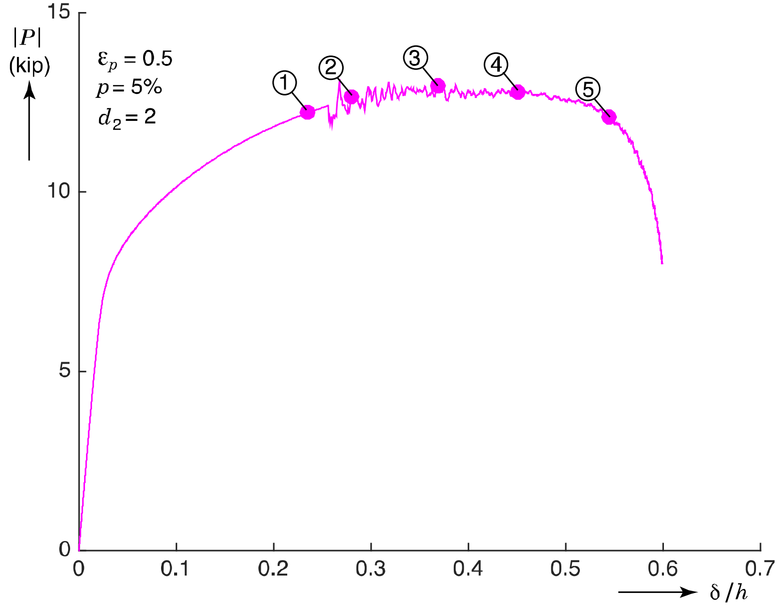
Two-Phase (Imperfect) Model Results

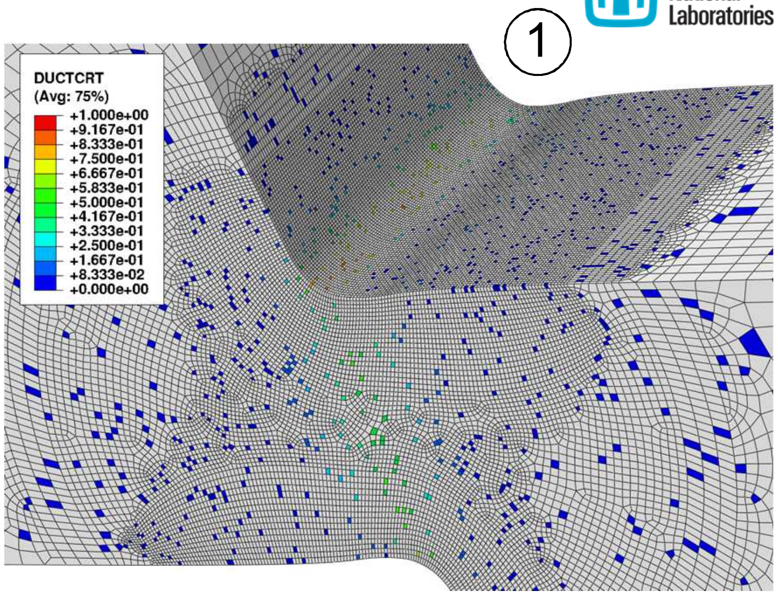


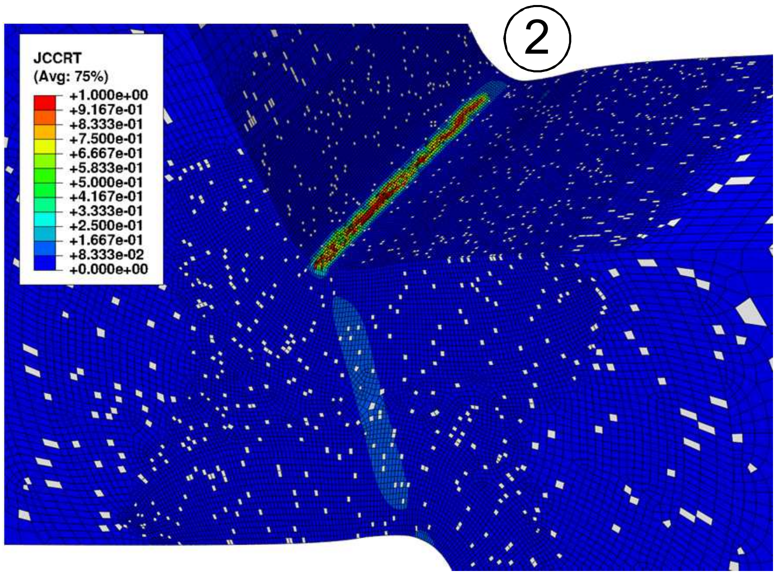


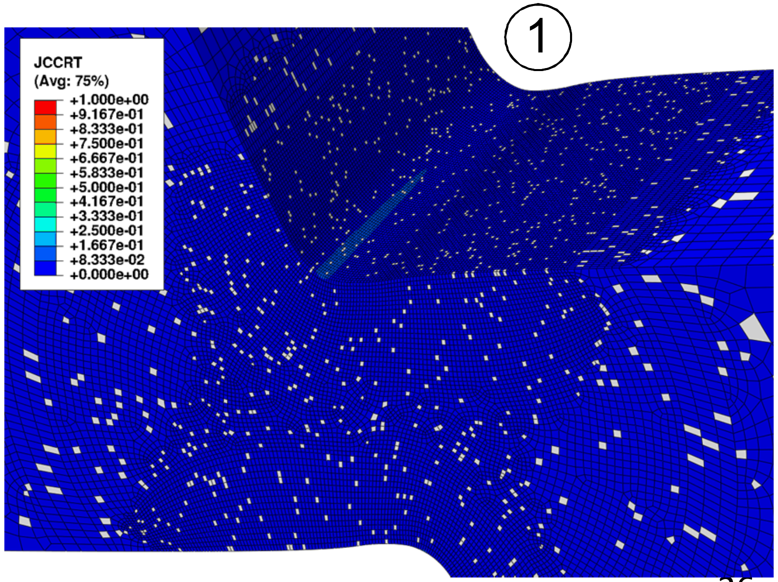


Model Configurations at Center

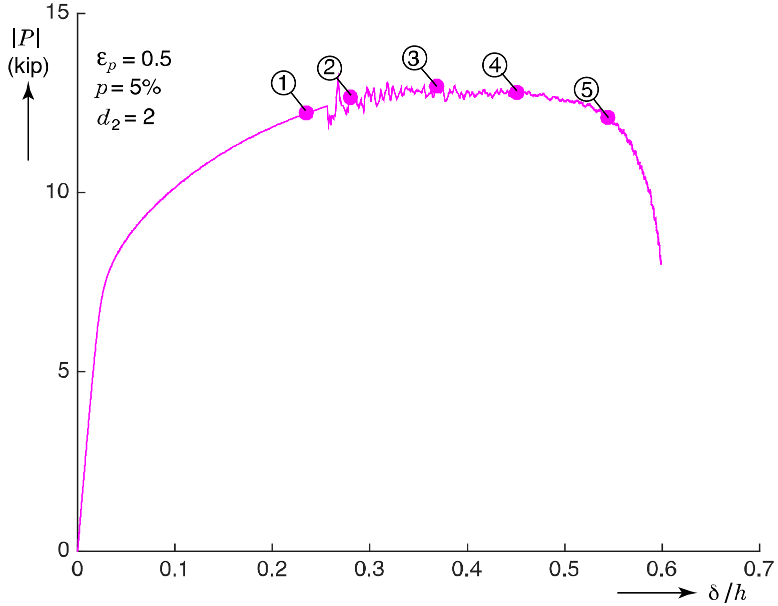




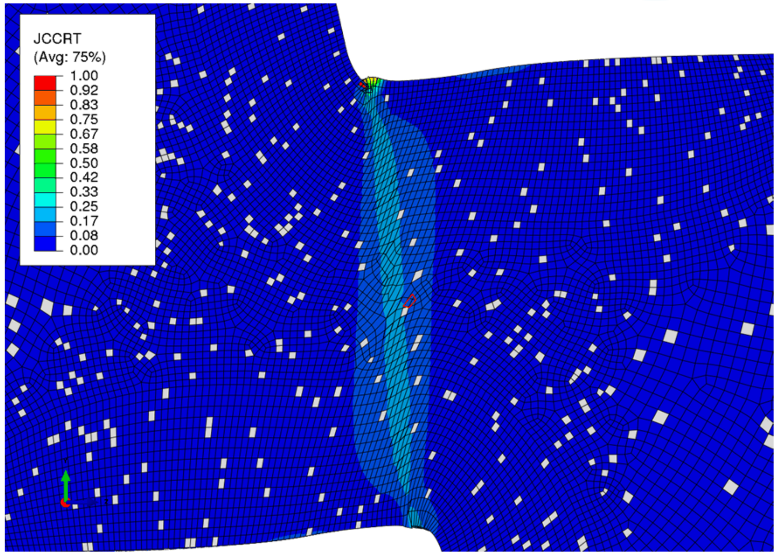




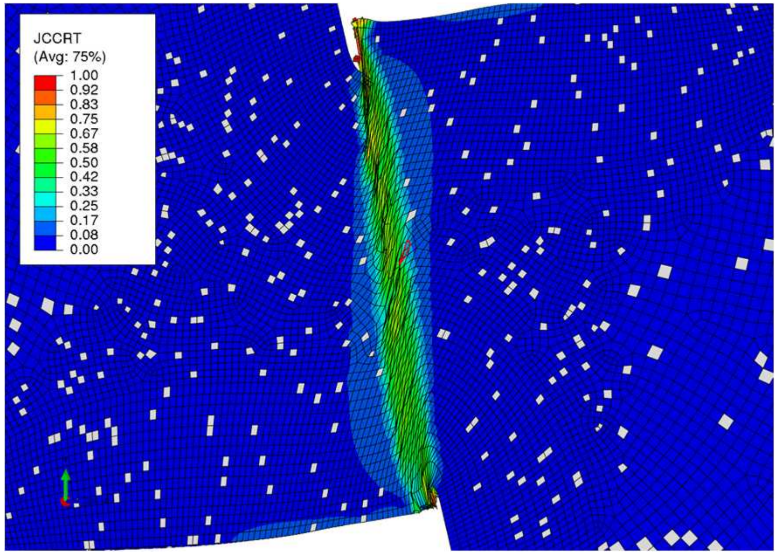
Model Configurations Center - 2



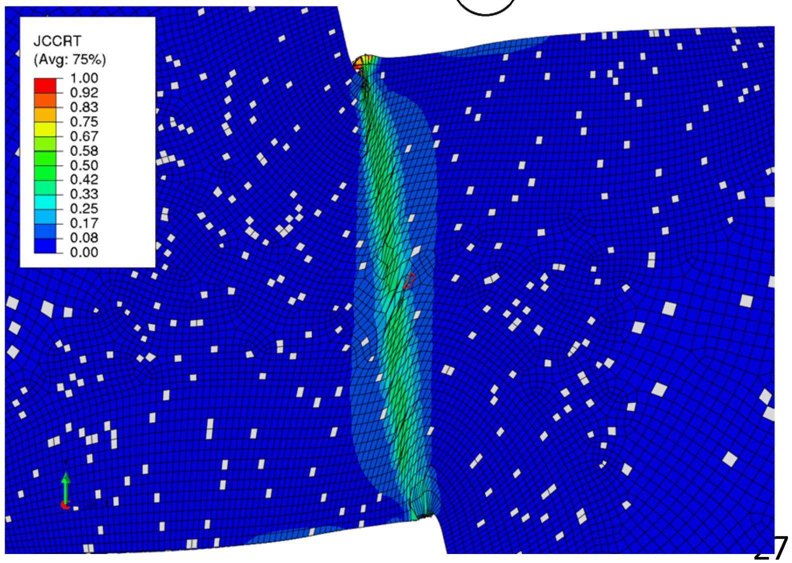
3



5



4



Conclusions

- The dependence on triaxiality of the plastic strain to failure of the Johnson-Cook failure criterion seems appropriate for the Al 7075-T651 tested.
- The same cannot be said of the Steel A286 alloy. J-C calibrated from notched tension test specimens overestimated significantly the plastic strain to failure.
- The limit load seen in the Steel A286 hat specimens is the result of material damage.
- Need to lower the plastic strain at failure for Steel A-286 at low triaxialities in comparison to calibrated J-C model.
- Several ways to achieve this can be implemented. Here, we chose an "imperfection" approach that precipitated failure at critical locations.
- This approach allowed our calculations to show the development of the maximum load.

Extra Slides

Johnson-Cook Strength and Failure Models

Strength Model:

J_2 isotropic hardening

Hardening curve:

$$\sigma_e = \left[A + B\left(\varepsilon_e^p\right)^n\right]\left[1 + C\ln\left(\frac{\dot{\varepsilon}_e^p}{\dot{\varepsilon}_o}\right)\right]\left[1 - \hat{T}^m\right]$$

Calibration

1. Quasi-static uniaxial tension test $\rightarrow A, B, n$
2. Quasi-static high-temperature uniaxial tension tests $\rightarrow m$
3. High strain-rate tension tests $\rightarrow C$

Johnson-Cook Strength and Failure Models

Failure Model:

$$\varepsilon^p_{ef} = \left[d_1 + d_2 e^{d_3 \eta}\right] \left[1 + d_4 \ln\left(\frac{\dot{\varepsilon}^p_e}{\dot{\varepsilon}_o}\right)\right] \left[1 + d_5 \hat{T}\right]$$

where

$$\eta = \sigma_m / \sigma_e$$

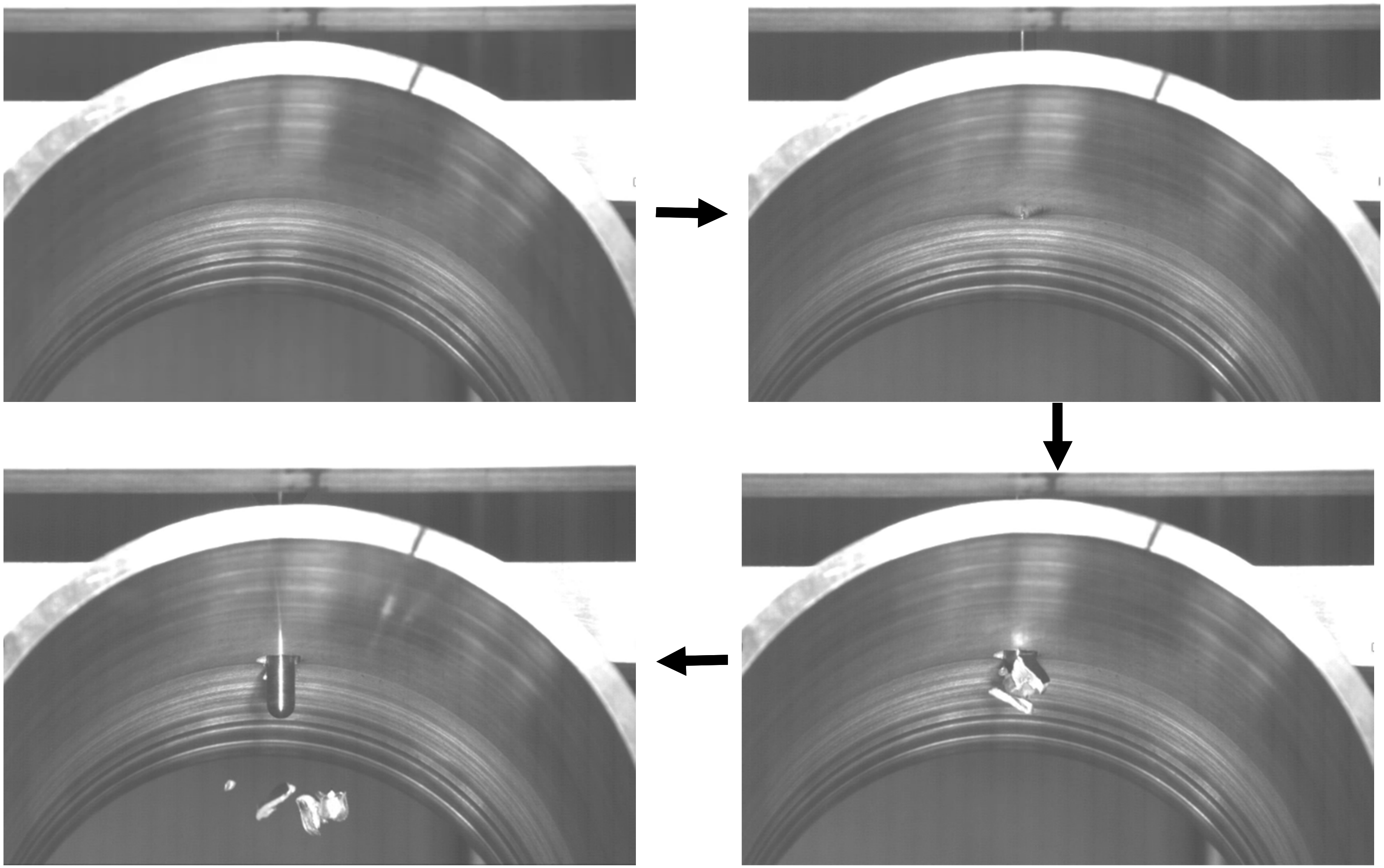
Damage accumulation

$$\bar{D} = \int \frac{d\hat{\varepsilon}^p_e}{\varepsilon^p_{ef}} \quad \text{and} \quad 0 \leq \bar{D} \leq 1$$

Calibration:

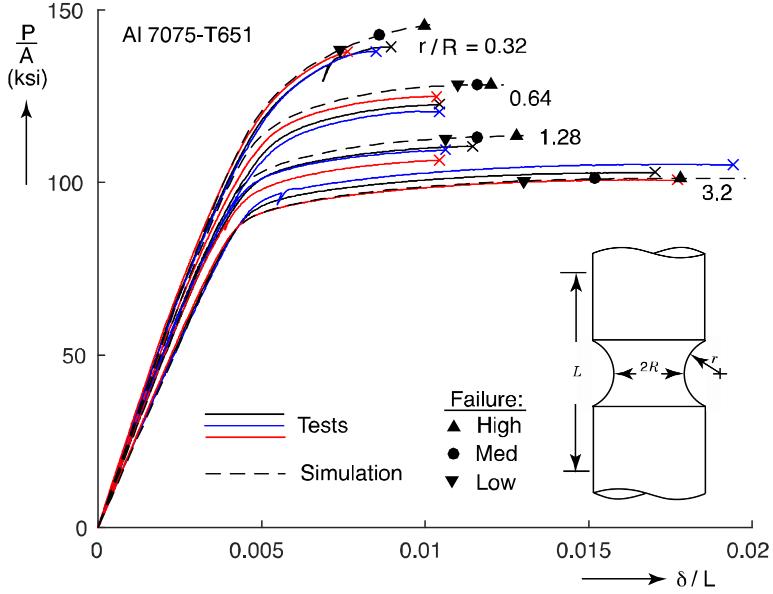
1. Notched tension tests $\rightarrow d_1, d_2, d_3$
2. Quasi-static high-temperature uniaxial tension tests $\rightarrow d_5$
3. High strain-rate tension tests $\rightarrow d_4$

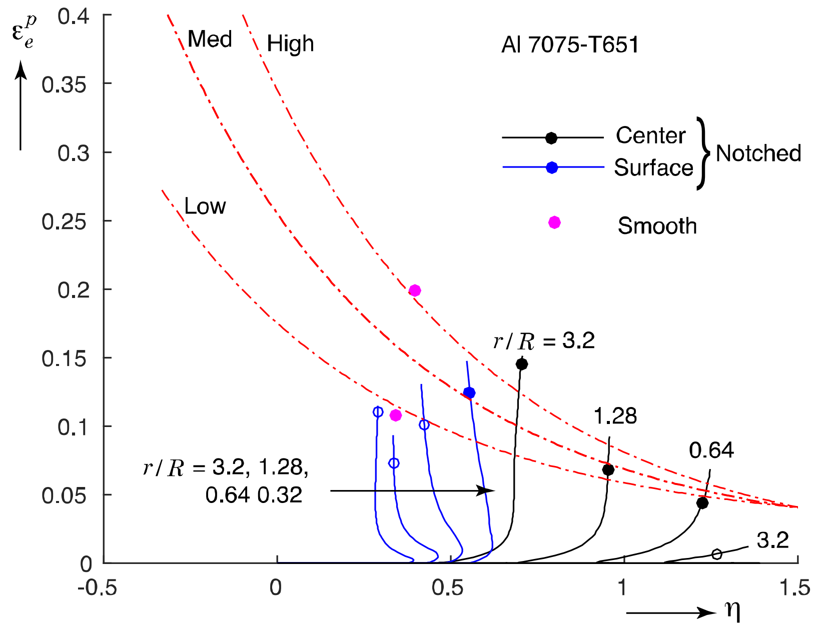
Puncture of Al 7075 Cylinder by Cylindrical Punch



Triaxiality Dependence (Al7075-T651)

$$\varepsilon_{ef}^{p} = d_1 + d_2 e^{d_3 \eta}$$

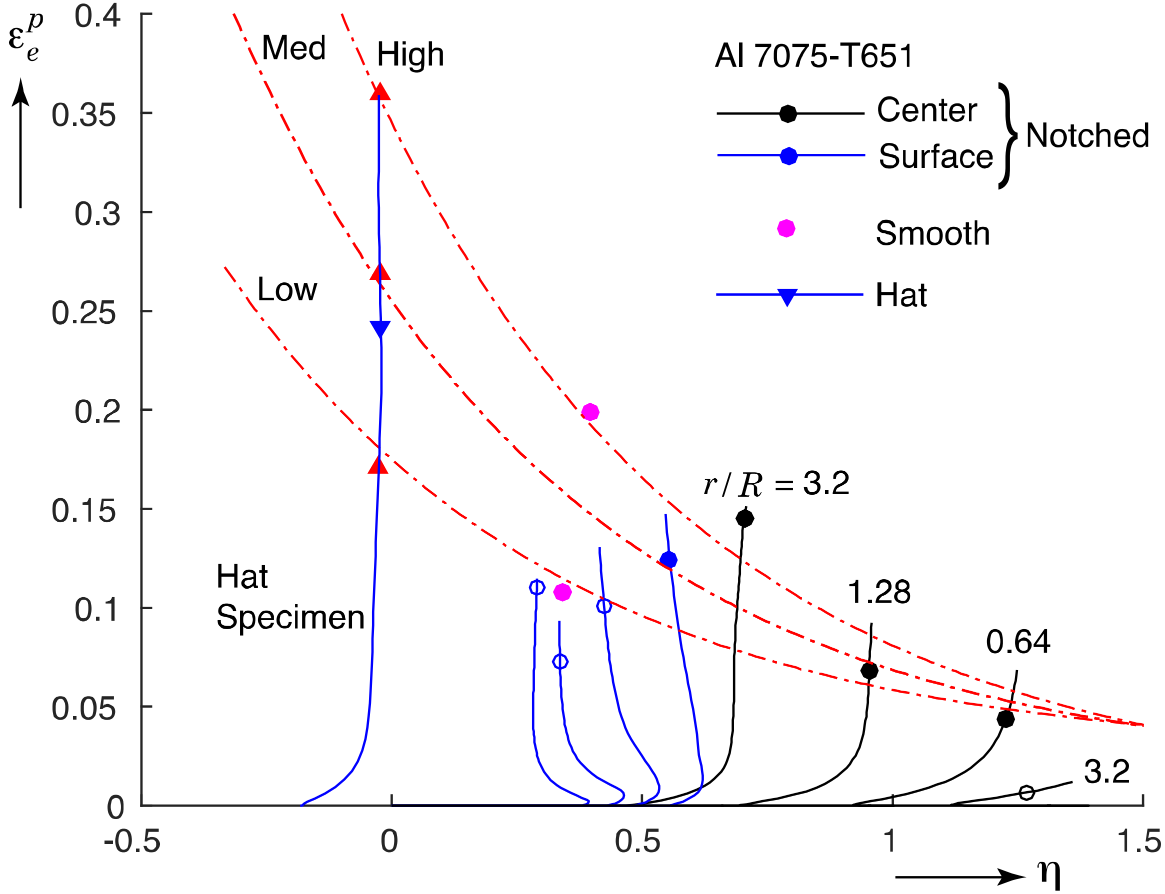




High: (0.005, 0.34, -1.5)
Mid: (0.015, 0.24, -1.5)
Low: (0.000, 0.15, -1.5)

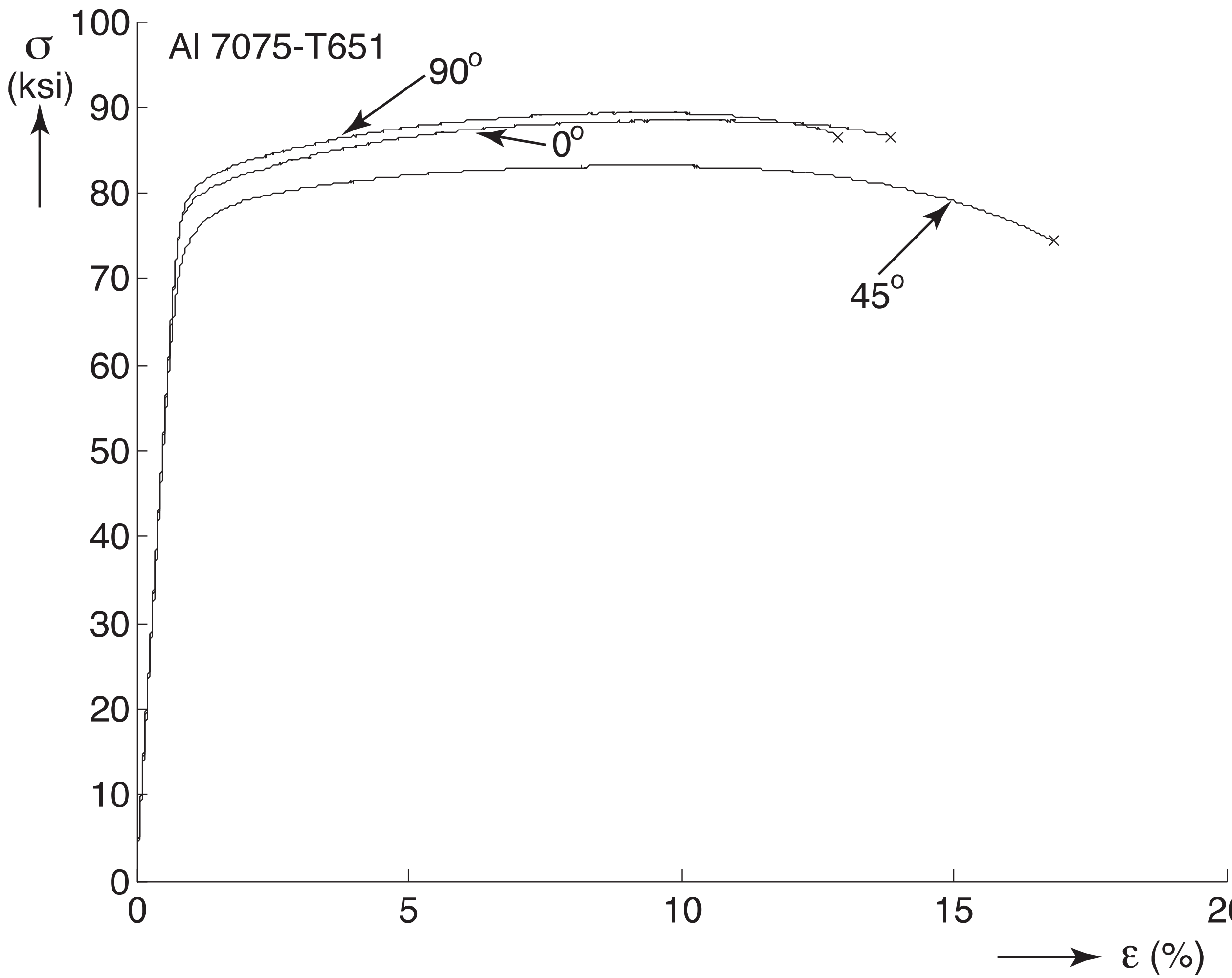
What about the region around η = 0?

Triaxiality Dependence with Hat Specimen

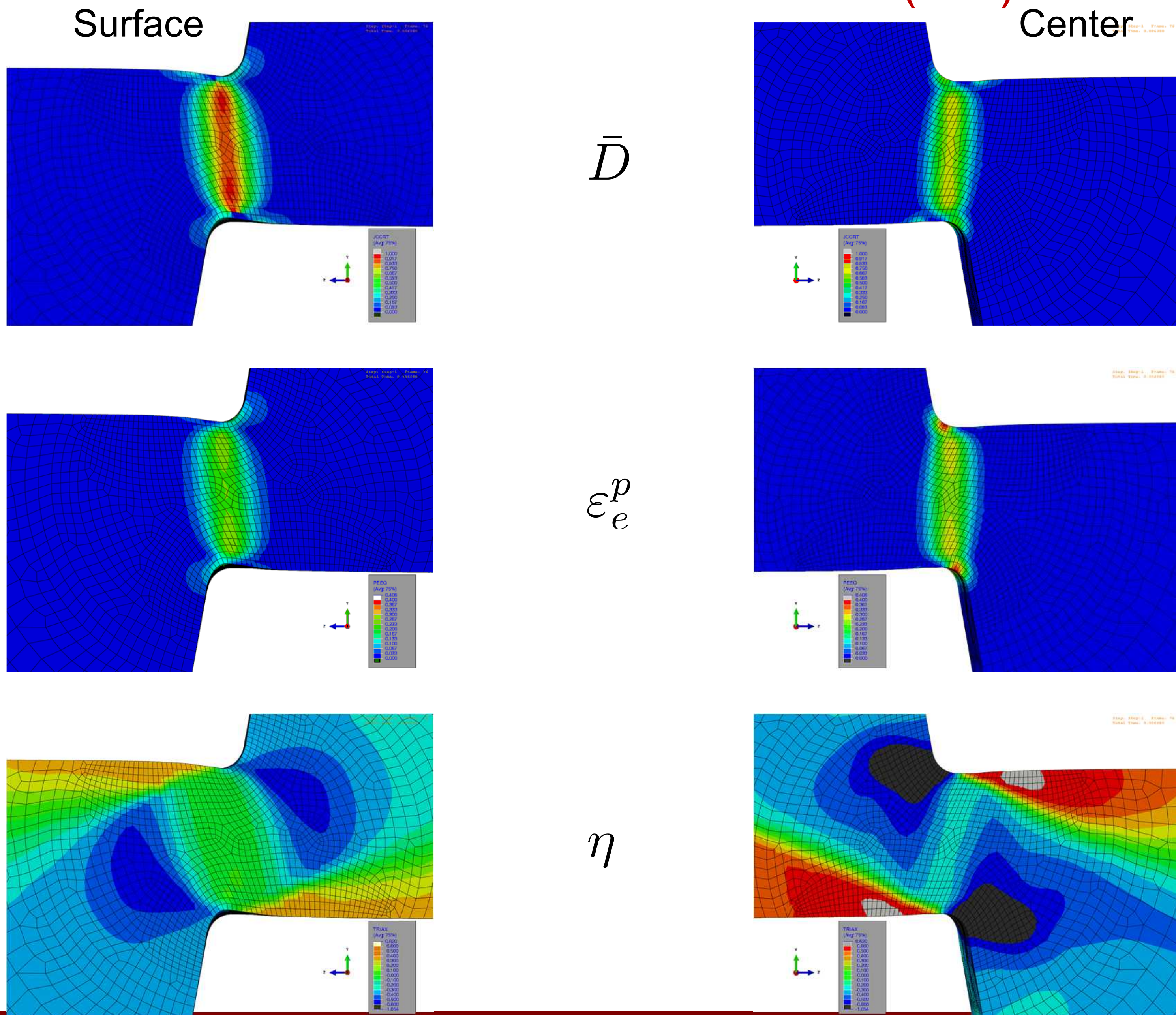


Hat specimen provides evidence to prefer the “Med” fit for Al 7075 T651.

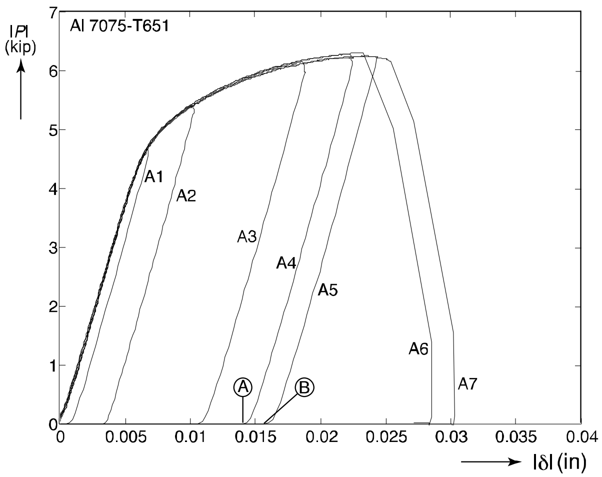
Uniaxial Stress-Strain Curves – Al7075-T651



State Just Prior to Failure (Mid)

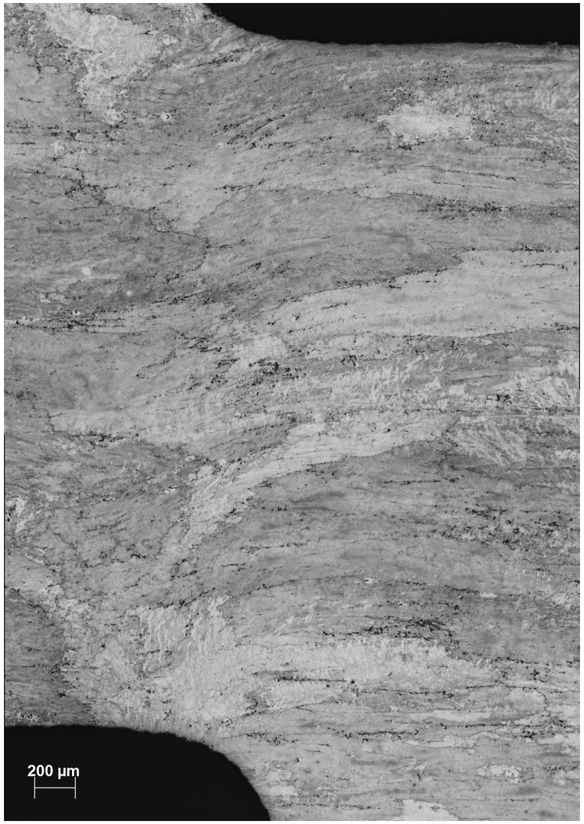


Micrography: Just Prior to Failure



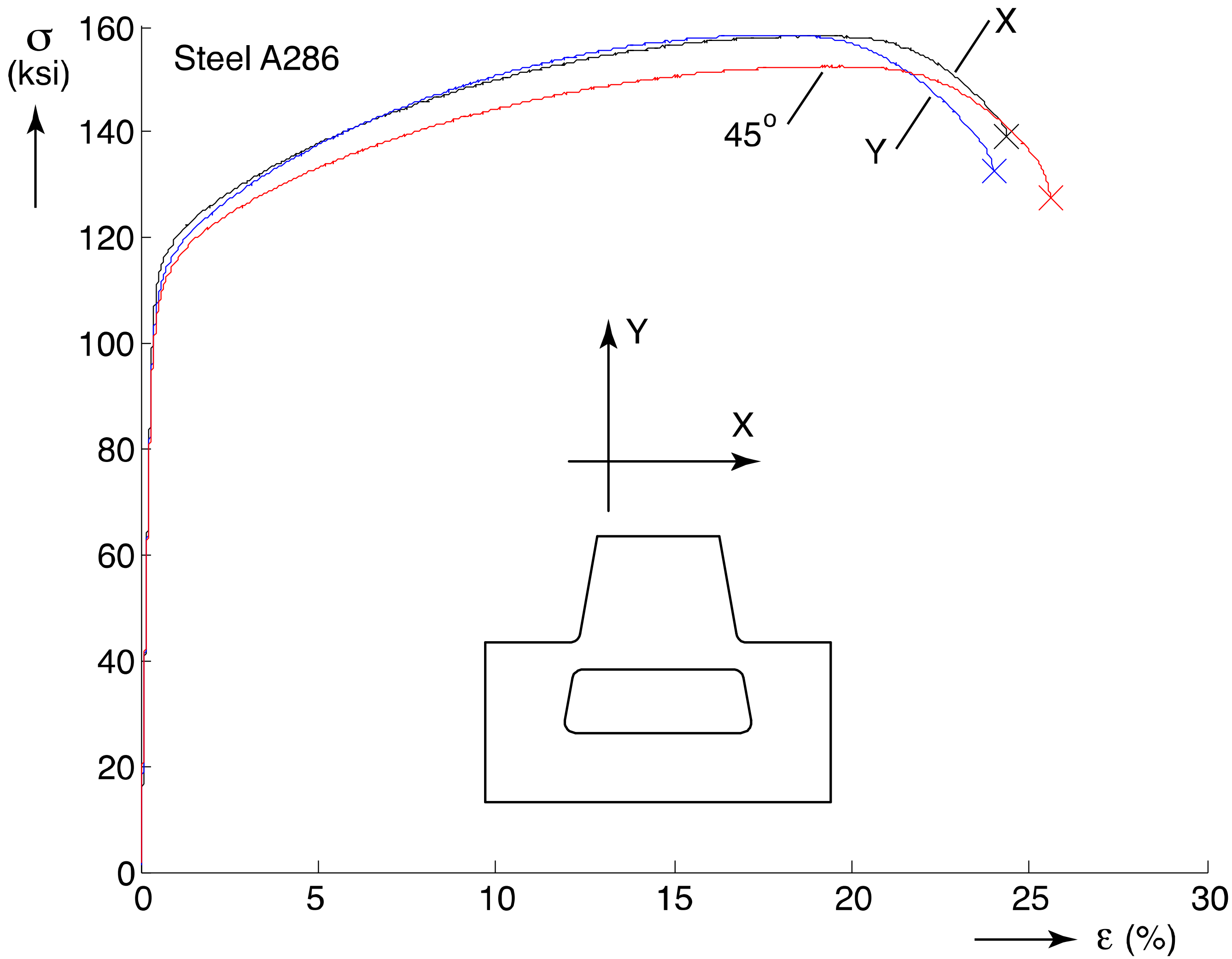
Specimen A5 at Ⓑ

Surface

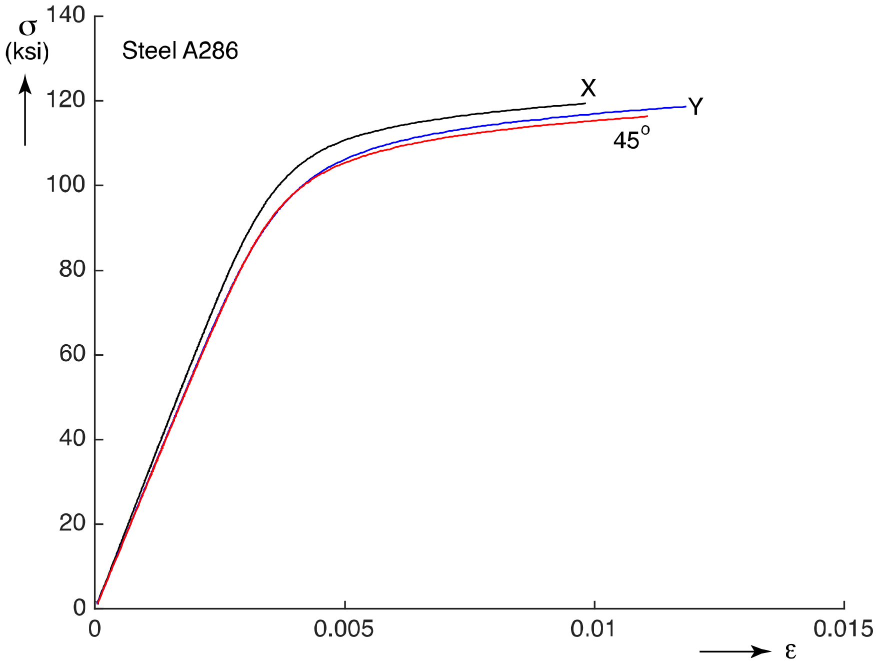


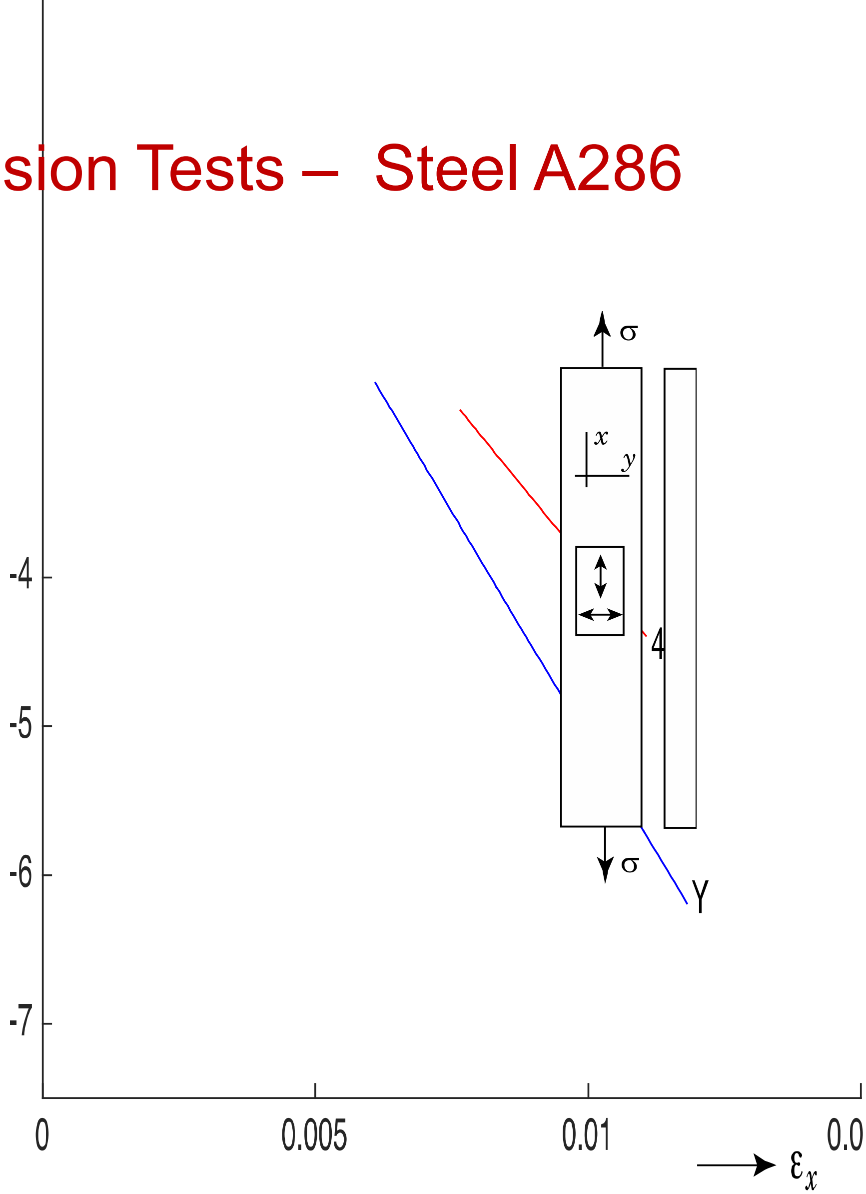
Center

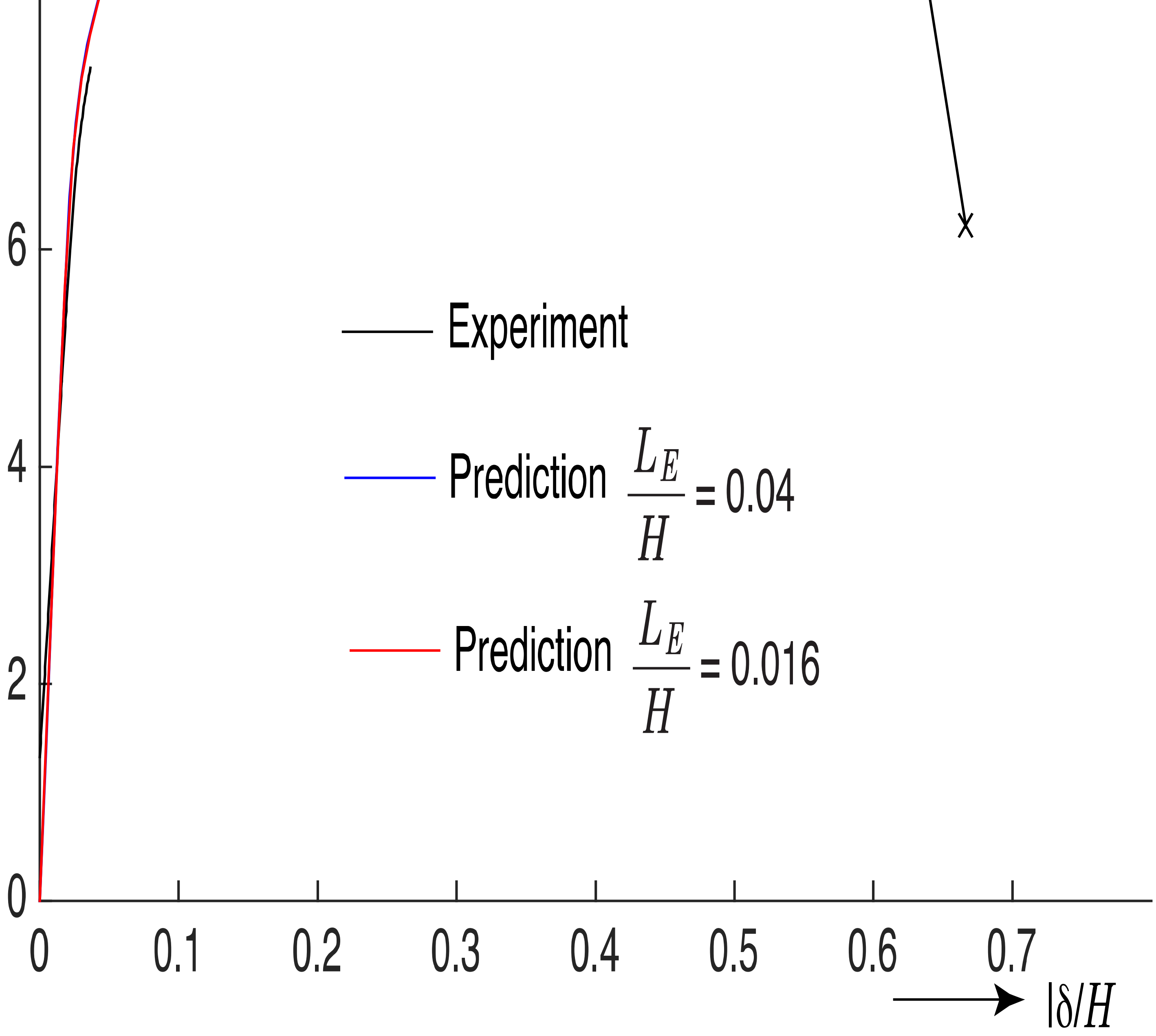
Uniaxial Stress-Strain Curves – Steel A286



Strain Gage Measurement in Tension Tests – Steel A286





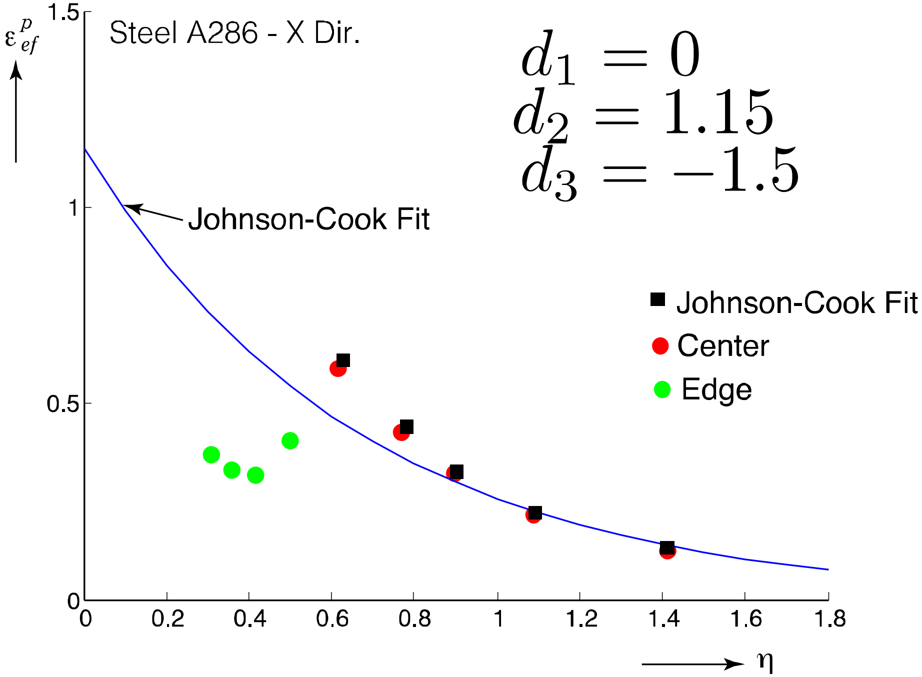


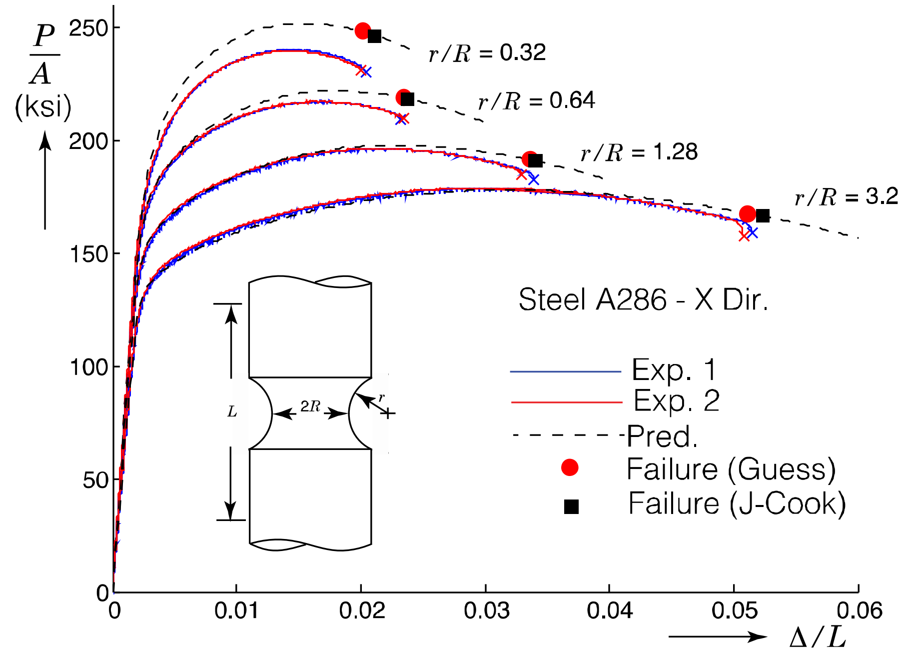
6
4
2
0
Experiment
Prediction $\frac{L_E}{H}$ = 0.04
Prediction $\frac{L_E}{H}$ = 0.016
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$|\delta/H$

Johnson-Cook Failure Calibration for Steel A286

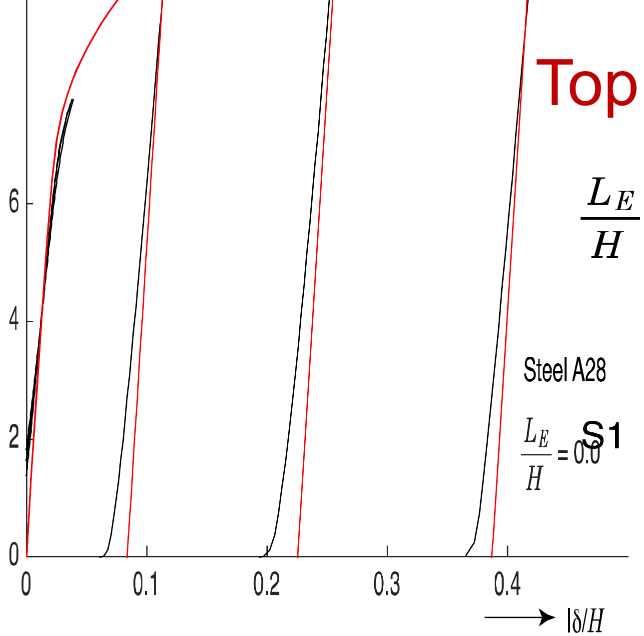
$$\varepsilon_{ef}^{p} = d_1 + d_2 e^{d_3 \eta}$$

$$d_1 = 0$$
$$d_2 = 1.15$$
$$d_3 = -1.5$$





Top Profile Comparisons



$$\frac{L_E}{H} = 0.016$$

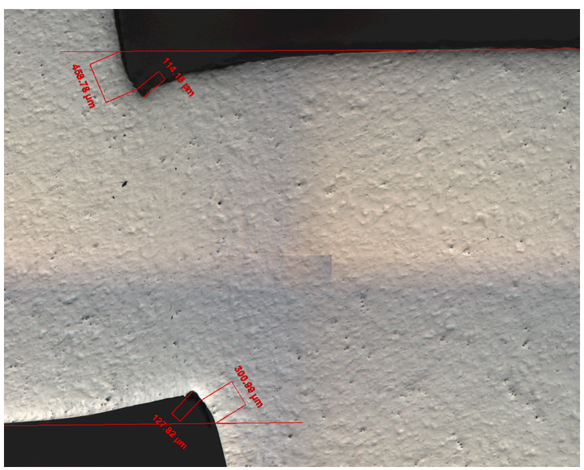
Center

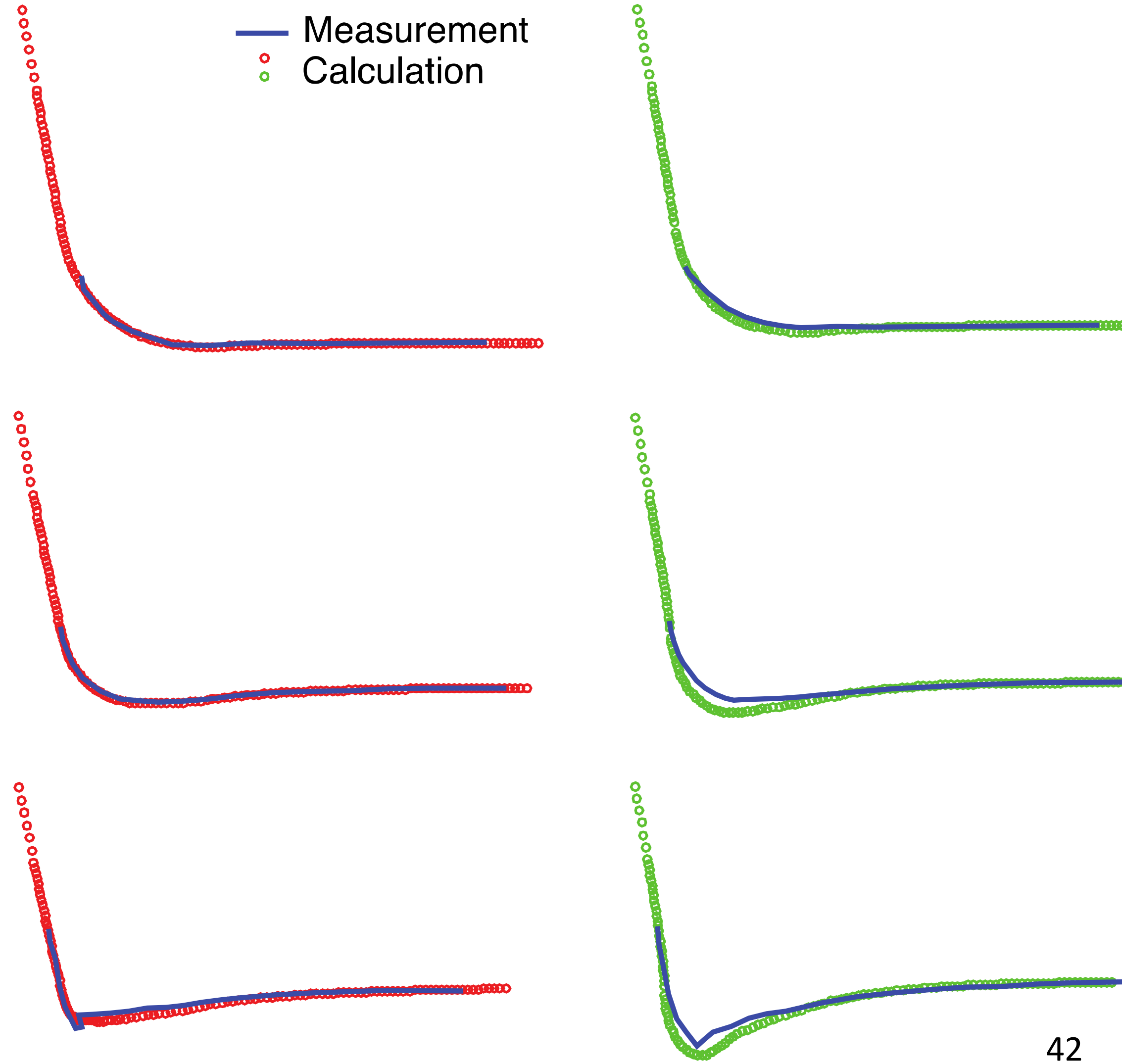
Surface

S1

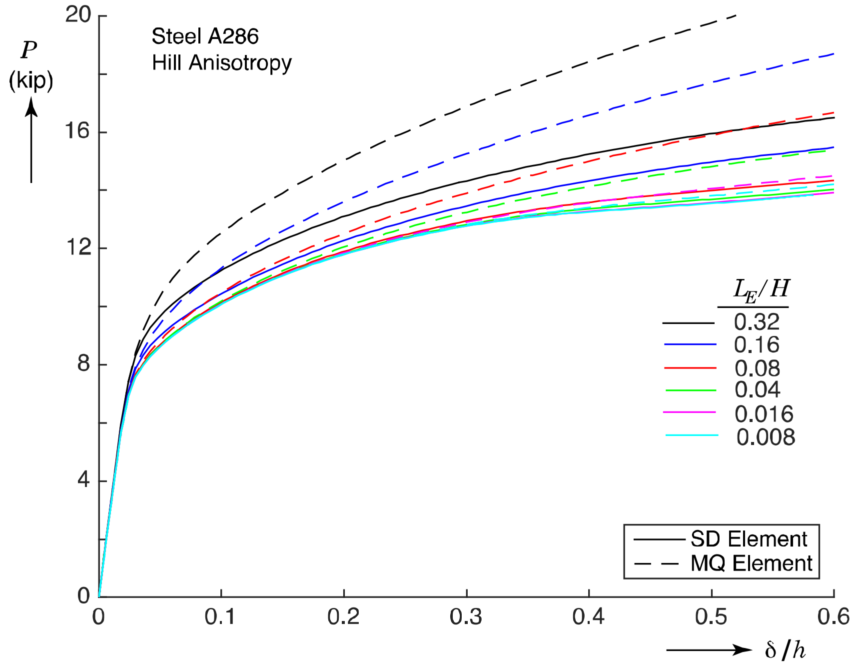
S2

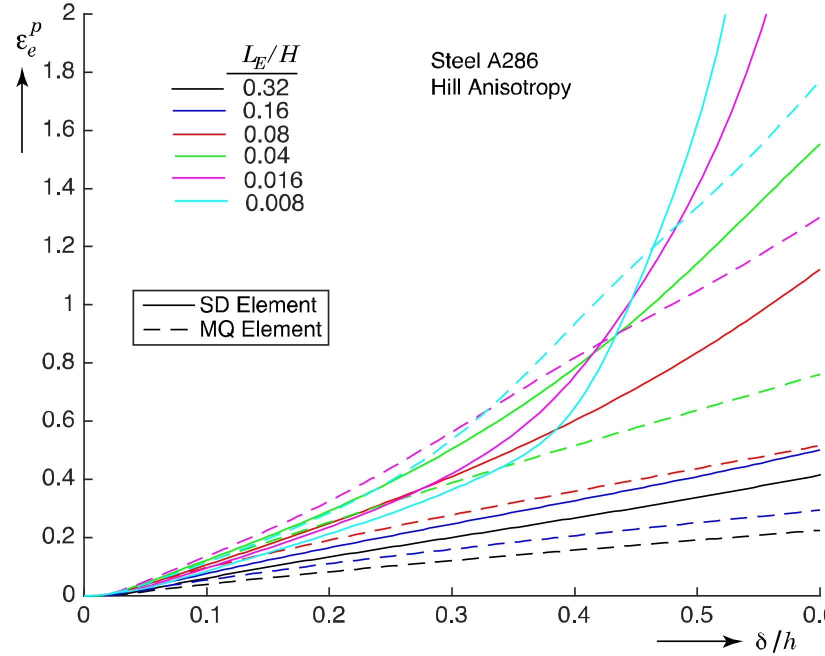
S3



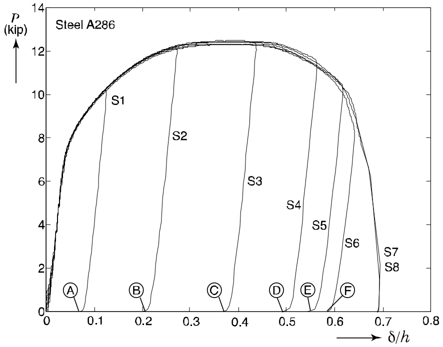


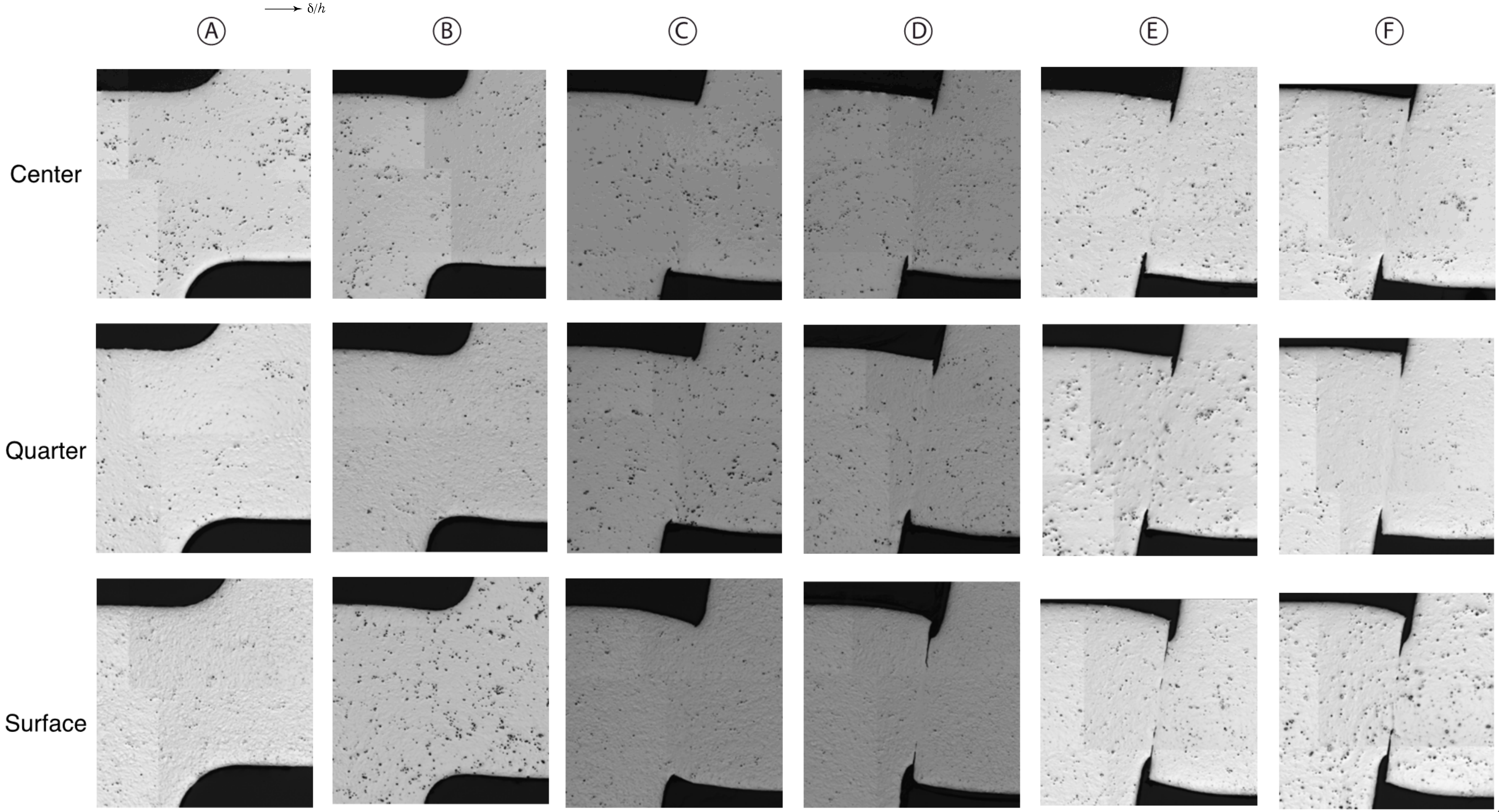
Mesh Convergence Study



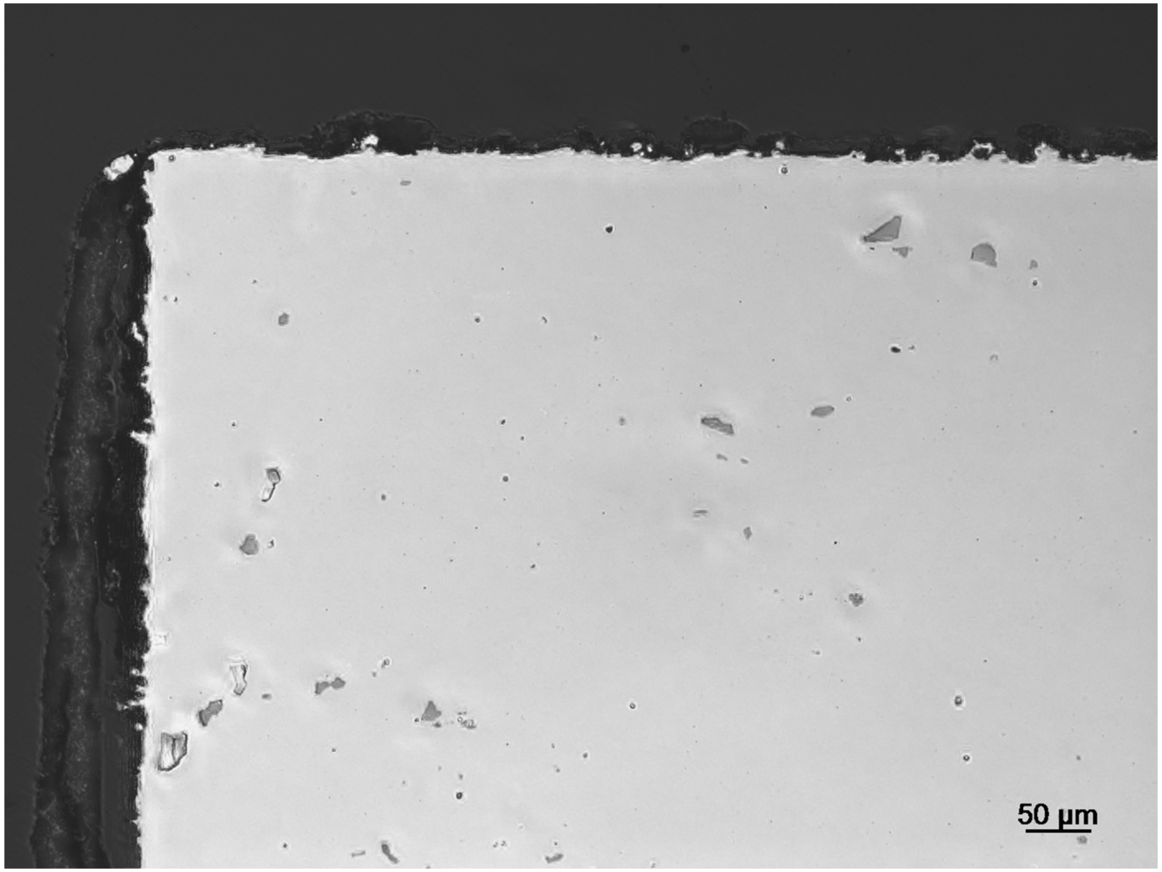


Micrographs for Steel A286 Specimens (Left Side)

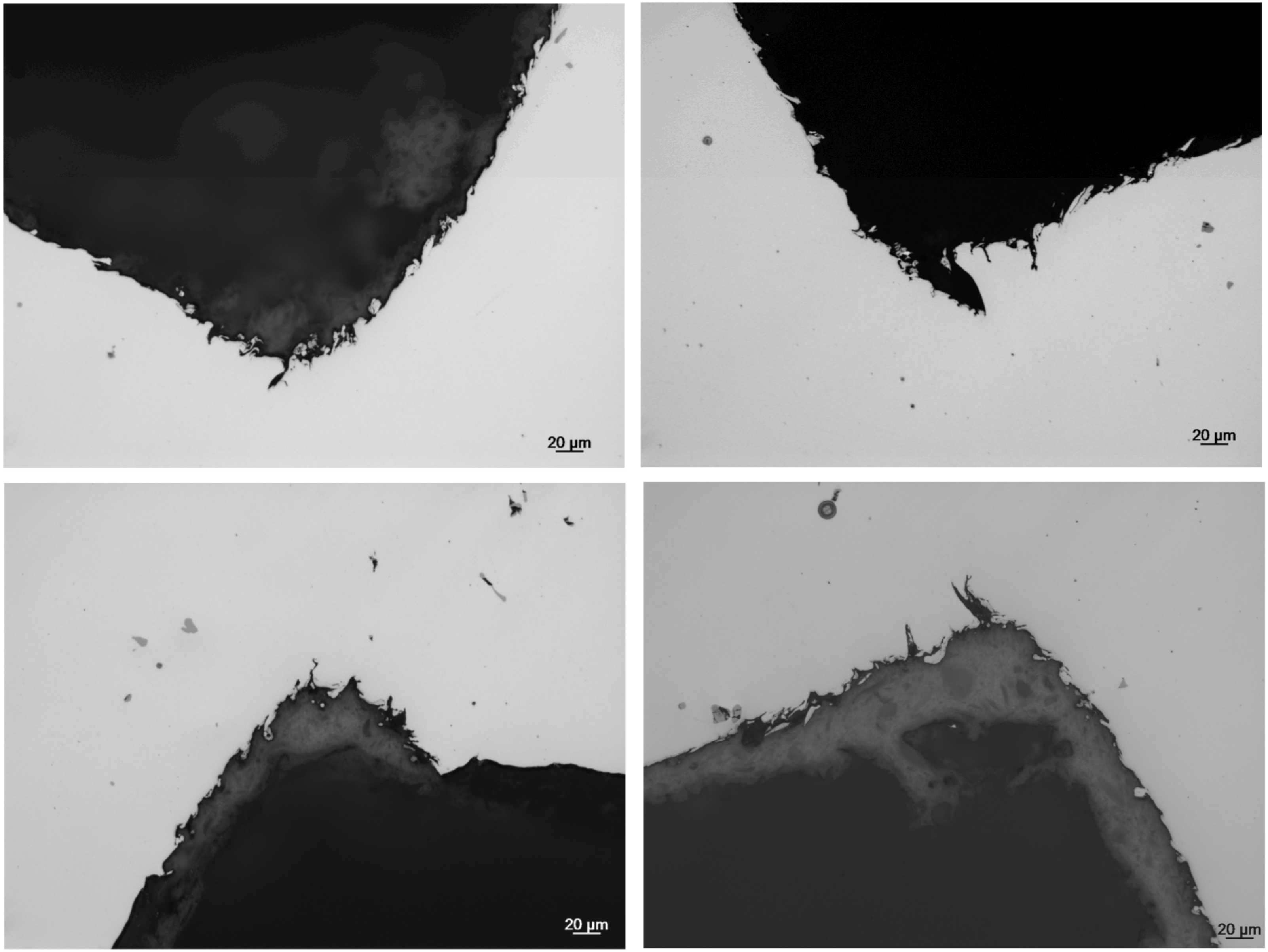




Surface Roughness and Internal Microstructure in A286 Specimens

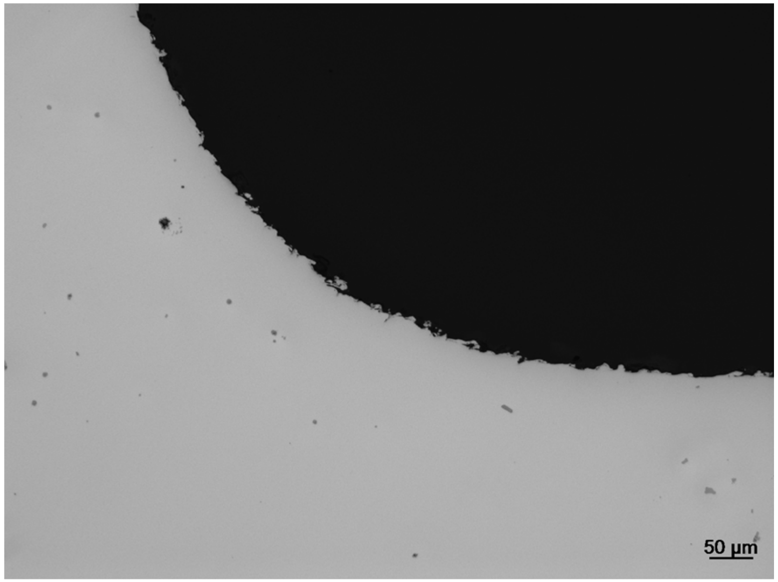


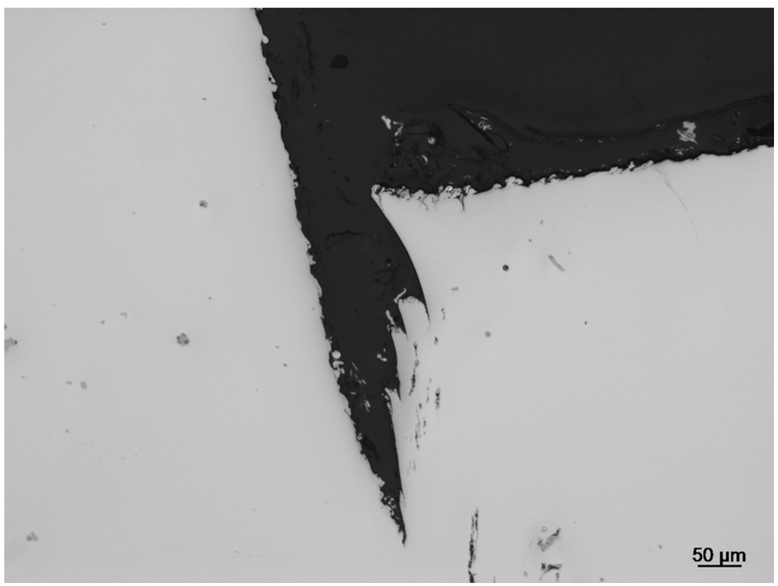
Four Critical Regions Surface of S3 (Max Load)



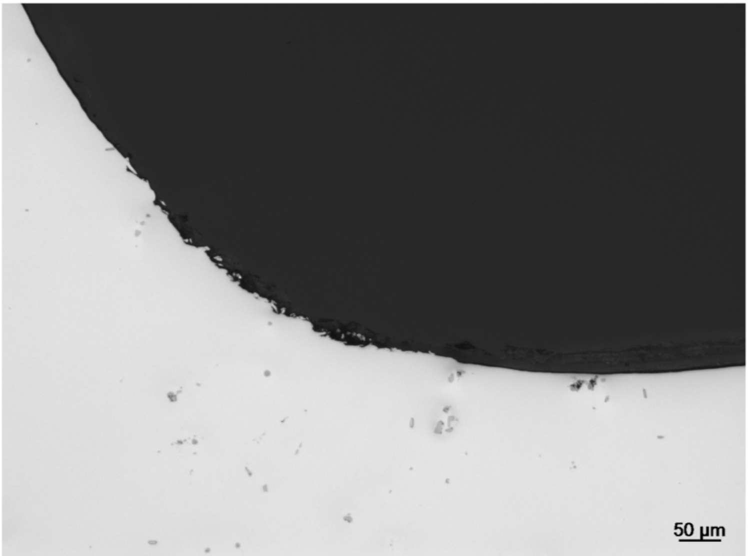
Damage Progression: Center, S2, S3, S4

Sandia National Laboratories

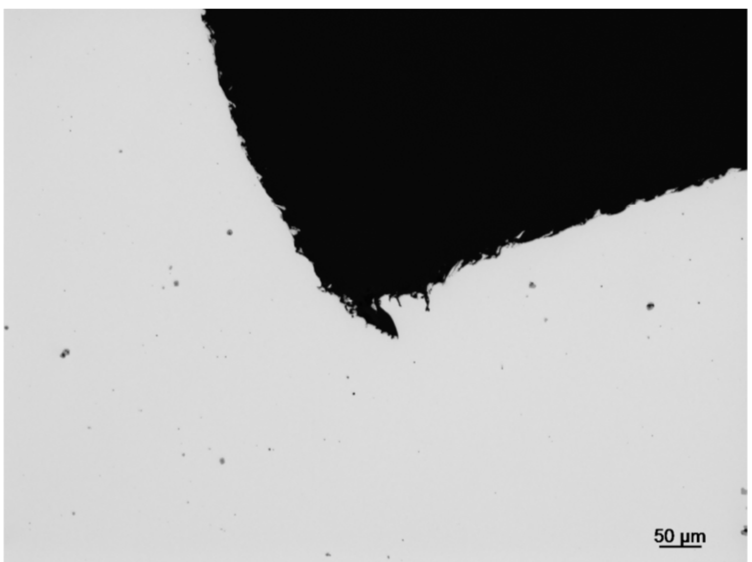




Damage Progression: Surface, S2, S3, S4



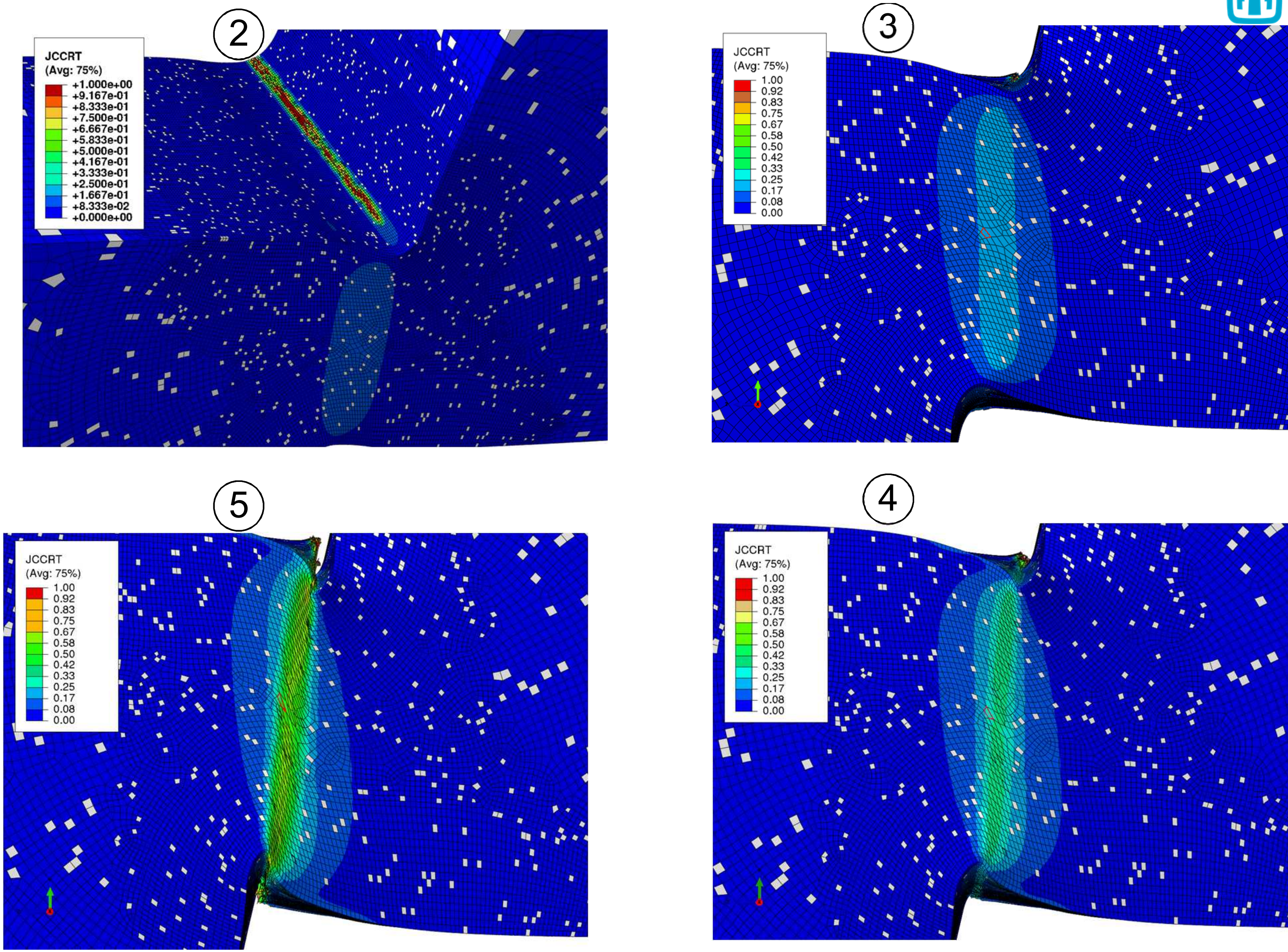
(a)



(b)

(c)

Model Configurations - Surface



Strain Measurement by DIC – Steel A286