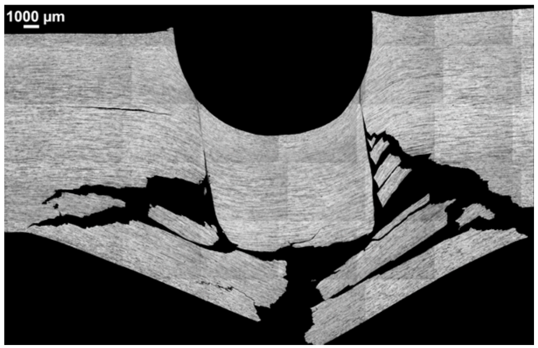

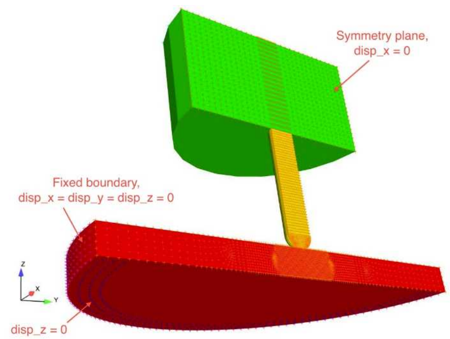

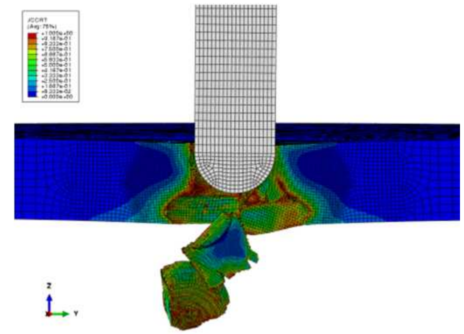

Puncture of Aluminum 7075 Plates: Experiments, Numerical Simulations and Model Validation

E. Corona[1], M.A. Spletzer[2], G.E. Orient[3], N.L. Breivik[1] and T.E. Córdova[4]

[1]Solid Mechanics, [2]Experimental Environment Simulation, [3]V&V, UQ, Credibility Process, [4]Vibration/Acoustics Simulation (formerly Structural Mechanics Laboratory staff)

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

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Problem Schematic

$m = 306 \text{ lb}$

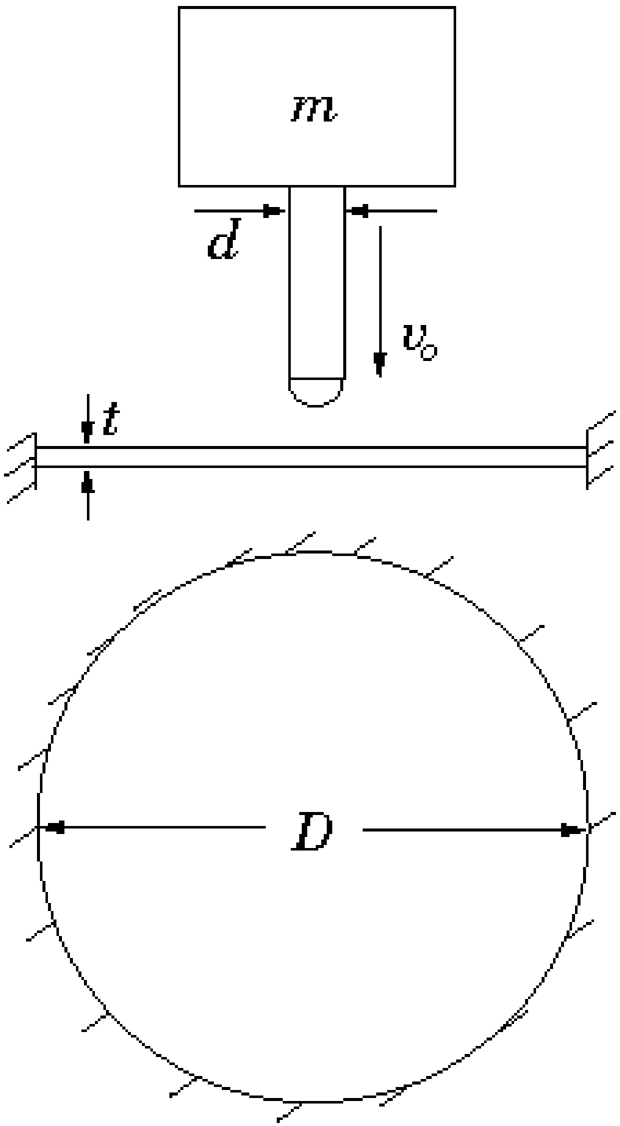
$d = 0.5 \text{ in}$

$t = 0.5 \text{ in}$

$D = 6.75 \text{ in}$

Al 7075-T651

- Determine threshold velocity
- Observe failure mode



A Brief Review…

Backman and Goldsmith, US Naval Weapons Center, 1978. Review article. Attribute first studies on ballistic penetration to Euler and Robbins in the 1700's.

Wilkins, Lawrence Livermore Laboratory, 1978. Excellent, concise description of penetration and perforation concepts.

Corbett, Reid and Johnson, Univ. of Aberdeen, UMIST, 1996. Review article post 1978. Section on numerical modeling.

Borvik et al, Norwegian University of Science and Technology, late1990's to present). Experimental and numerical FE simulation, work includes 7075-T651 plates, and use of the Johnson-Cook and other constitutive and failure models.

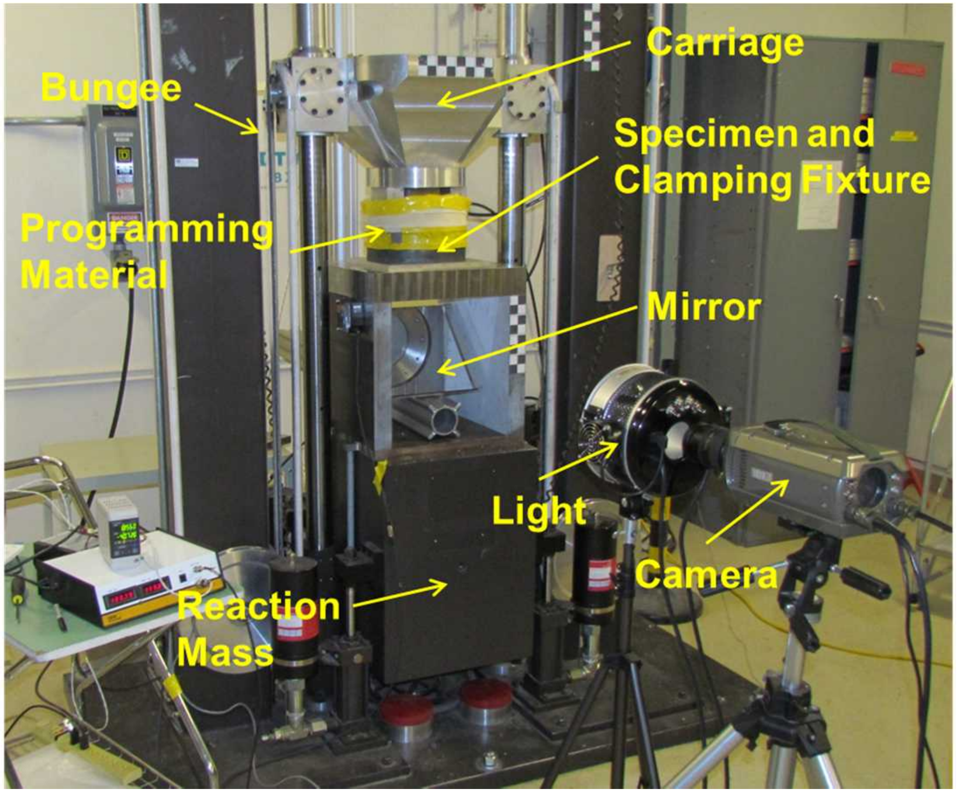
Teng, Wierzbicki, MIT, 2006. Evaluated fracture models for perforation problem. Bao-Wierzbicki and Johnson-Cook models gave reasonable predictions.

Jones, Univ. of Liverpool, 2012. Comments on numerical predictions requiring a extensive companion experimental program.

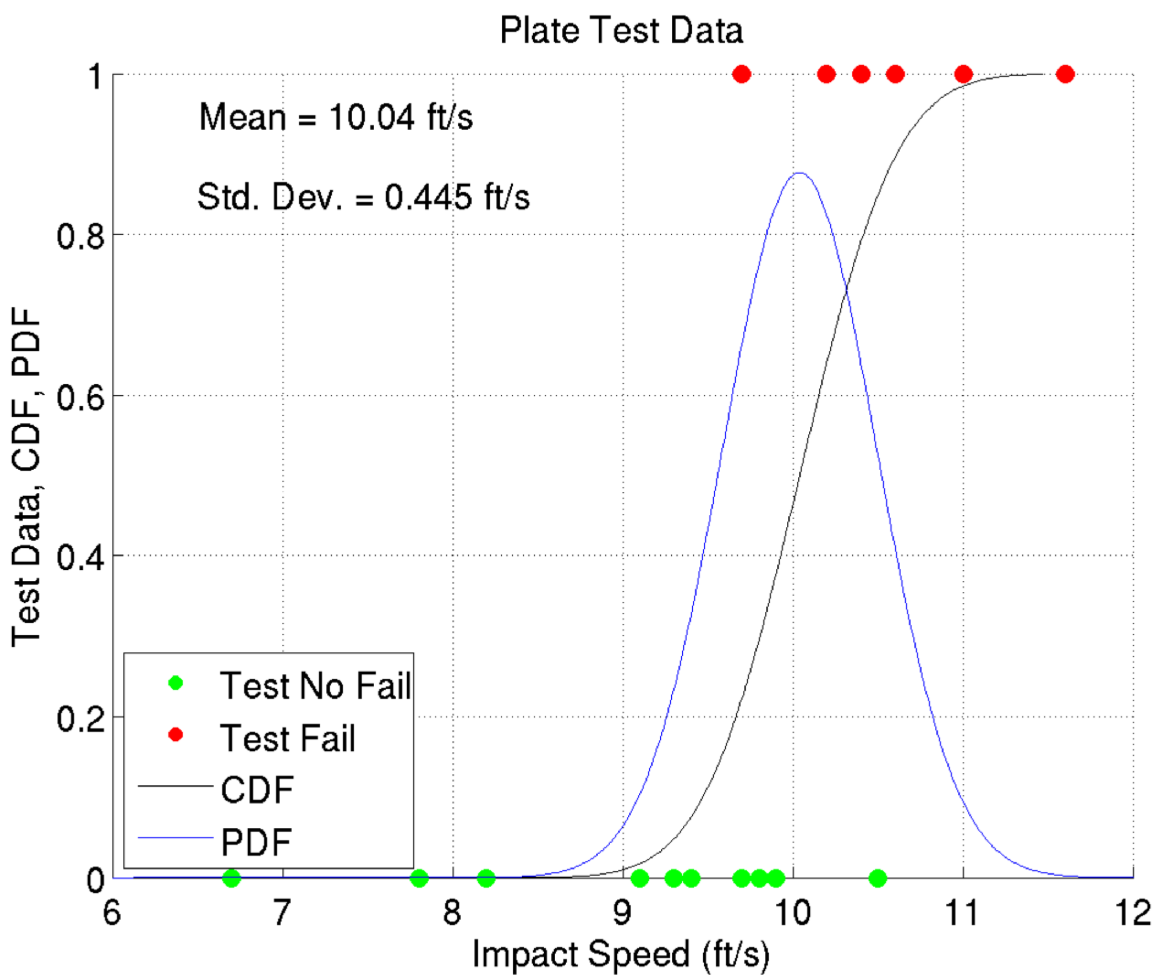
Experimental Set-up

Instrumentation:

- 2000g carriage accelerometer
- Laser carriage position sensor
- Phantom video camera
  (7000 frames/sec)
- Data acquisition system
  - 16 bit
  - 2.5 MHz sampling rate
  - Low pass filter to 500Hz
- Uncertainties
  - Impact velocity +/- 0.15 ft/s
  - Peak acceleration +/- 1.6g

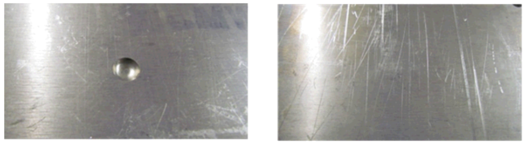


Experimental Results

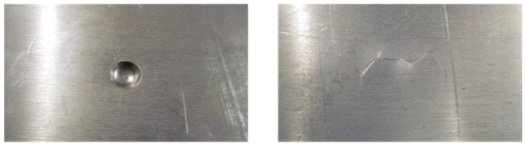


Threshold velocity: [9.7,10.5] ft/s

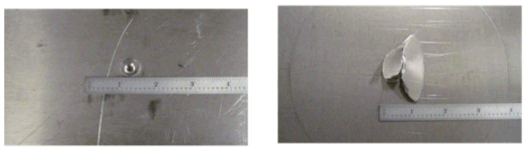
Levels of Damage



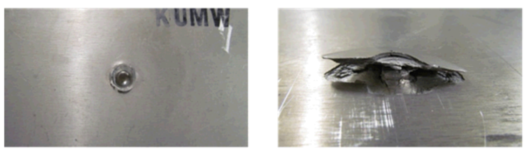
Damage level 1: Dimple / no crack



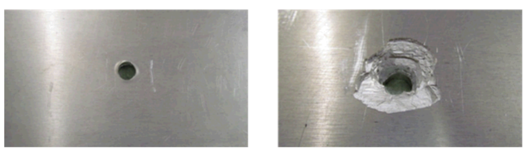
Damage level 2: Dimple / crack



Damage level 3: Dimple / scabbing / no leak

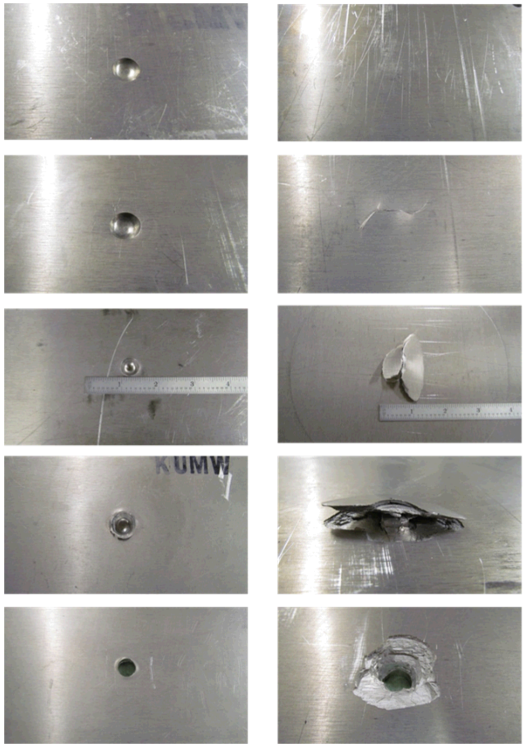


Damage level 4: Dimple / scabbing / leak



Damage level 5: Through hole

Levels of Damage



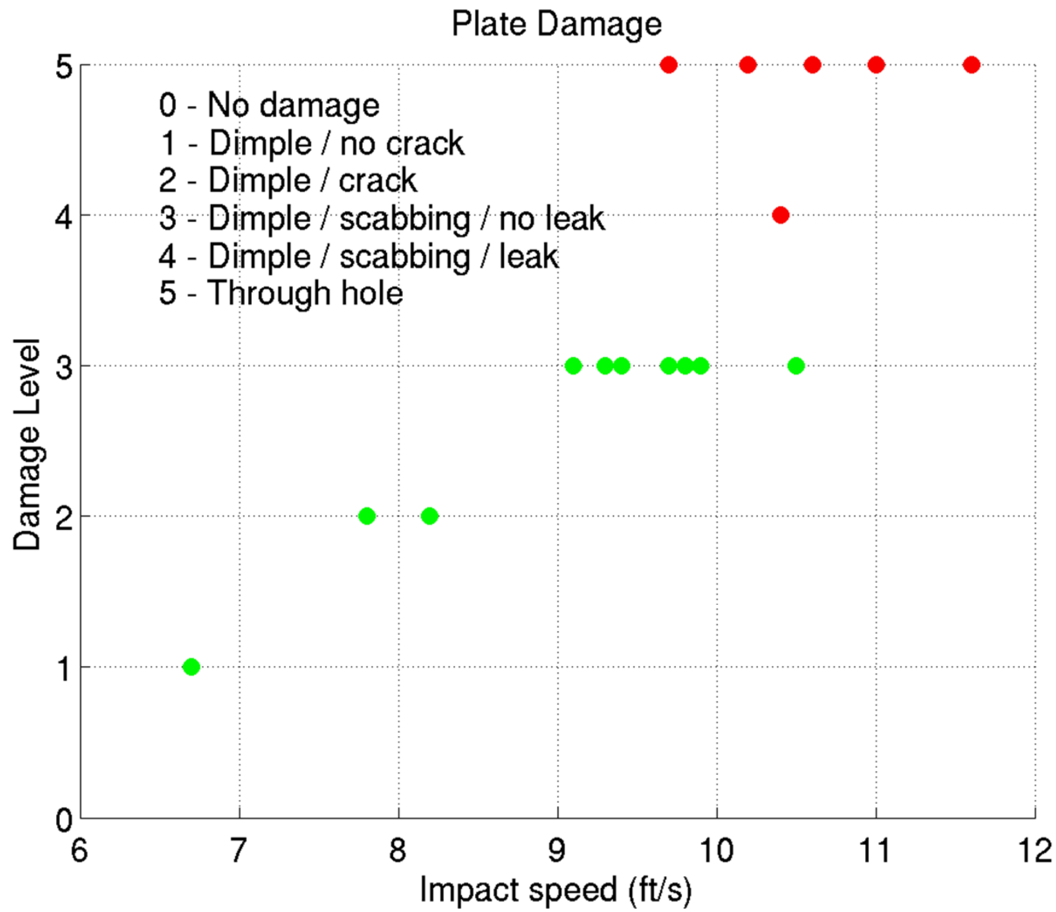
Damage level 1:

Damage level 2:

Damage level 3:

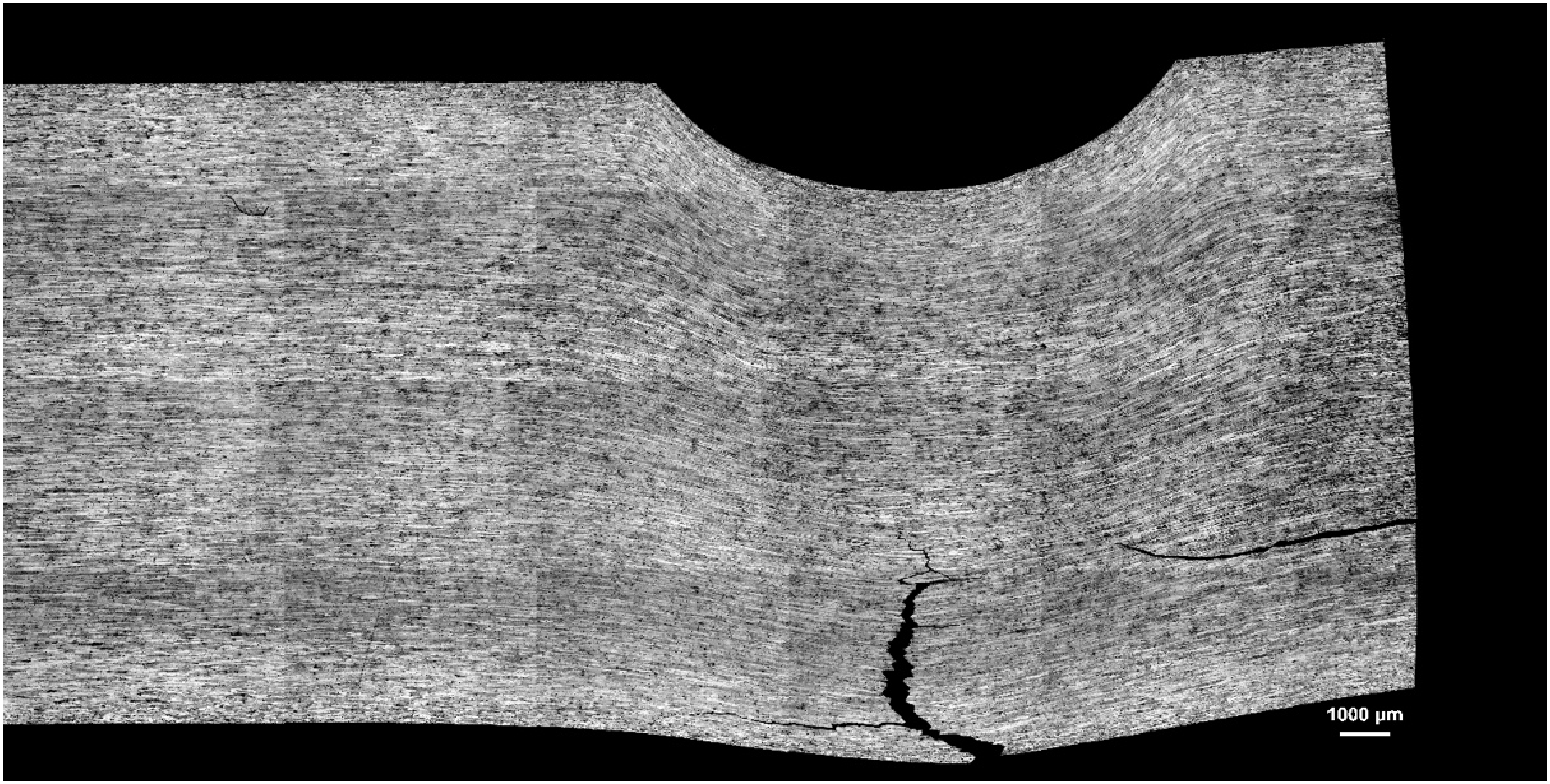
Damage level 4:

Damage level 5:



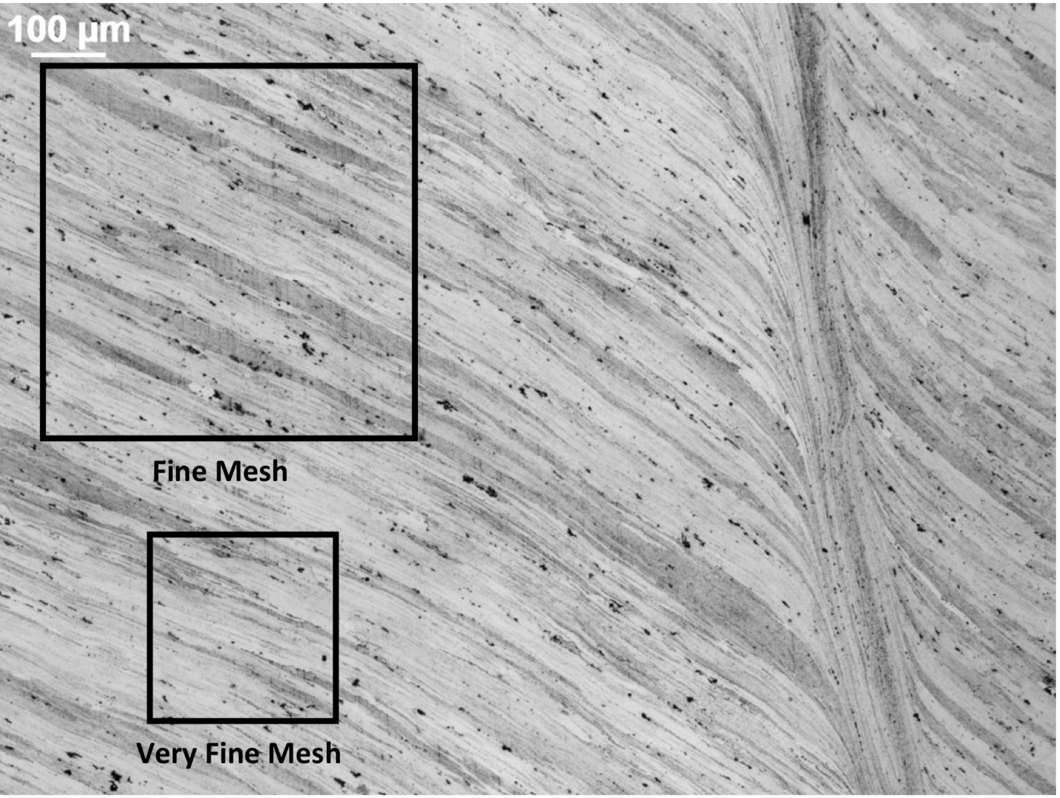
Puncture Video Record

8.2 ft/s Impact Speed

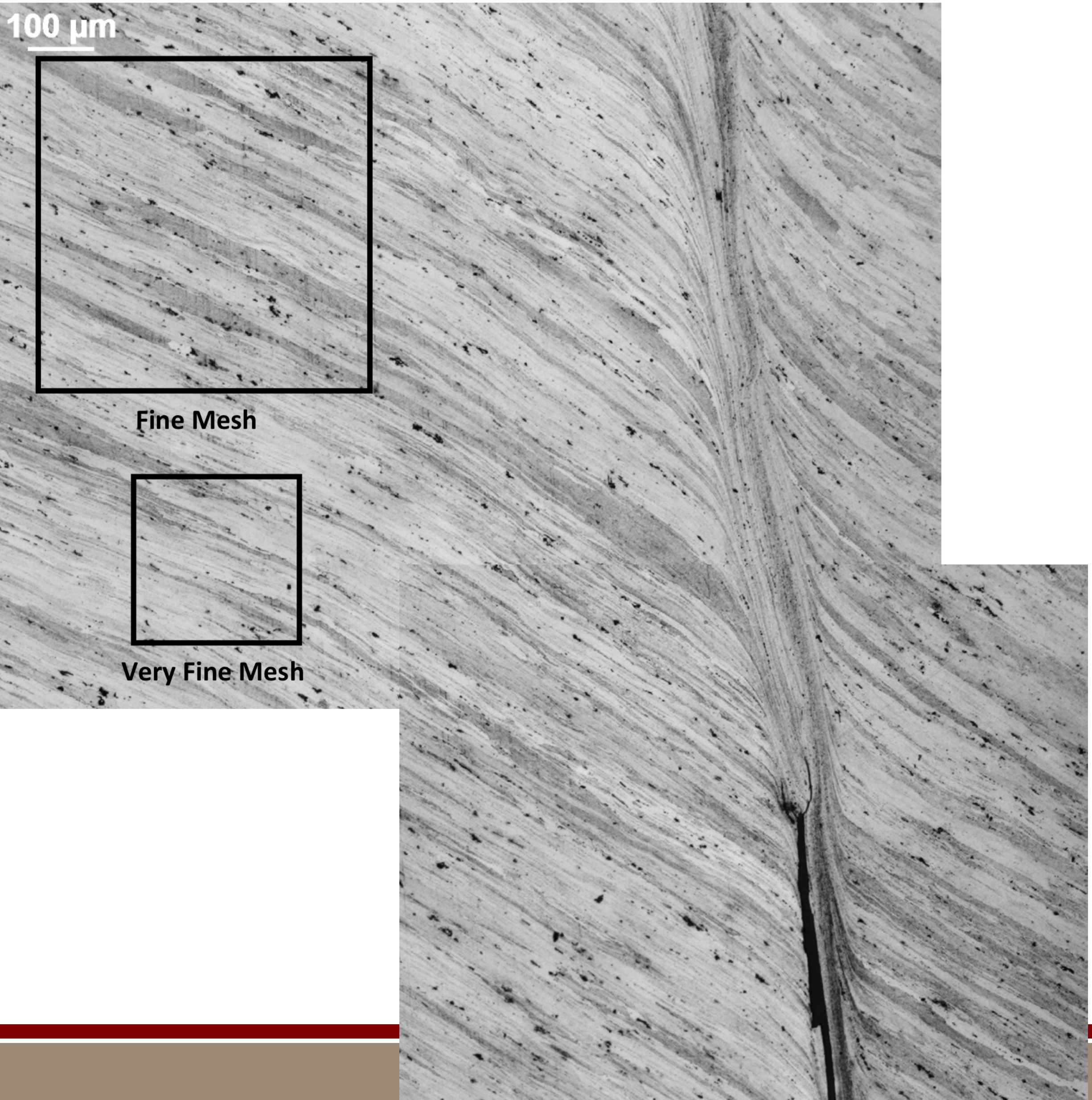


10.5 ft/s, No Failure

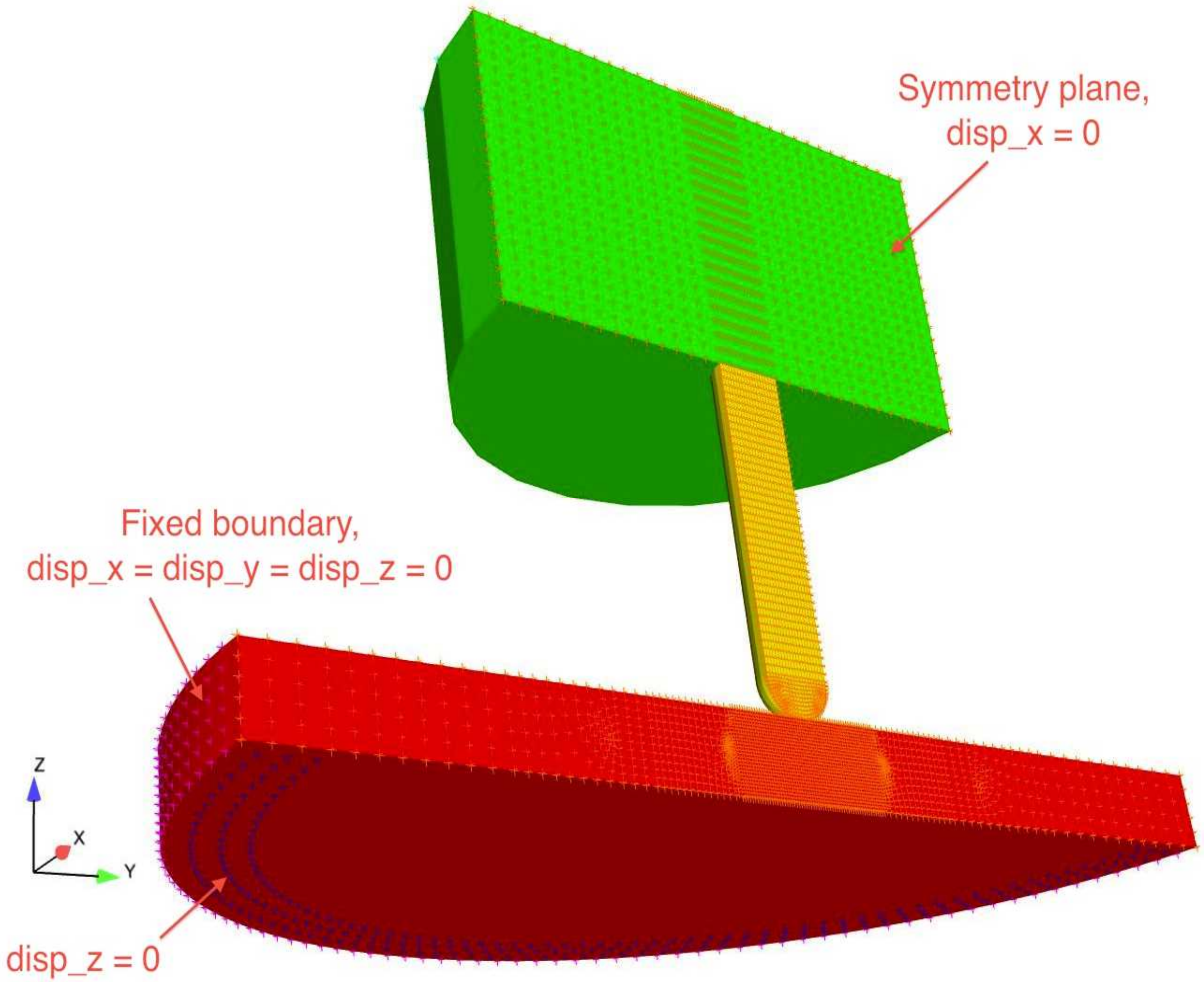
Microstructure of Plug Formation



Microstructure of Plug Formation



Finite Element Model



Johnson-Cook Material Characterization

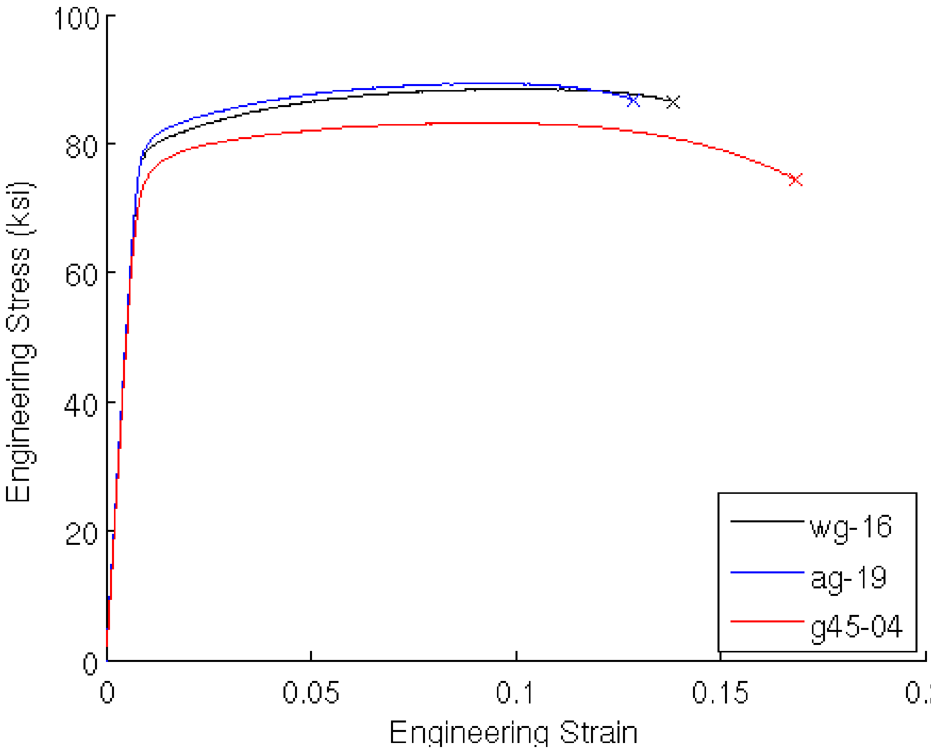
Sandia National Laboratories

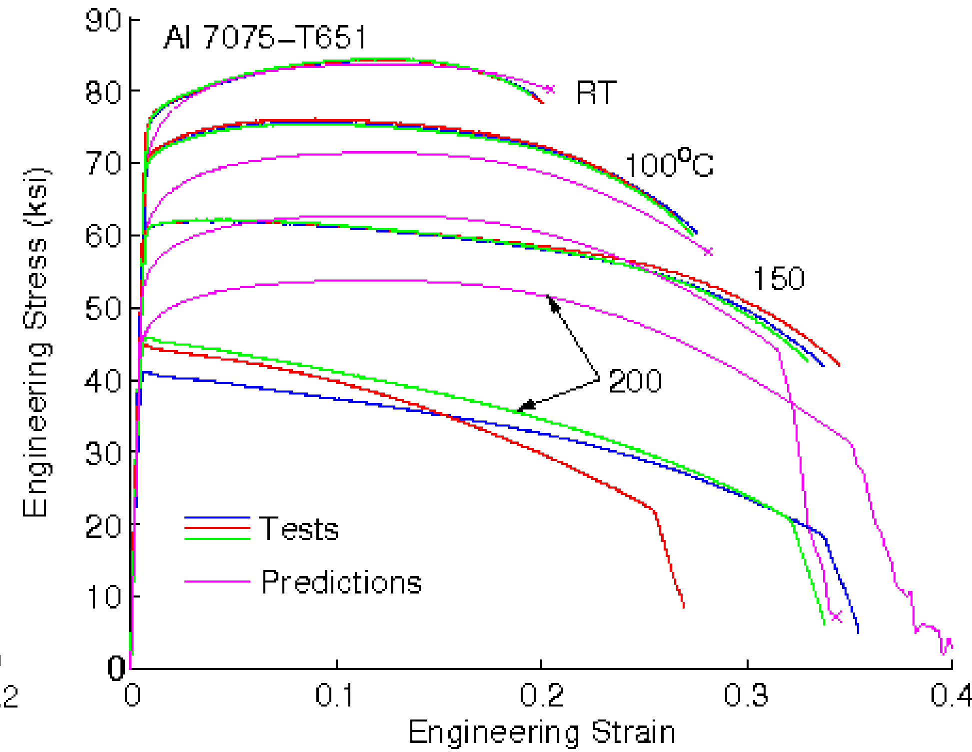
"Strength" Model

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

Failure Model

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





- Note anisotropy in yield and strain to failure
- Predictions at temperature partially good

Johnson-Cook Material Characterization

Sandia National Laboratories

"Strength" Model

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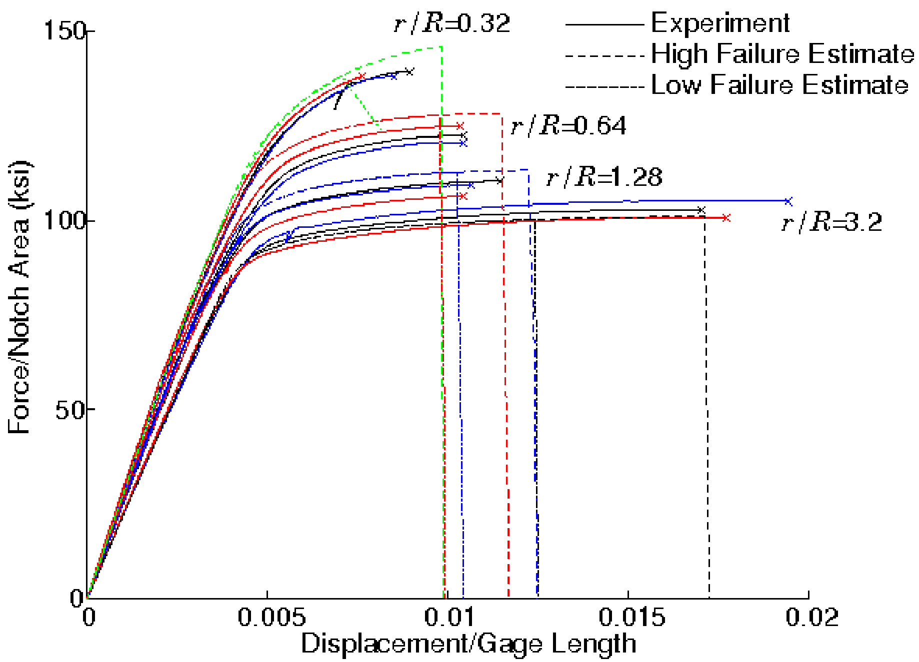
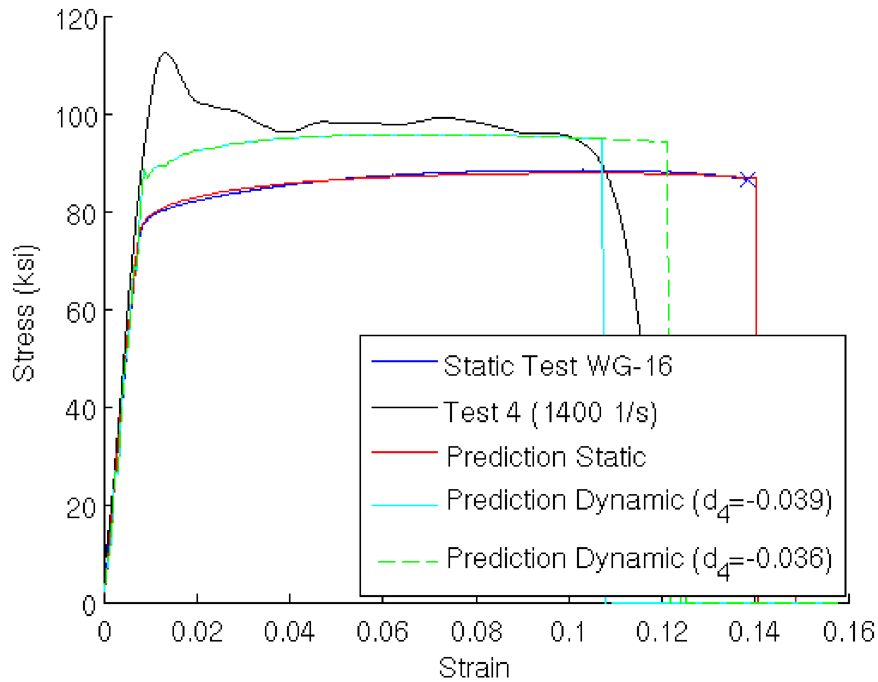
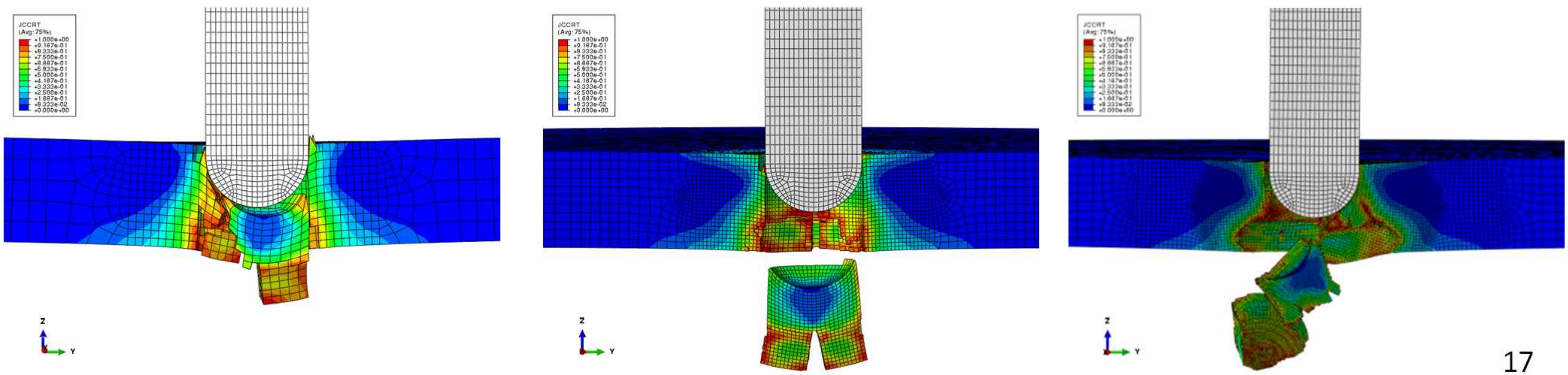


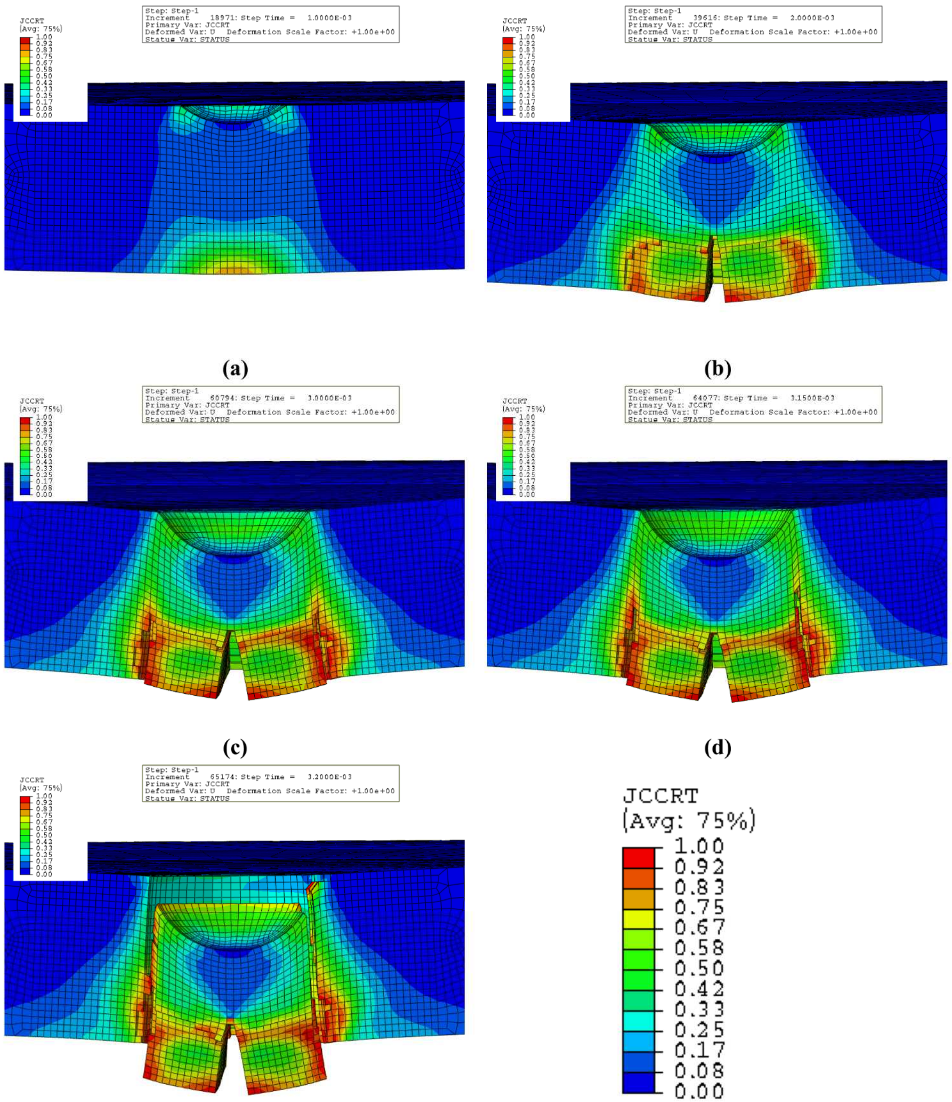


Numerical Simulation Results

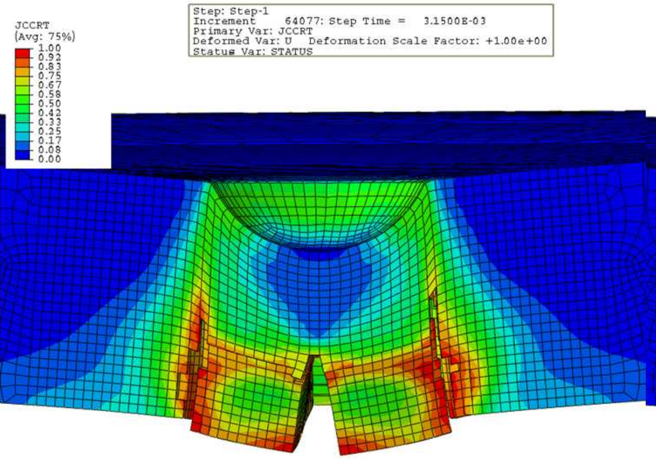
v_o, ft/s	Coarse	Fine	Very Fine
10.35		N	
10.45		N	
10.55		Y	
10.65		Y	
10.75		Y	
10.85	N	Y	N
10.95	N	Y	N
11.05	N	Y	N
11.15	N	Y	N
11.25	N		N
11.35	Y		N
11.45	Y		Y
11.55	Y		Y
11.65	Y		Y



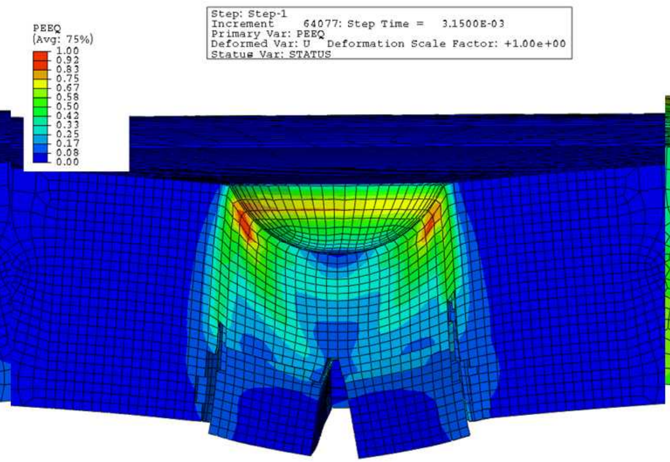
Evolution of Johnson-Cook Damage



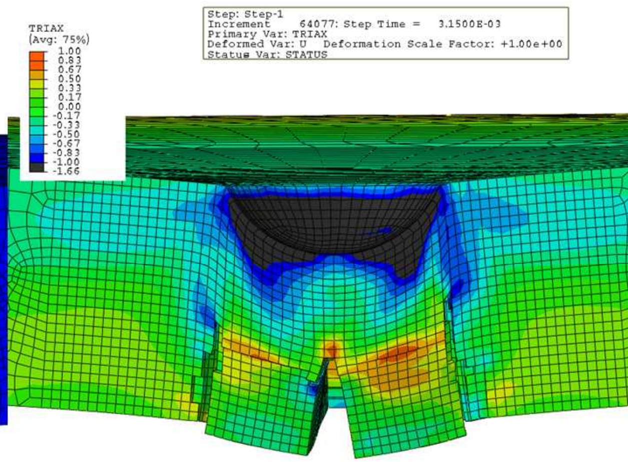
Just Prior to Plug Ejection…



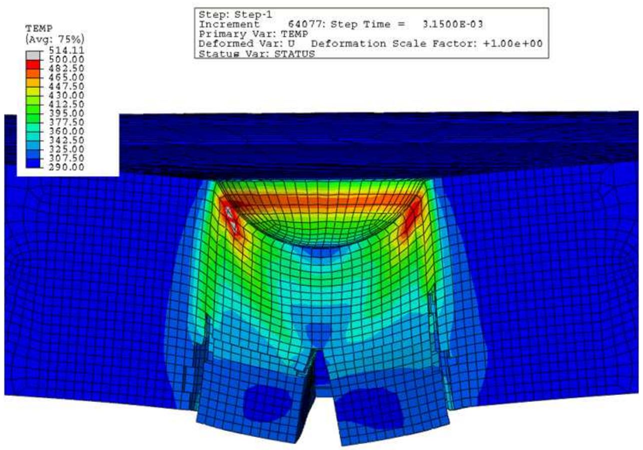
Damage



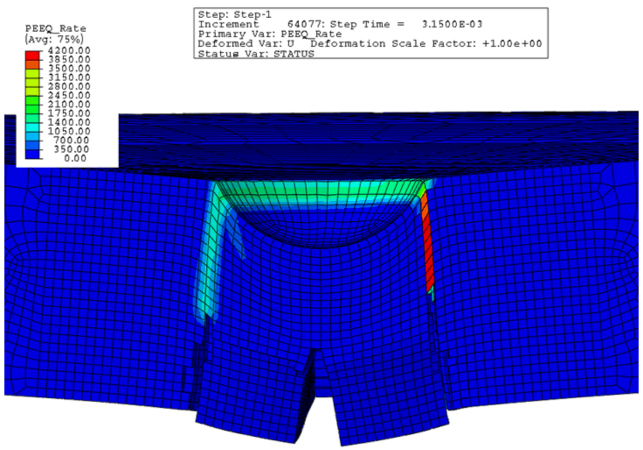
Equivalent Plastic Strain



Triaxiality

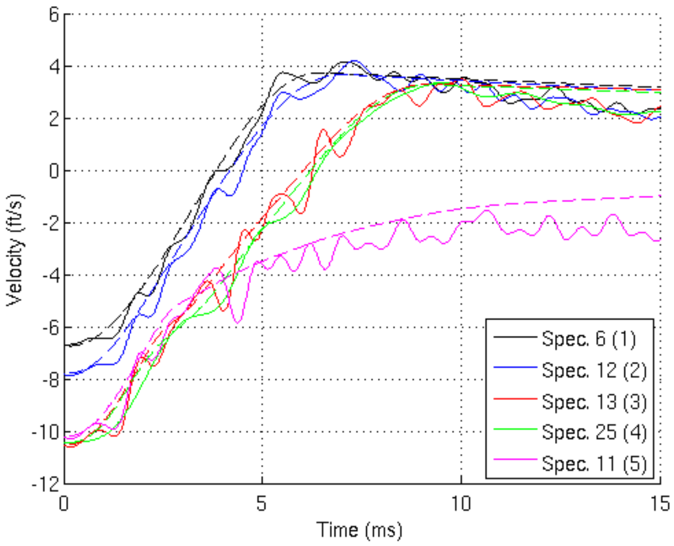


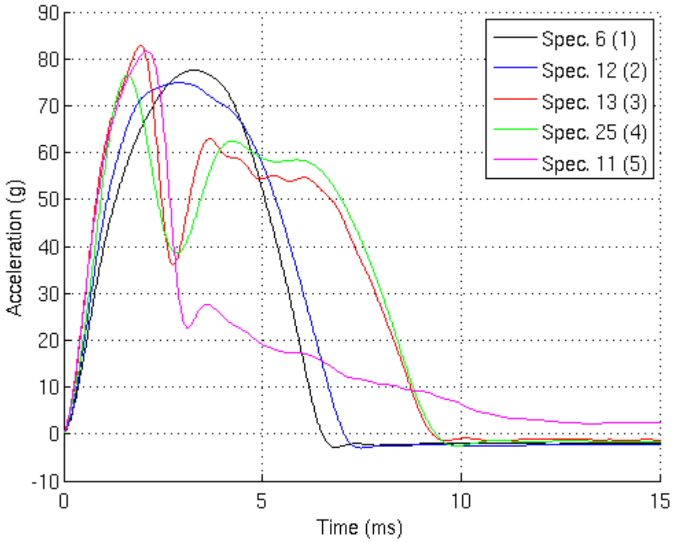
Temperature



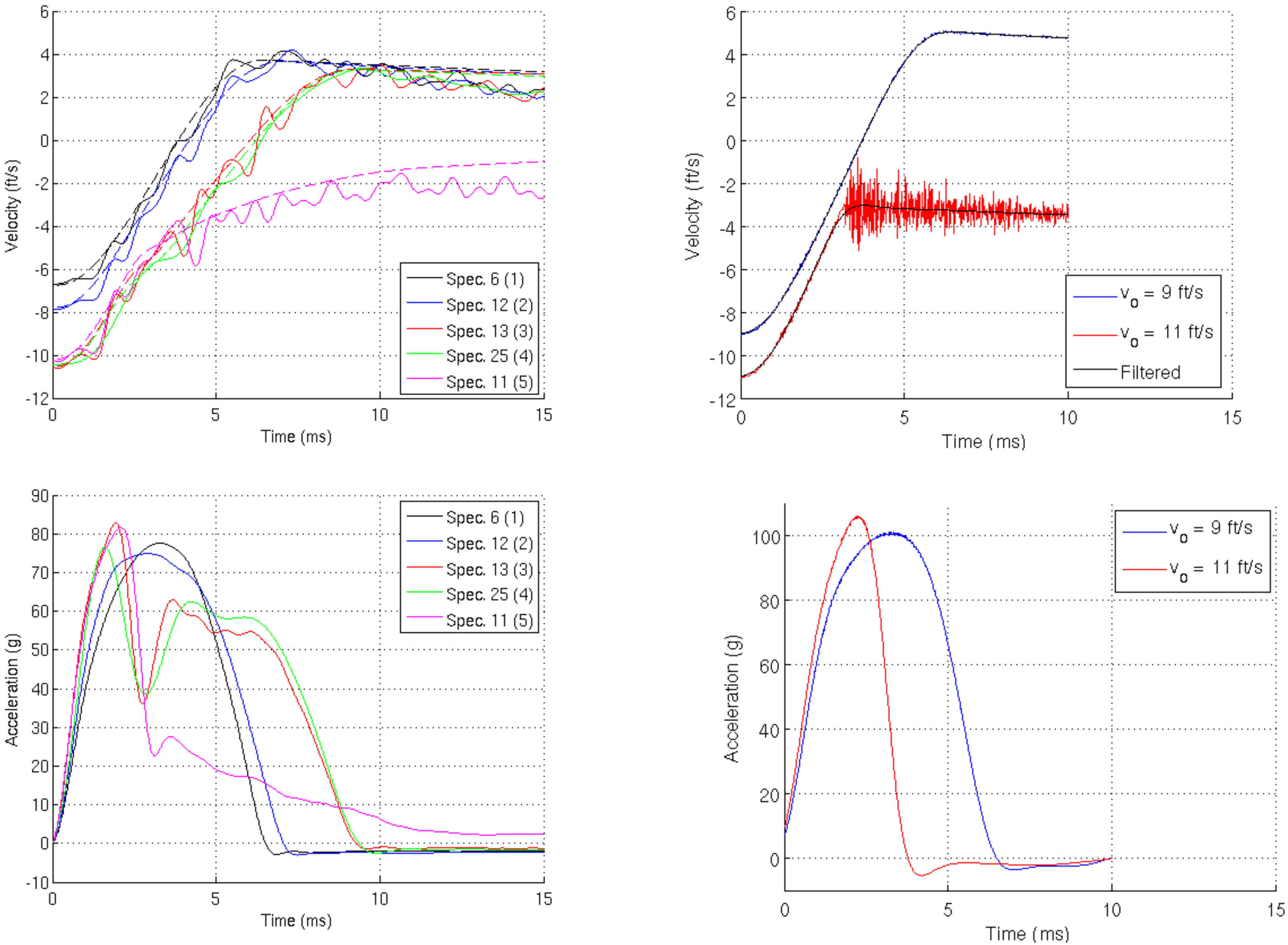
Equivalent Plastic Strain Rate

Carriage Velocity and Acceleration





Carriage Velocity and Acceleration



Conclusions

- Under the test conditions, the plates failed by plugging through a combination of fracturing and shear banding
- Reasonable predictions with adiabatic FE model
- Full fits of the Johnson-Cook strength and failure models based on experimental data were necessary
- Predictions mildly mesh dependent
- Most sensitive to
  - Triaxiality dependence of equivalent plastic strain to failure
  - Strain rate dependence of equivalent plastic strain to failure
- Mildly sensitive to
  - Adiabatic heating
  - Coefficient of friction
  - Hourglass stiffness

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Doubts

- Material model cannot account for all observed behavior
- Some material behavior not observed
- Had to extrapolate equivalent strain to failure data from high triaxiality data to low triaxiality regime
- Finite element model element size is large compared to shear band

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Were we lucky?

Doubts

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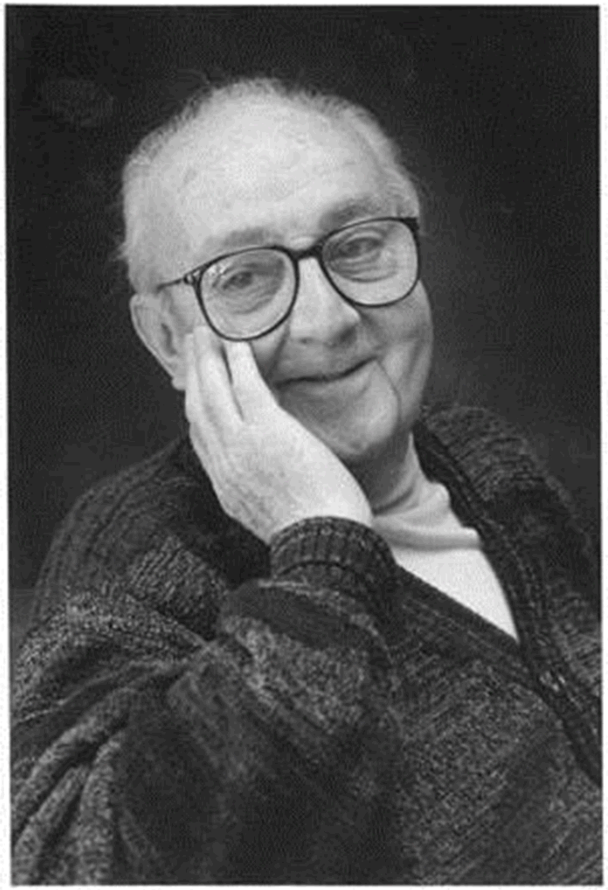
- Some material behavior not observed
- Had to extrapolate equivalent strain to failure data from high triaxiality data to low triaxiality regime
- Finite element model element size is large compared to shear band

Were we lucky?

What if we tried a punch with different mass and/or different shape? What if the impact was not normal?



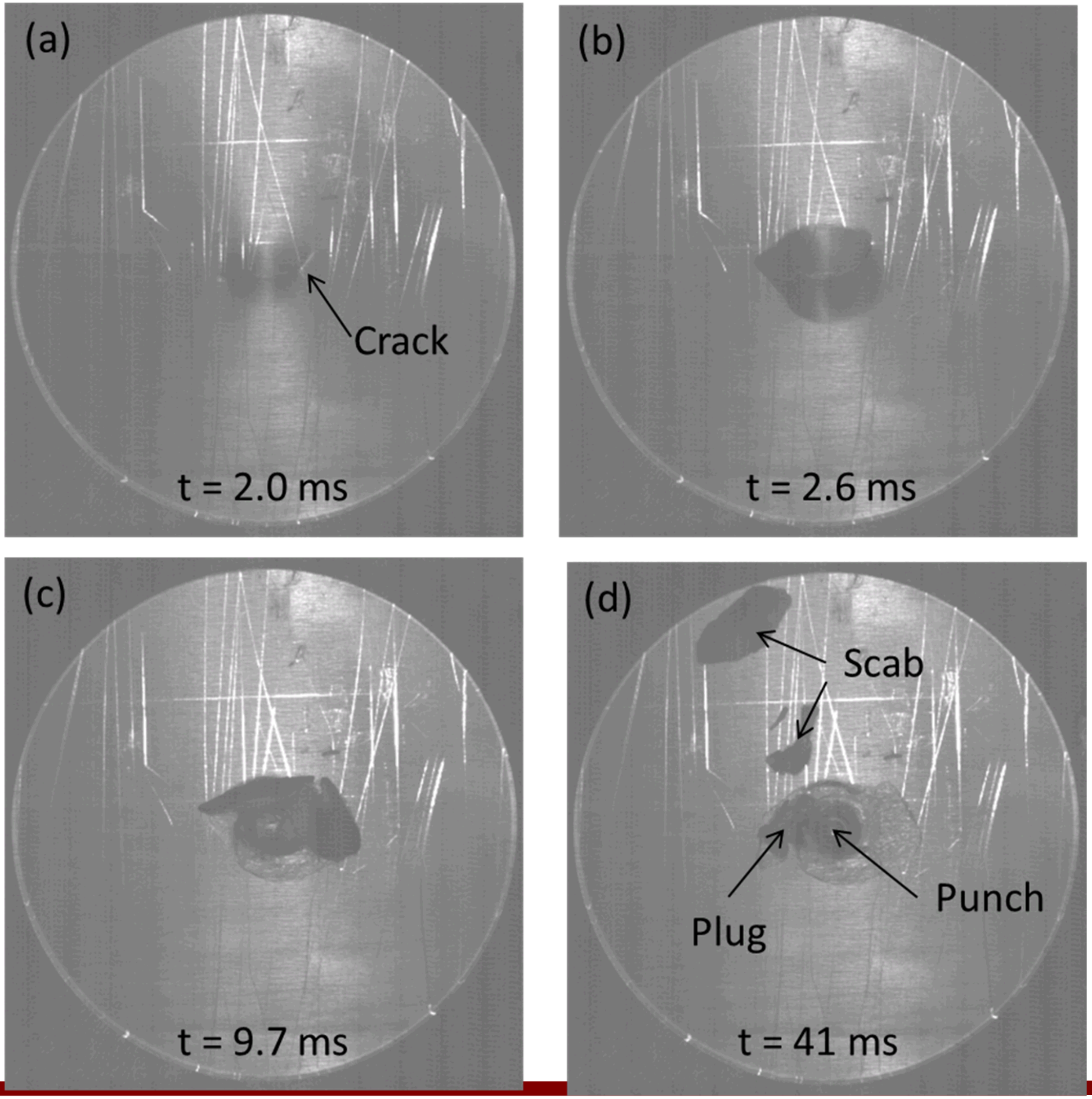
George E. P. Box (1919-2013)

British mathematician
Statistics professor at Univ. of WI

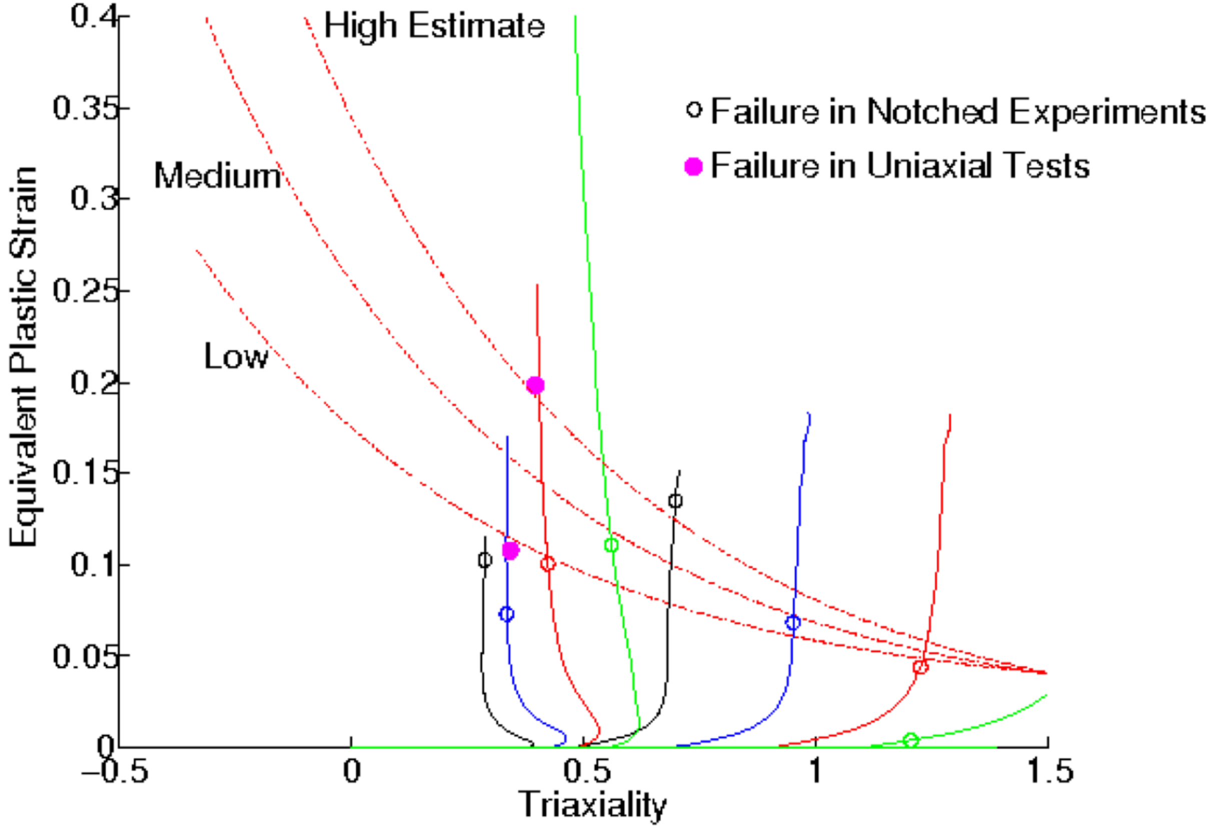
"Essentially, all models are wrong, but some are useful."

"Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful."

Puncture Event Sequence



Failure Dependence on Triaxiality



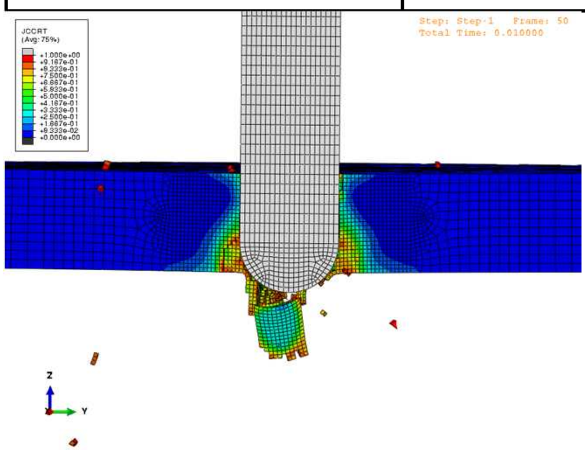
	Low	Medium	High
d_1	0.025	0.015	0.005
d_2	0.15	0.24	0.34
d_3	-1.5	-1.5	-1.5

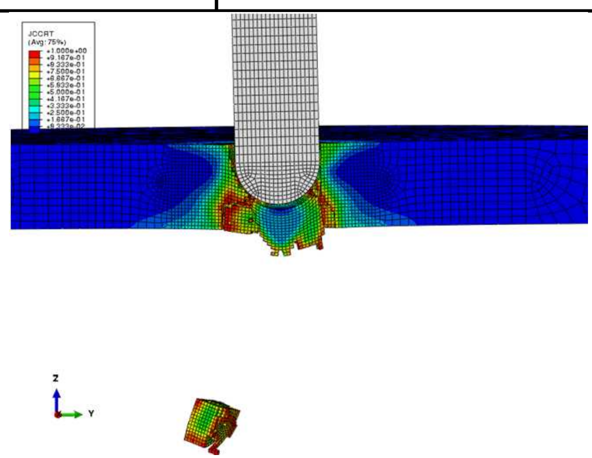
Material Model Property Values

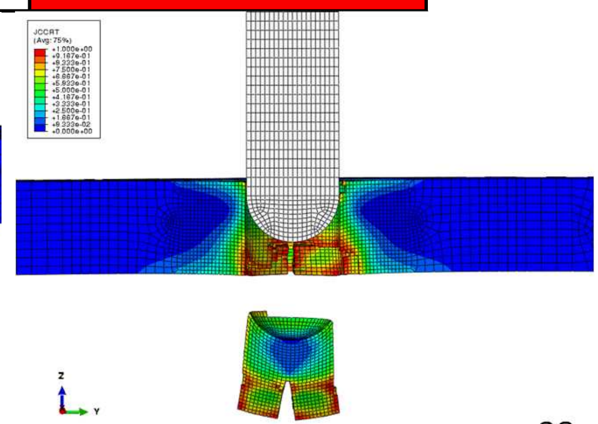
Strength Model Parameters				
A, MPa (ksi)	B, MPa (ksi)	n	C	m
517 (75.0)	405 (58.7)	0.41	0.0075	1.1
Failure Model Parameters				
d_1	d_2	d_3	d_4	d_5
See **Error! Reference source not found.**	See **Error! Reference source not found.**	-1.5	-0.039	8.0
Elastic Parameters				
E, GPa (ksi)	ν			
71.7 ($10.4\text{x}10^3$)	0.33			
Thermal Parameters				
c_p, J/(kg-K) (lb-in/(slug-ft/in ^{o}R))	T_m, K (^{o}R)	T_r, K (^{o}R)	β	
960 ($827\text{x}10^3$)	750 (1350)	293 (527)	0.95	
Other Parameters				
$\dot{\varepsilon}_e^p$	ρ, kg/m^3 (slug-ft/in/in^3)			
0.00016	2810 ($2.63\text{x}10^{-4}$)			

Effect of Triaxiality Fit

v_o , ft/s	Low	Medium	High
6	N		
6.5	N		
7	Y	N	
7.5	Y		
8	Y	N	
8.5	Y		N
9	Y	N	N
9.5	Y	N	N
10	Y	Y	N
10.5		Y	N
11		Y	Y
11.5		Y	Y
12			Y

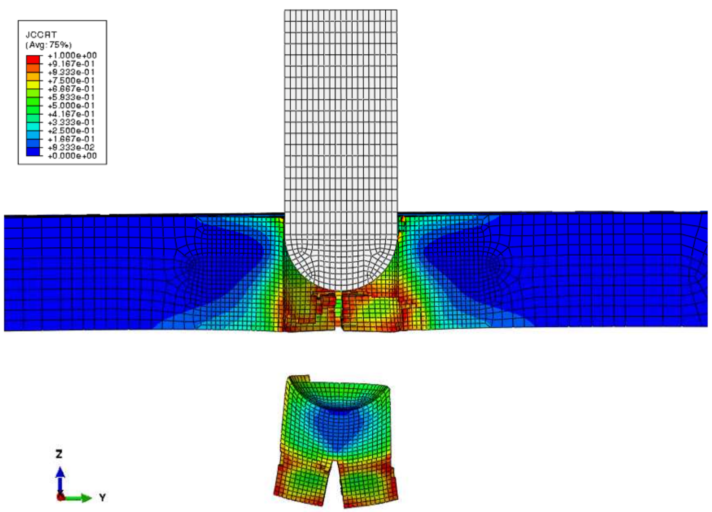


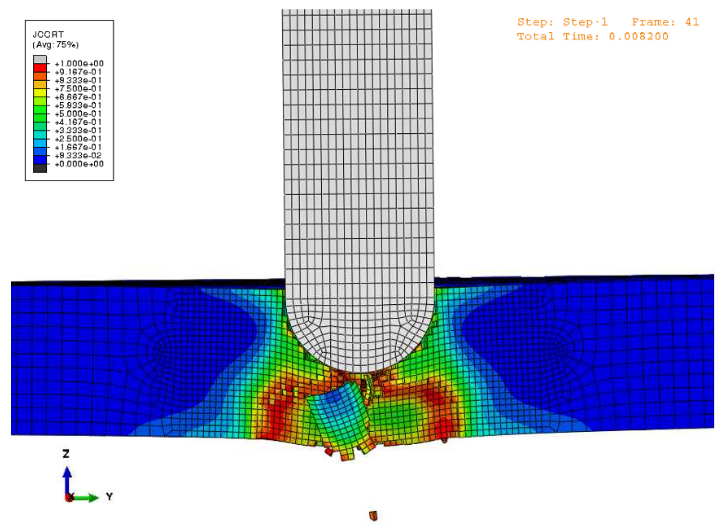




Effect of Adiabatic Heating

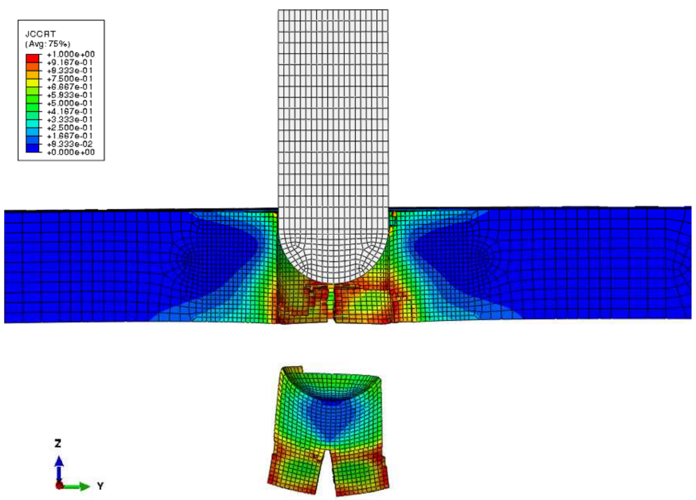
v_o , ft/s	$\beta = 0.95$	$\beta = 0$
9	N	N
9.5	N	Y
10	N	Y
10.5	N	Y
11	Y	Y
11.5	Y	Y

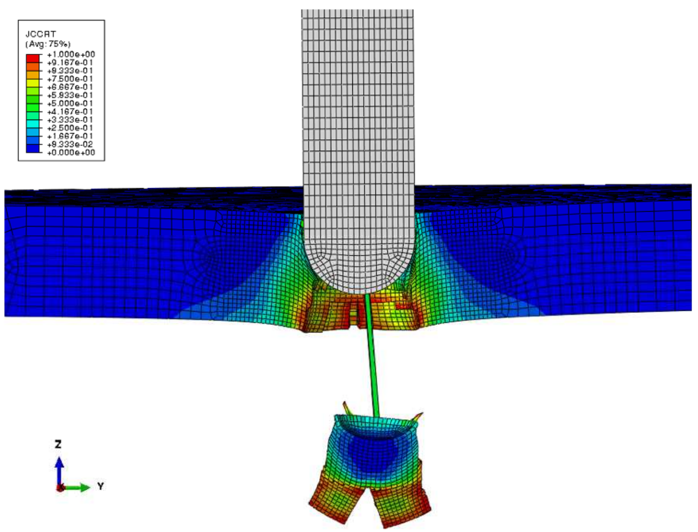




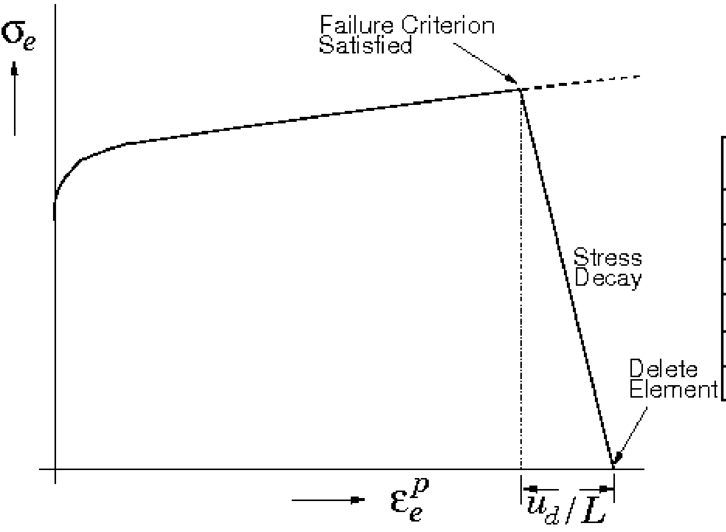
Effect of Strain Rate Dependence

v_o, ft/s	$d_4 = -0.036$	$d_4 = 0$
10.5	N	
11	Y	
14		N
14.5		Y

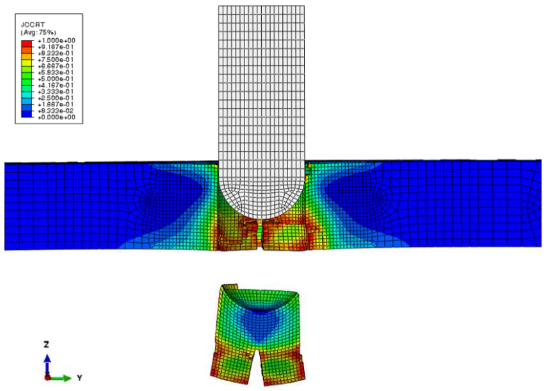


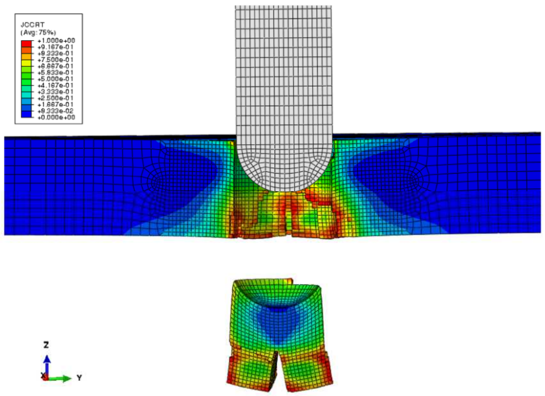


Effect of Stress Decay



v_o, ft/s	$u_d / L = 0$	$u_d / L = 2.3\times10^{-4}$	$u_d / L = 2.3\times10^{-3}$
9	N	N	N
9.5	N	N	N
10	N	N	N
10.5	N	N	Y
11.	Y	Y	Y
11.5	Y	Y	Y





Other Effects

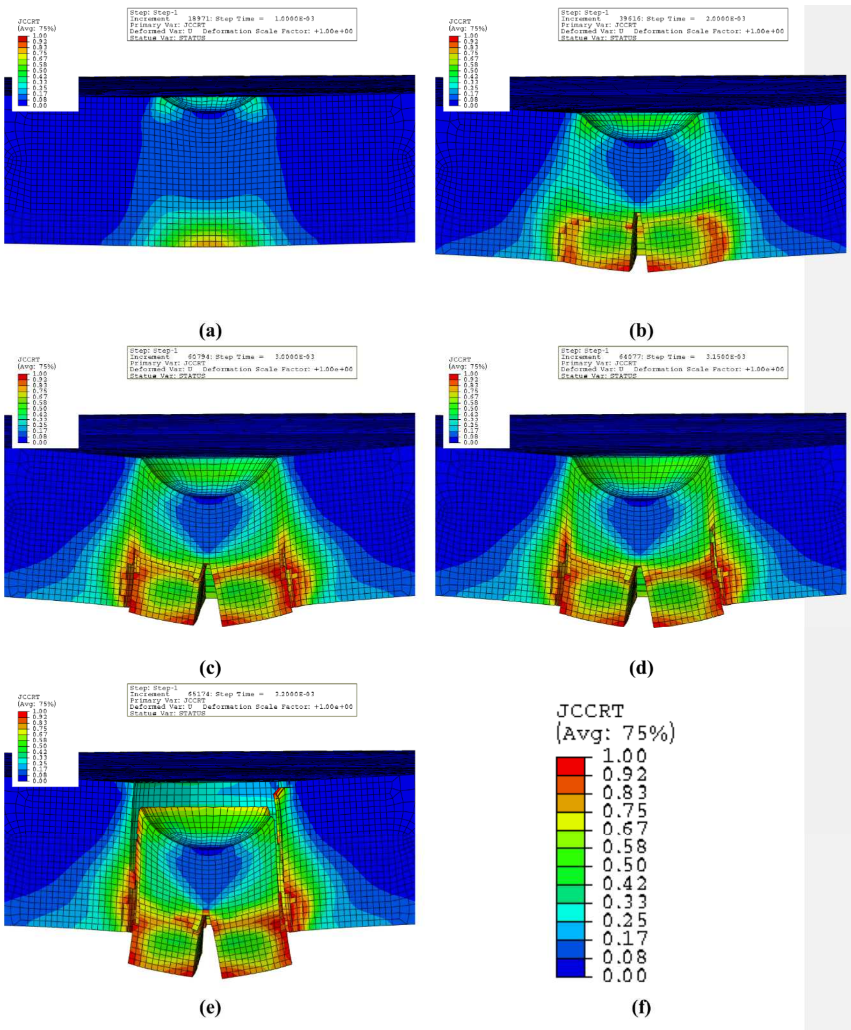
Friction:

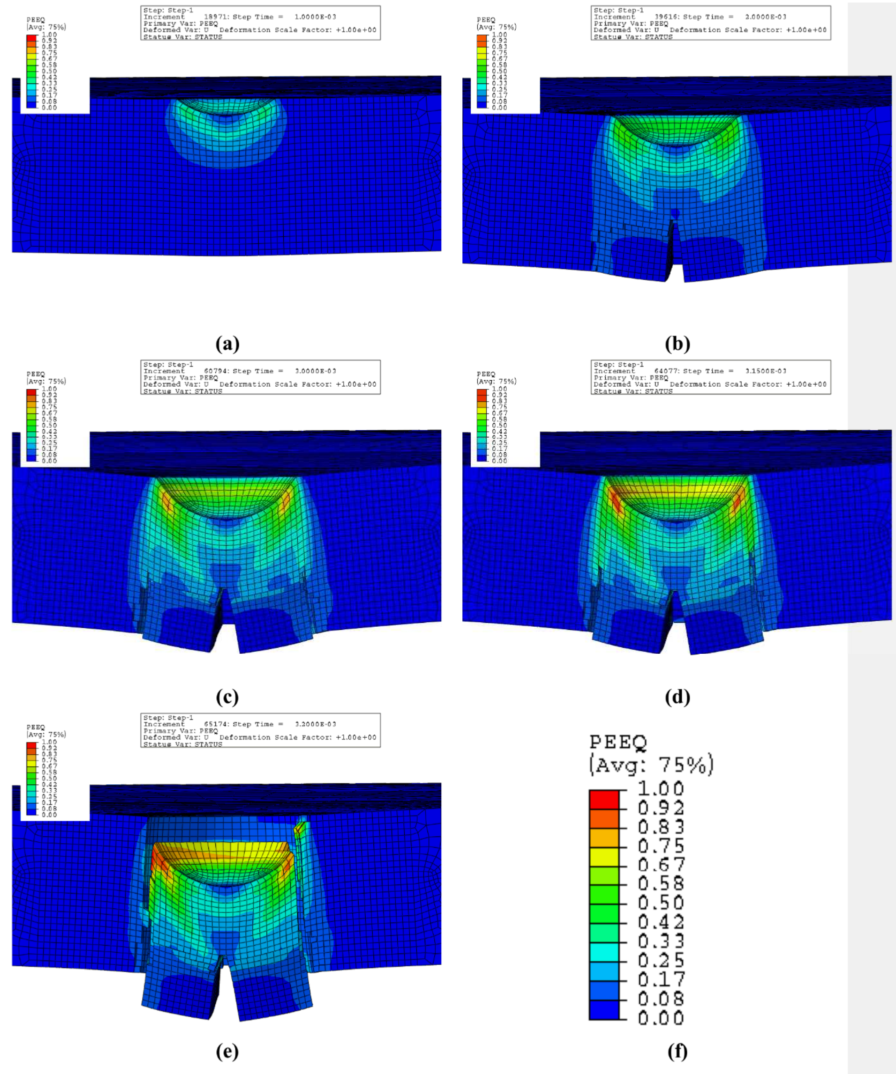
- No effect on threshold velocity with μ = 0.2, 0.4, 0.6

Hourglass Stiffness:

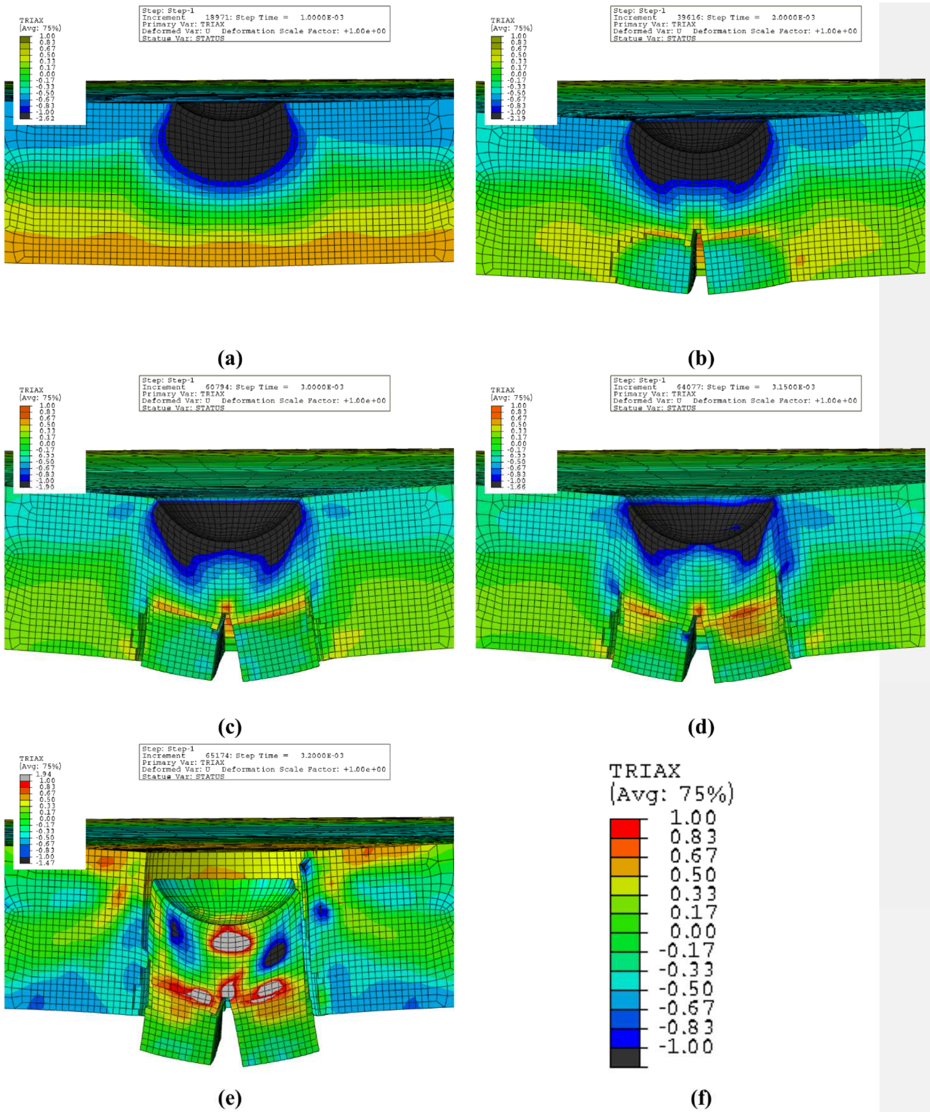
- Minimum effect for recommended range: 10.1 to 10.2 ft/s for hourglass 0.2 of recommended value and 10.4-10.5 for 3 times the recommended value.

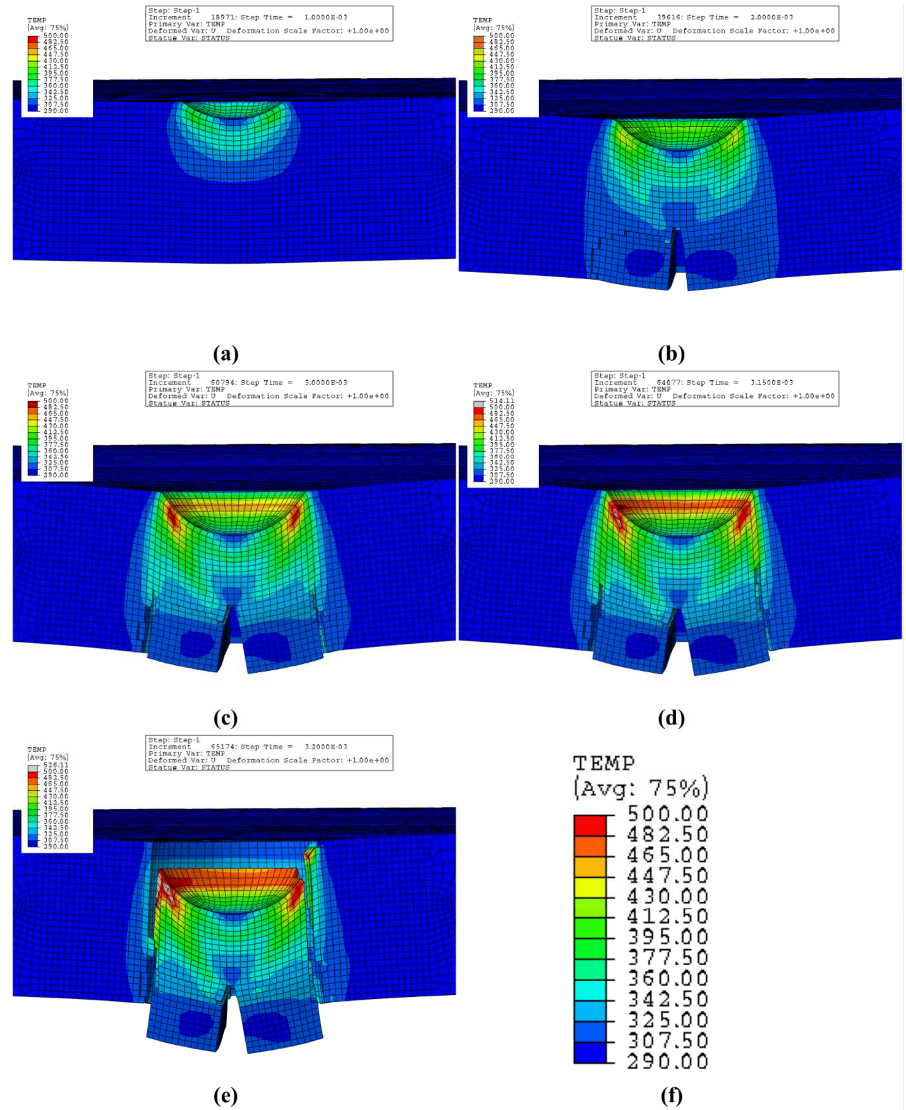
J-C Damage and Equiv. Plastic Strain





Triaxiality and Temperature





Equivalent Plastic Strain Rate