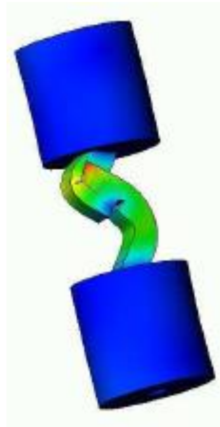
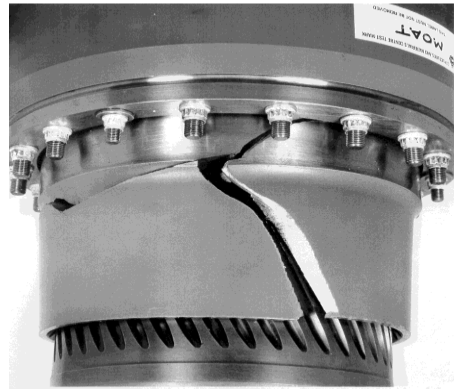
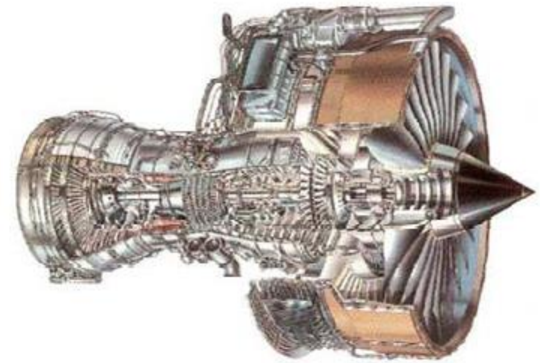
Exceptional service in the national interest







Validation of Puncture Simulations with Various Probe Geometries

Students: C J Taylor Mason (University of Alabama), Devyn D Rice (New Mexico State University), and Christopher J Salazar (University of Rhode Island)

Mentors: Emily Miller (Sandia National Laboratories), Neal Hubbard (Sandia National Laboratories), Edmundo Corona (Sandia National Laboratories), and Yu-Lin Shen (University of New Mexico)

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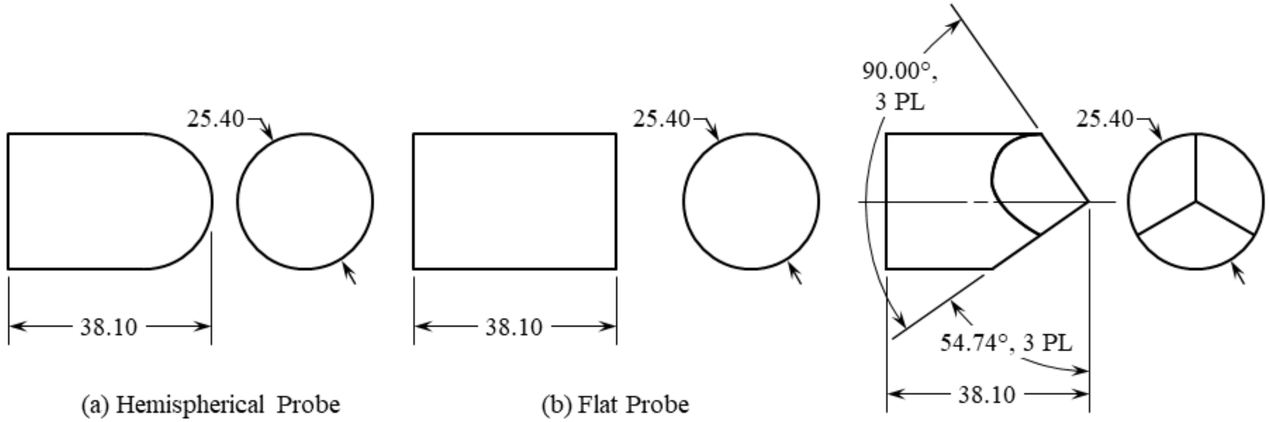
SAND2019-8709 PE

Project Overview

- Goals:
  - Determine the effect that differing probe geometries have on the energy required to puncture AA7075-T651 and SS304L plates
- Technical Approach:
  - Calibrate Johnson-Cook plasticity and failure model to experimental results for AA7075-T651
  - Select plasticity and failure model for SS304L simulations
  - Simulate three differing probe geometries impacting two different coupon geometries for both AA7075-T651 and SS304L

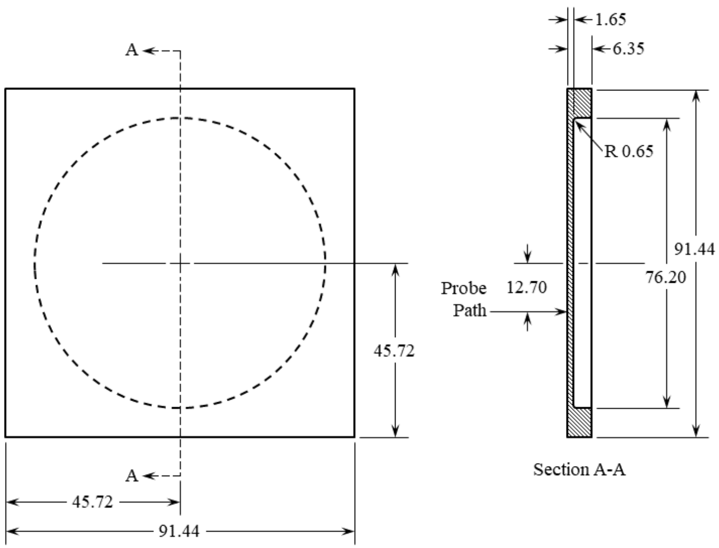
AA7075-T651 Coupon and Probe Geometries



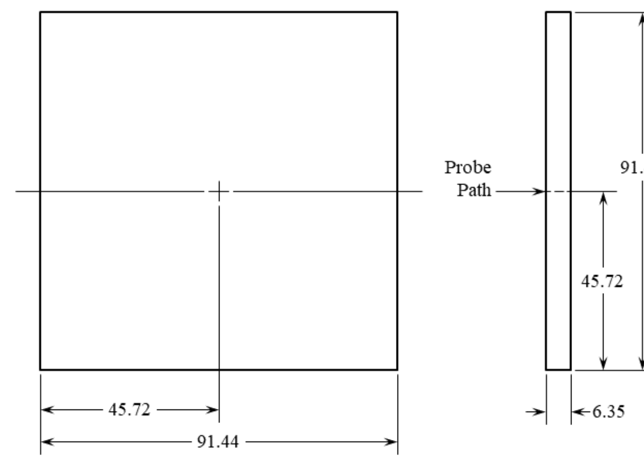
(a) Hemispherical Probe

(b) Flat Probe

(c) Corner Probe



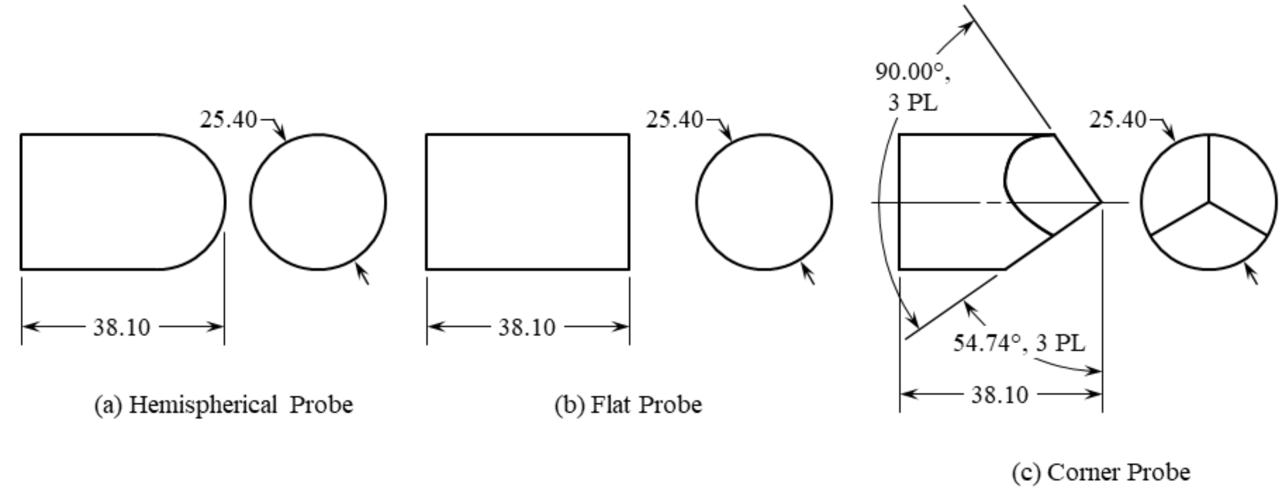
Thin AA7075-T651 Coupon

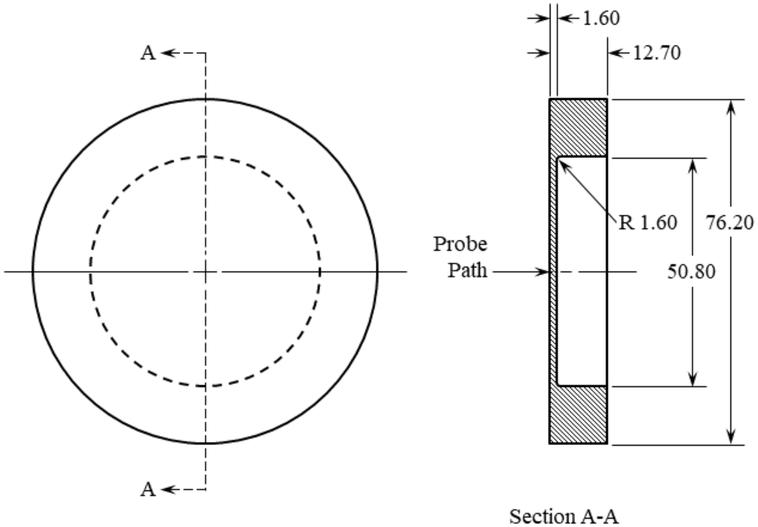


Thick AA7075-T651 Coupon

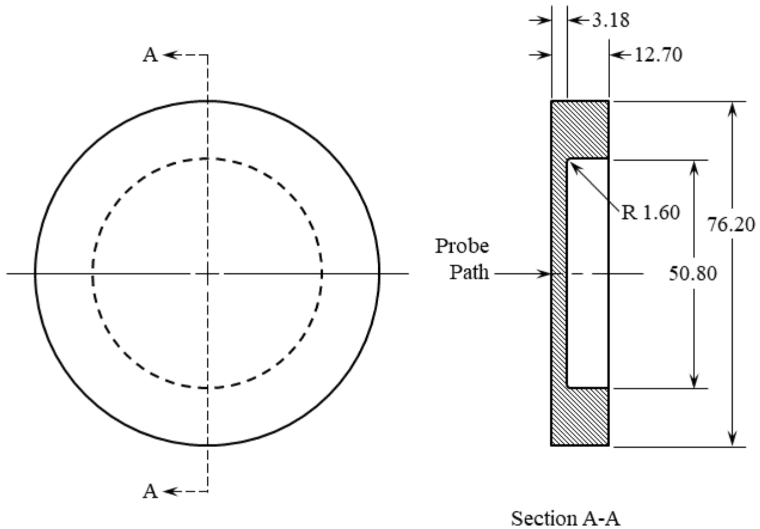
Dimensions in Millimeters

SS304L Coupon and Probe Geometries





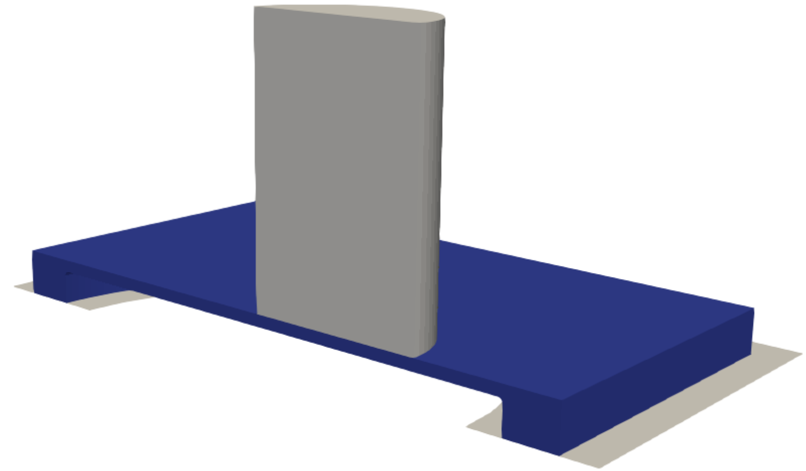
Thin SS304L Coupon



Thick SS304L Coupon

Dimensions in Millimeters

AA7075-T651 Thin Coupon Boundary Conditions



- The thin aluminum coupon is 1.65 mm thick
- The energy absorbed by the coupon for three different probes were evaluated; Flat probe, Corner probe, Hemispherical probe

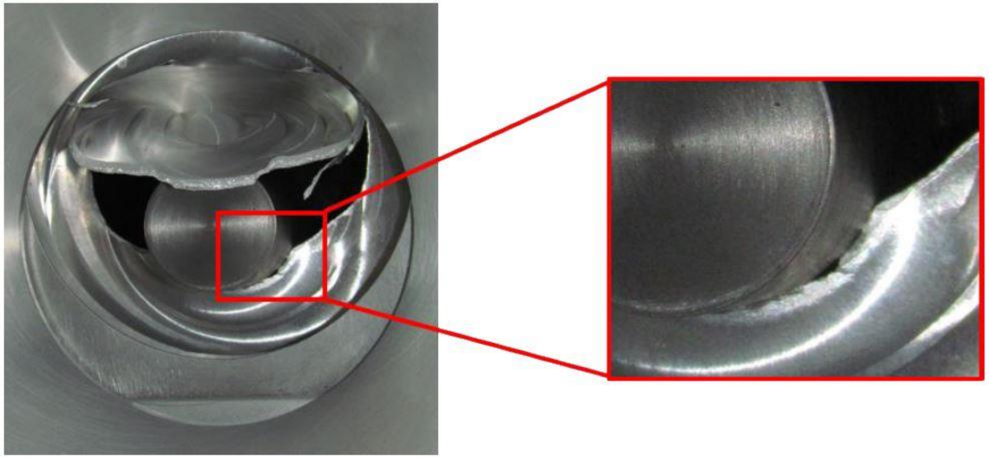
- Plasticity Model: Johnson-Cook (Corona et al)
  - $\sigma = \left[A + B\varepsilon_p{}^n\right][1 + Cln(\dot{\varepsilon}^*)[1 - T^{*m}]$
- Damage Model: Johnson-Cook (Brar et al)
  - $\varepsilon^f = (D_1 + D_2 e^{D_3\sigma^*})(1 + D_4 ln\dot{\varepsilon}^*)(1 + D_5 T^*)$
- Initial Total Probe Kinetic Energy: 200 J

E. Corona, W. Witkowski, N. Breivik, K. Hu, J. Gorman, M. Spletzer and T. Cordova, "SAND2012-7604: ASC V&V L2 Milestone No. 4485 Puncture Failure Simulations," Sandia National Laboratories, 2012.

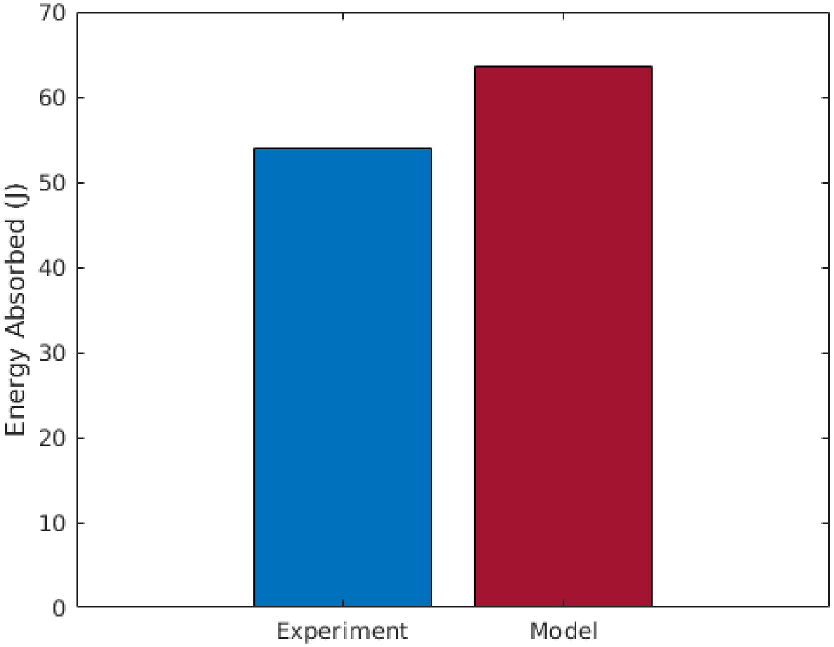
N. Brar, V. Joshi and B. Harris, "Constitutive Model Constants Al 7075-T651 and Al 7075-T6," in *American Institute of Physics*, 2009.

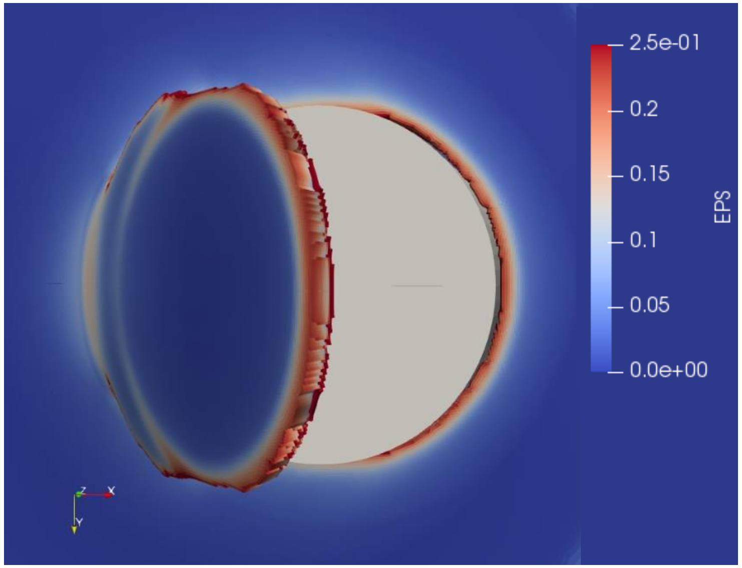
Flat Probe is Close to Experimental Results

- ~16% difference in energy absorbed between experiments and the model
- Reduction in velocity of the probe in the model is within ~7.6% of experimental data



Fracture surface of flat probe experiment

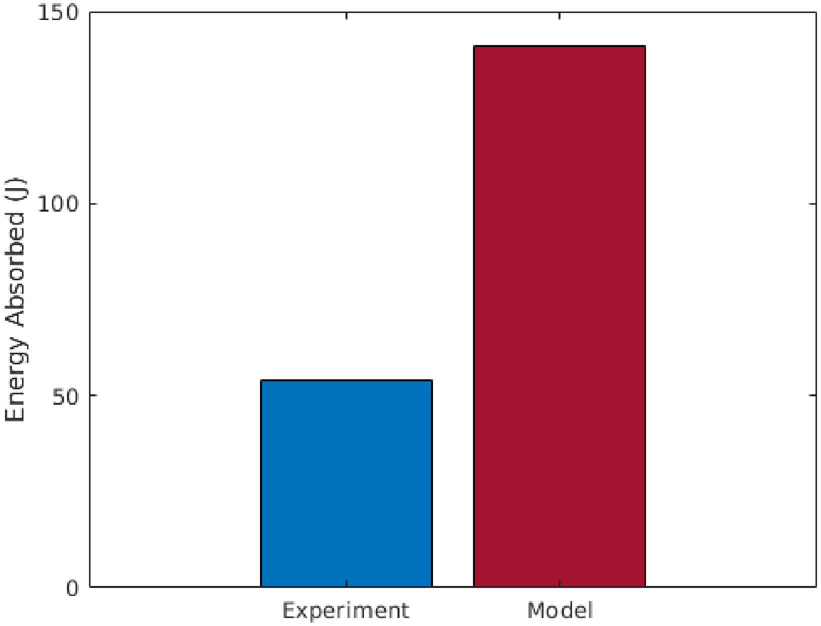


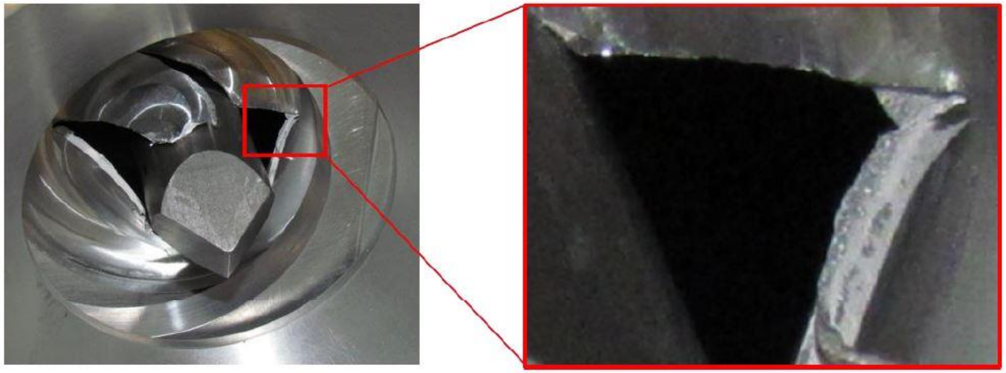


Flat probe model crack propagation

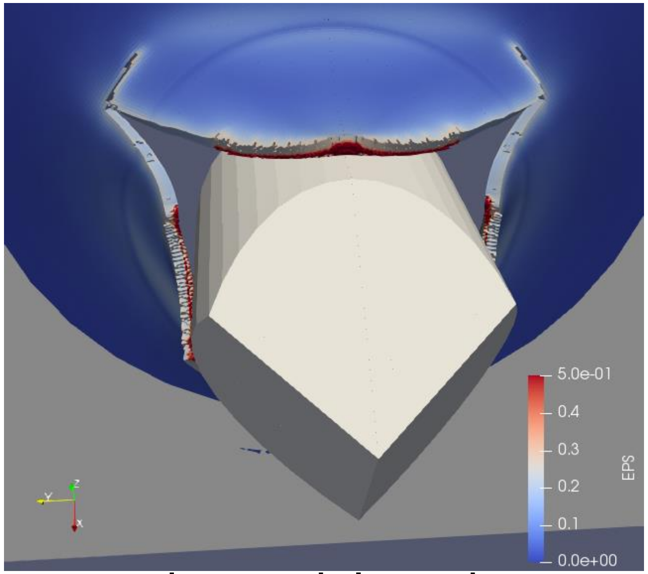
Corner Probe Model Fracture Surface Resembles Experimental Fracture Surface

- ~158% difference in energy absorbed between experiments and the model
- Reduction in velocity of the probe in the model is within ~61% of experimental data

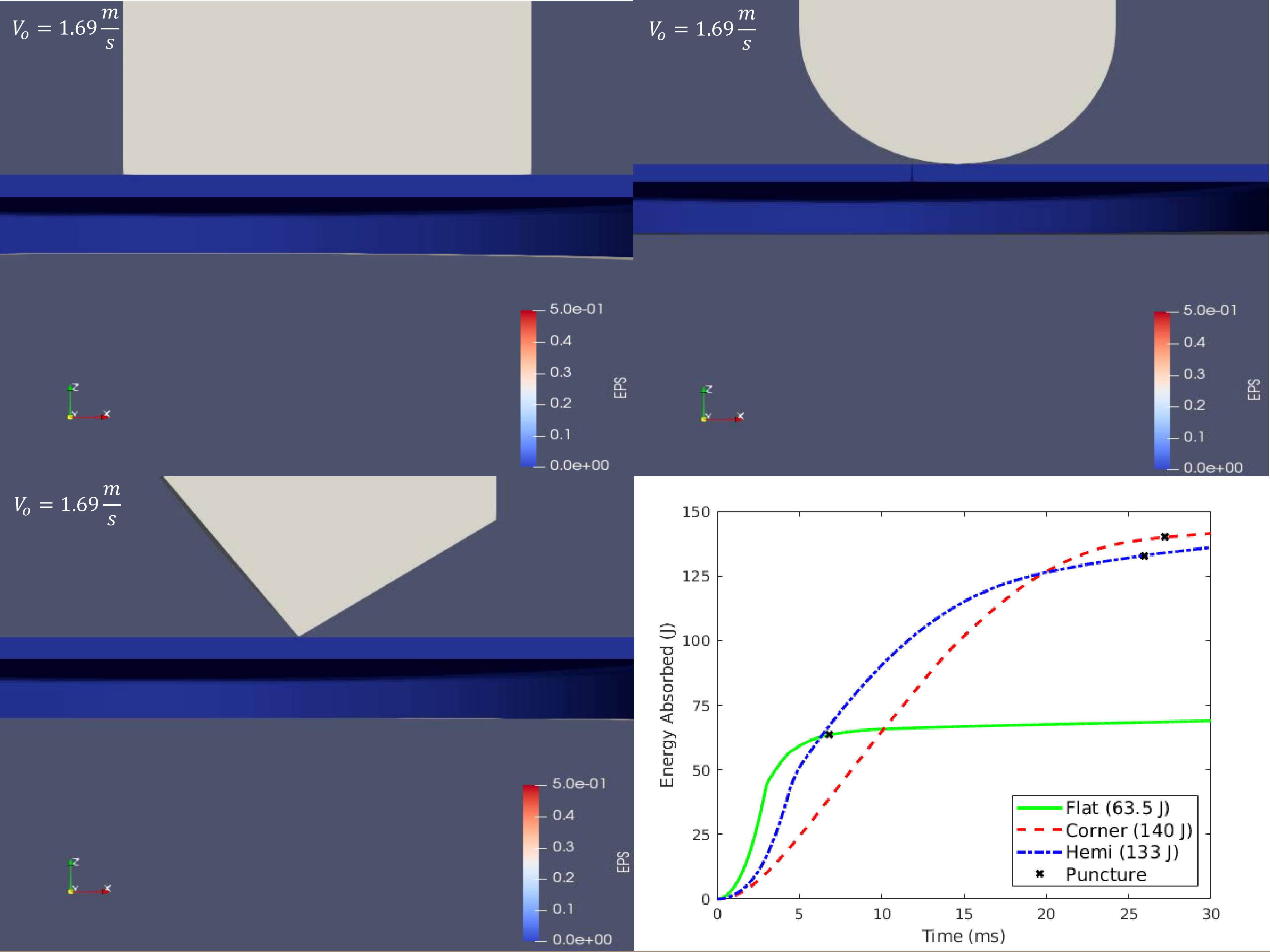




Fracture surface of corner probe experiment

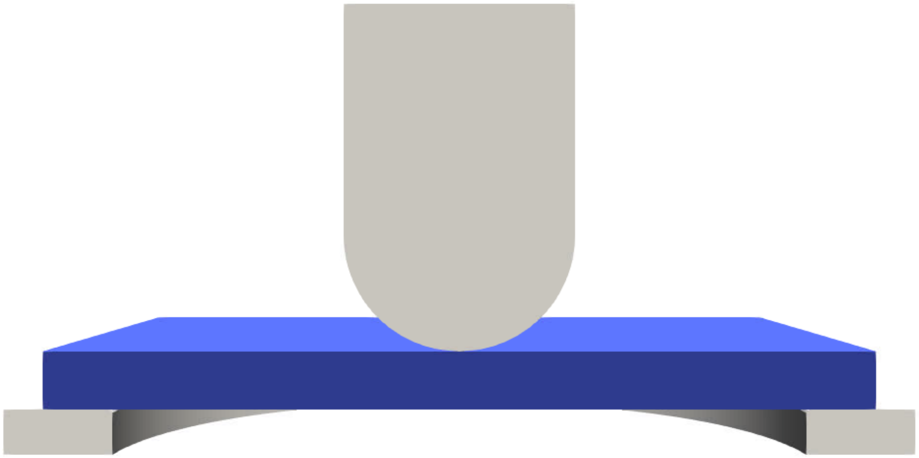


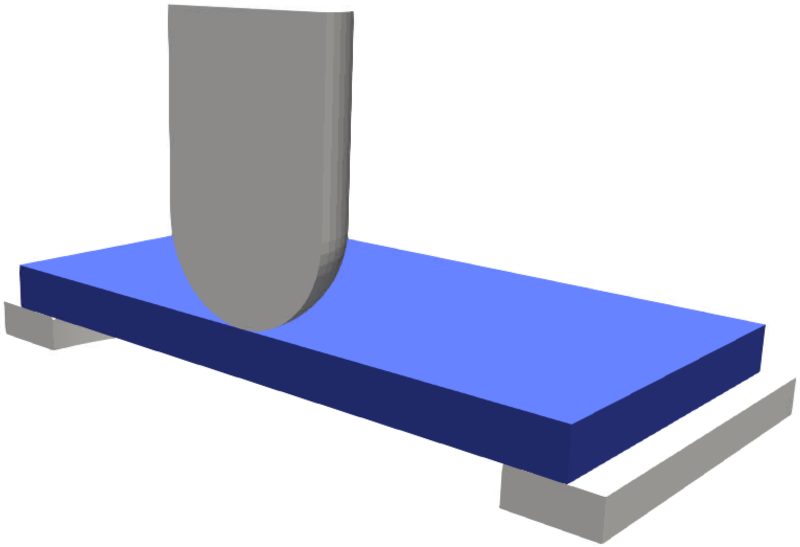
Corner probe model crack propagation



$V_o = 1.69\,\frac{m}{s}$
5.0e-01
0.4
0.3
0.2
0.1
0.0e+00
EPS
$V_o = 1.69\,\frac{m}{s}$
5.0e-01
0.4
0.3
0.2
0.1
0.0e+00
EPS
$V_o = 1.69\,\frac{m}{s}$
5.0e-01
0.4
0.3
0.2
0.1
0.0e+00
EPS
Energy Absorbed (J)
Time (ms)
Flat (63.5 J)
Corner (140 J)
Hemi (133 J)
Puncture

AA7075-T651 Thick Coupon Boundary Conditions



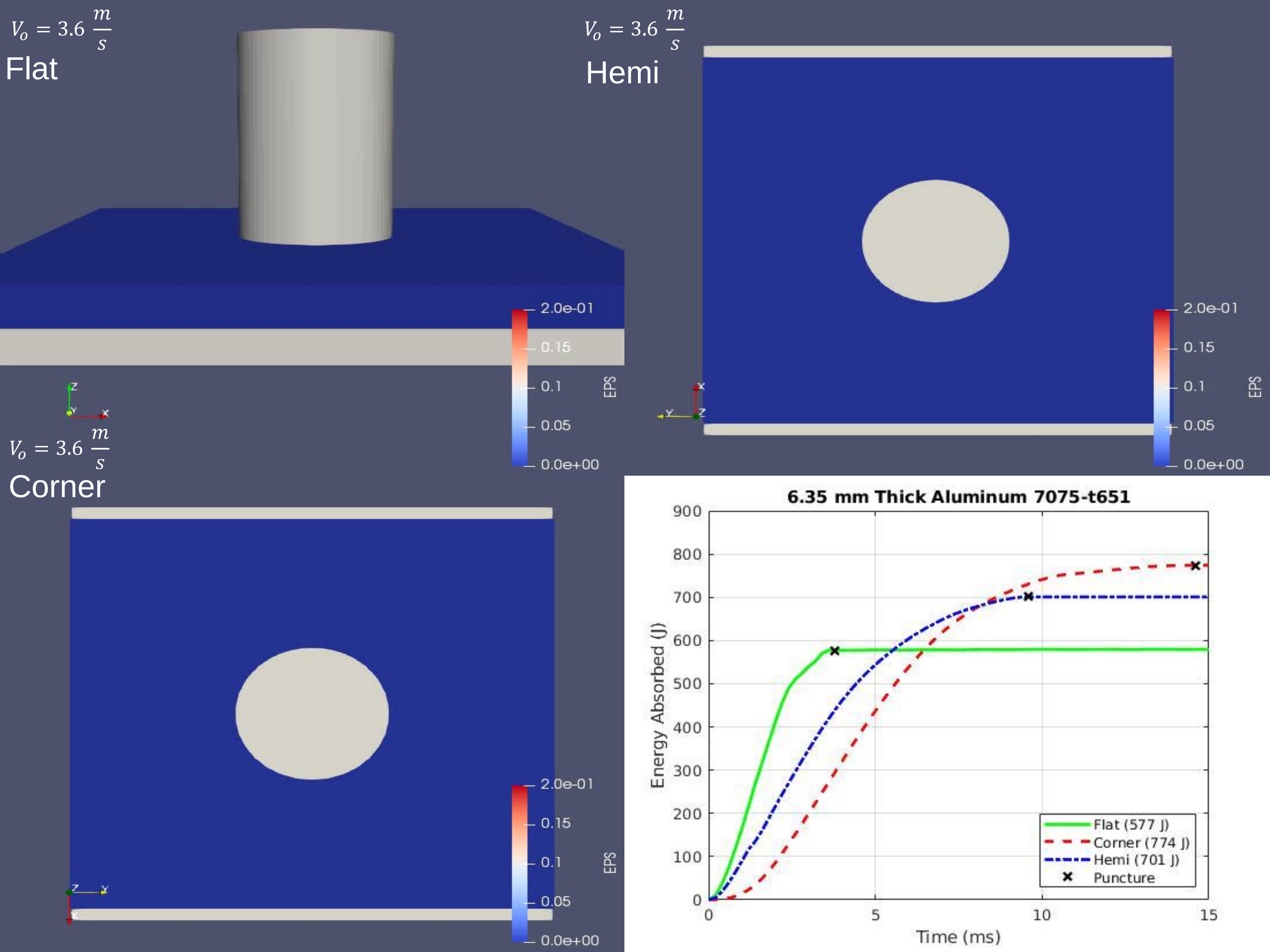


- The thin aluminum coupon is 6.25 mm thick (0.25")
- Initial Probe Kinetic Energy: 450 J

- Plasticity Model: Johnson-Cook (Corona et al)
  - $\sigma = \left[A + B{\varepsilon_p}^n\right]\left[1 + Cln(\dot{\varepsilon}^*)\right]\left[1 - {T^*}^m\right]$
- Damage Model: Johnson-Cook (Brar et al)
  - $\varepsilon^f = (D_1 + D_2 e^{D_3 \sigma^*})(1 + D_4 ln\dot{\varepsilon}^*)(1 + D_5 T^*)$
- Failure Criterion: Equivalent Plastic Strain 0.2

E. Corona, W. Witkowski, N. Breivik, K. Hu, J. Gorman, M. Spletzer and T. Cordova, "SAND2012-7604: ASC V&V L2 Milestone No. 4485 Puncture Failure Simulations," Sandia National Laboratories, 2012.

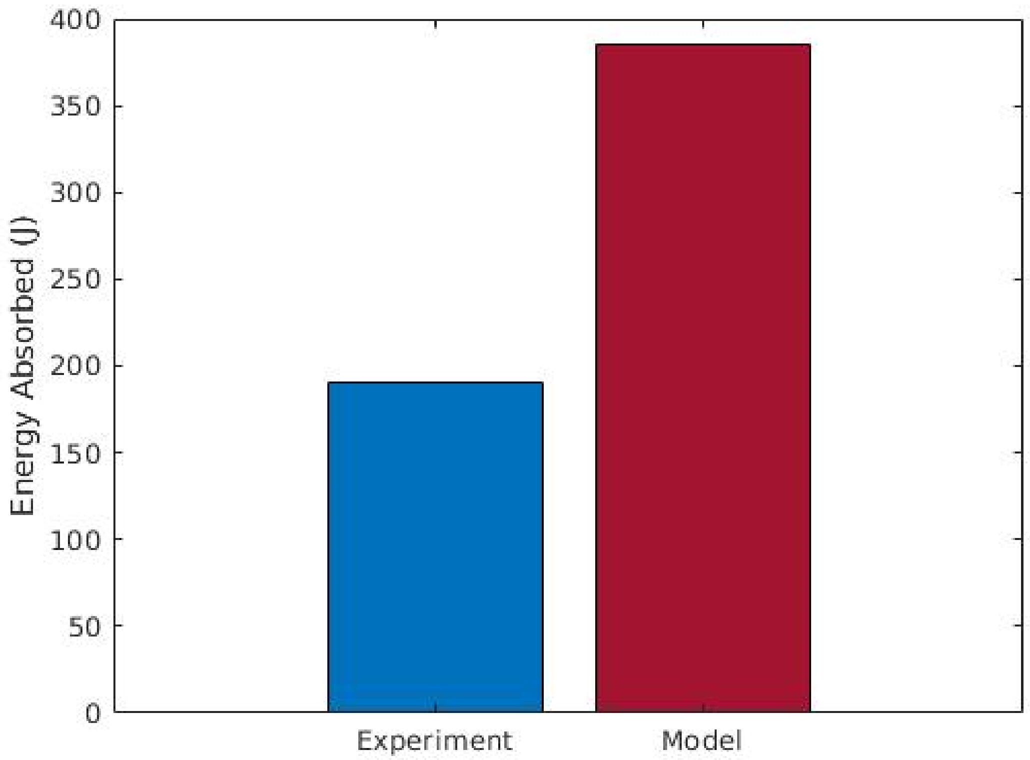
N. Brar, V. Joshi and B. Harris, "Constitutive Model Constants Al 7075-T651 and Al 7075-T6," in *American Institute of Physics*, 2009.


$V_o = 3.6\ \frac{m}{s}$
Flat
$V_o = 3.6\ \frac{m}{s}$
Hemi
$V_o = 3.6\ \frac{m}{s}$
Corner
2.0e-01
0.15
0.1
0.05
0.0e+00
EPS
6.35 mm Thick Aluminum 7075-t651
Energy Absorbed (J)
Time (ms)
Flat (577 J)
Corner (774 J)
Hemi (701 J)
Puncture

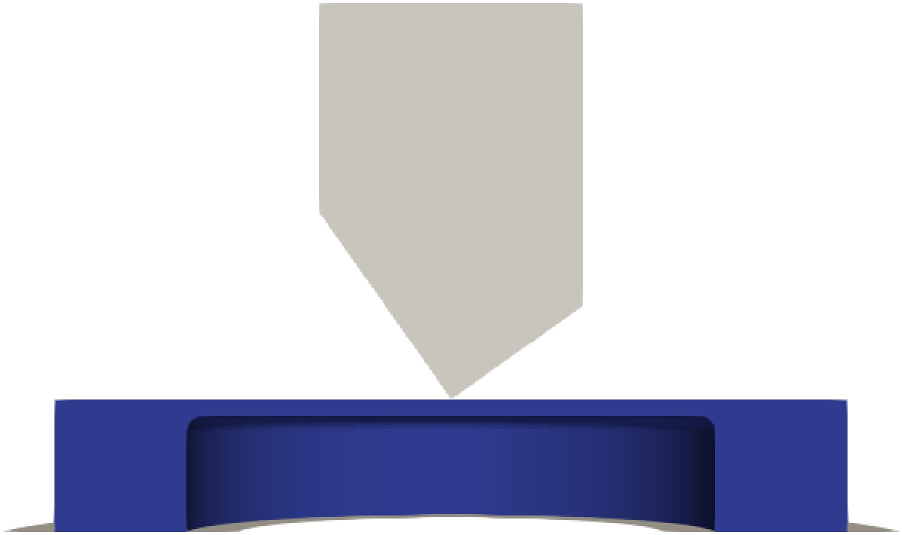
Thick Aluminum Plate Experimental Results Comparison (Corner Probe)

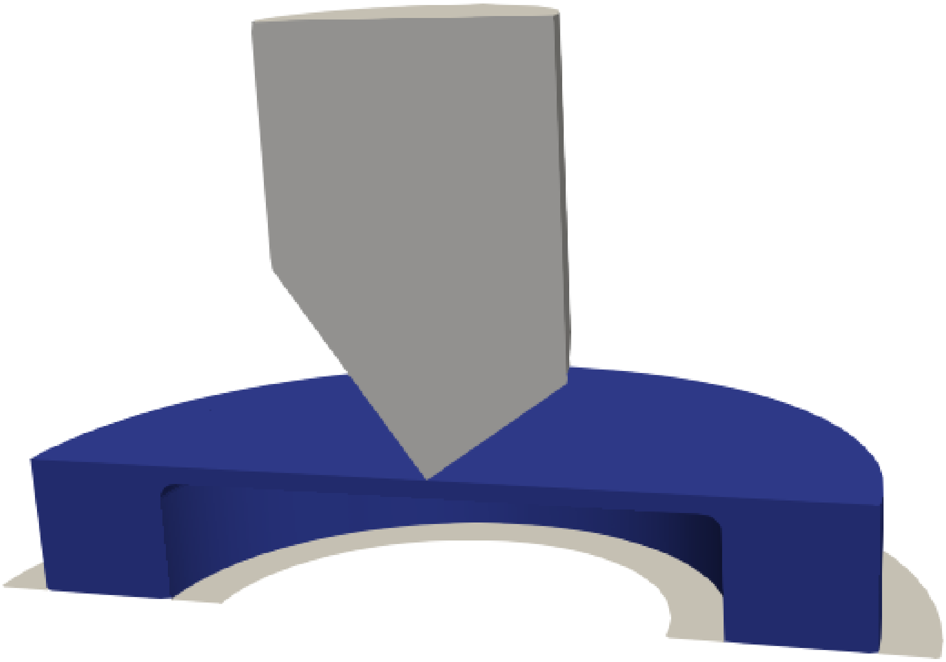
~102% difference in energy absorbed between experiments and the model

Reduction in velocity of the probe in the model is within ~42% of experimental data



1.60 mm Thick SS304L Coupon

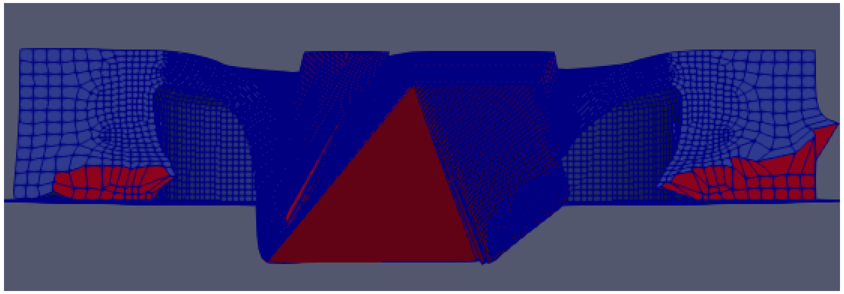




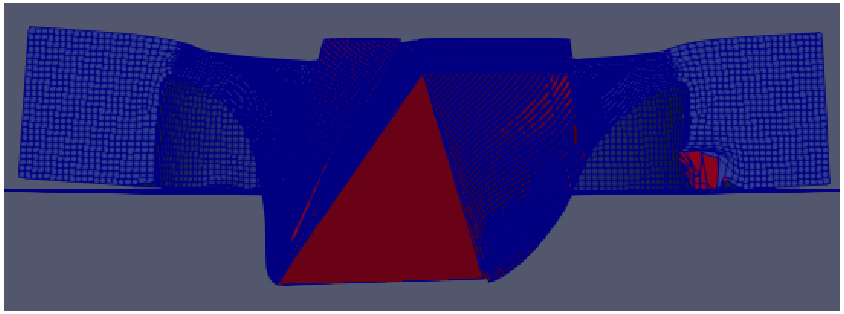
- Plasticity Model: BCJ (Horstemeyer et al)
- Damage Model: Max eqps (Blandford et al)
- Coupon Mesh Quality: 0.83
- Flat Probe Initial KE: 1000 J
- Corner Probe Initial KE: 1000 J
- Hemi Probe Initial KE: 2000 J

Horstemeyer et al, "Micromechanical Finite Element Calculations of Temperature and Void Configuration Effects on Void Growth and Coalescence," Int J. Plasticity, Vol. 16, 2000.
Blandford et al, "Tensile Stress-Strain Results for 304L and 316L Steel Plate at Temperature," ASME. Pressure Vessels and Piping Conference, *Volume 6: Materials and Fabrication* ():617-628. doi:10.1115/PVP2007-26096.

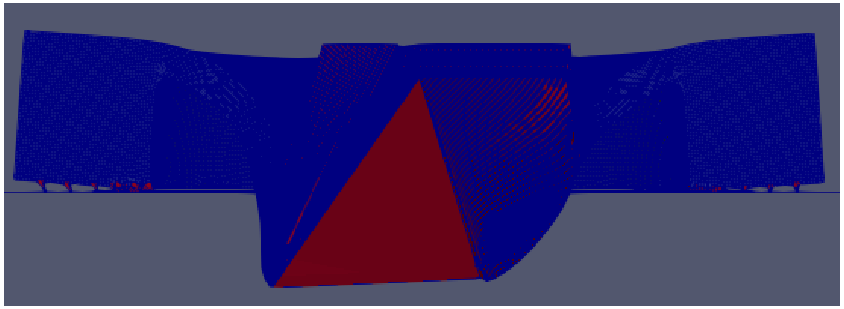
Mesh Refinement Study



Elements: 365,720
Hourglass Energy: 8398 J
Probe ΔKE: 397.2 J



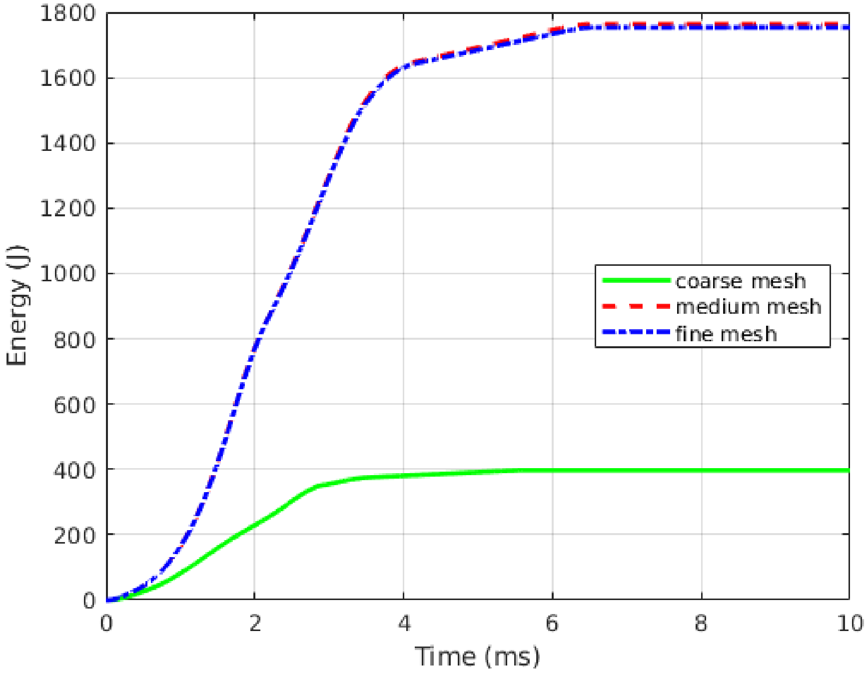
Elements: 387,770
Hourglass Energy: 1005 J
Probe ΔKE: 1764 J



Elements: 969,200
Hourglass Energy: 224.5 J
Probe ΔKE: 1753 J

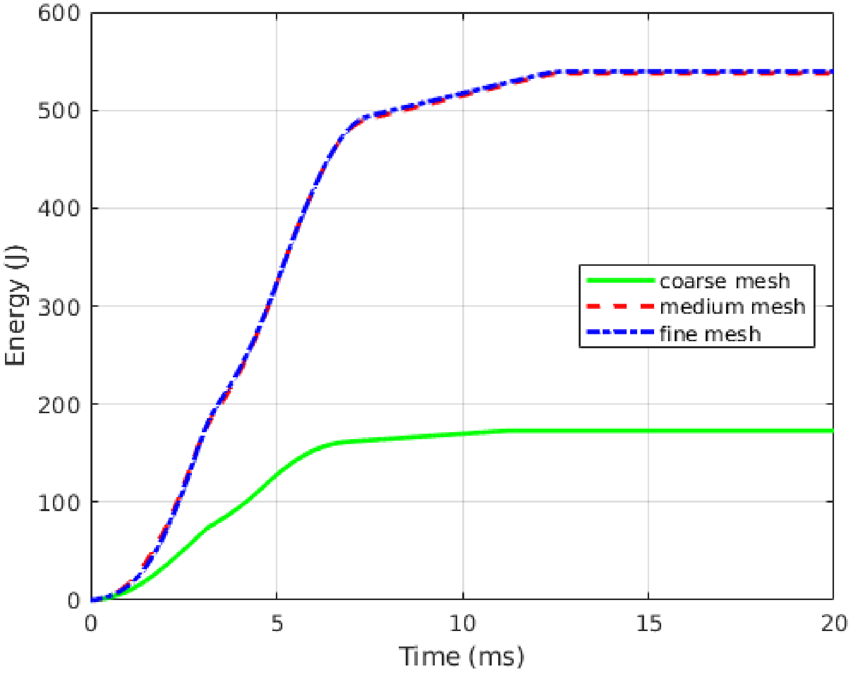
Mesh Refinement Study (Cont.)

3.2 mm thick 304L Steel Coupon, BCJ

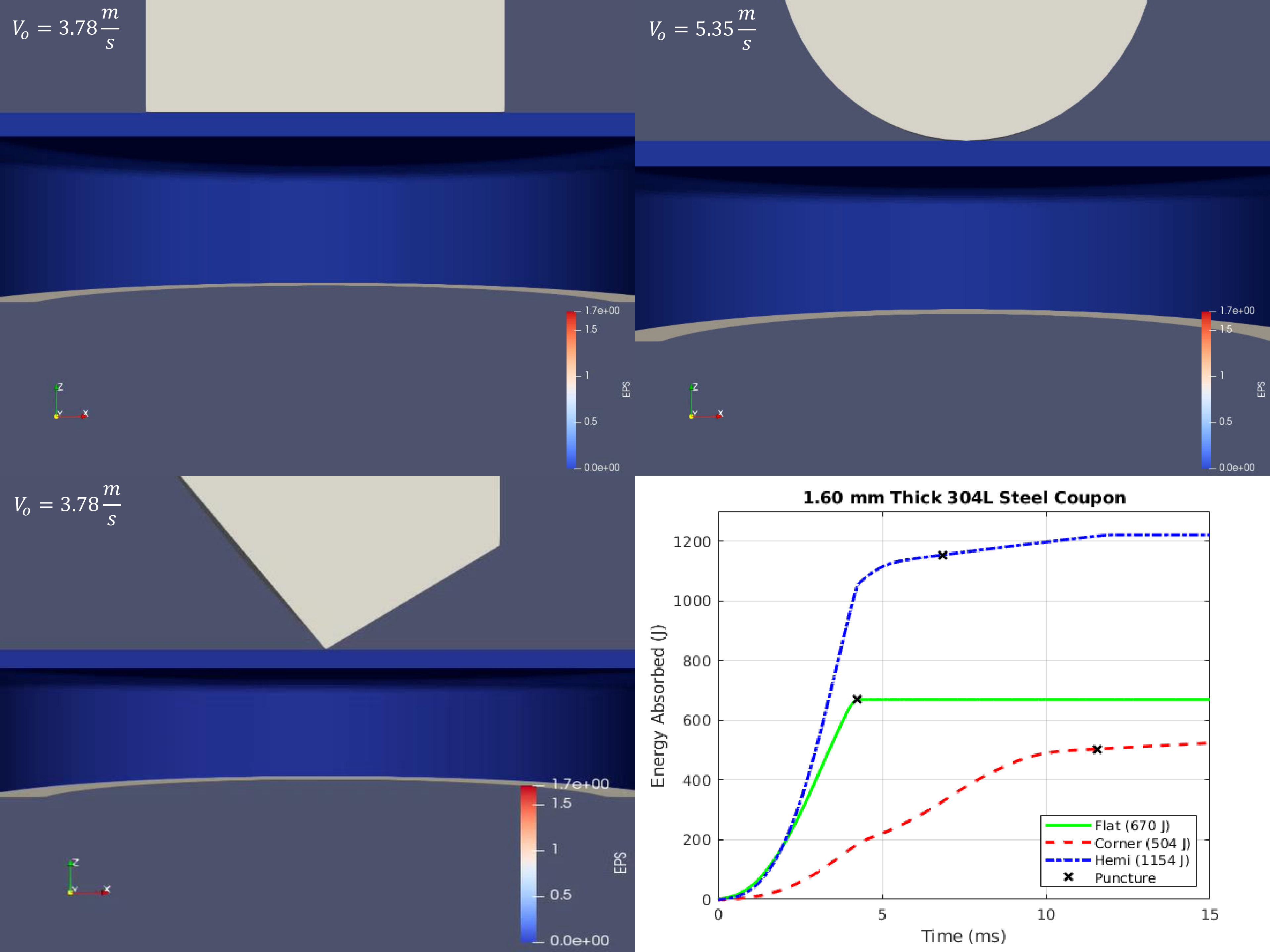


Mesh refinement results in a **314 % increase** in energy

1.6 mm thick 304L Steel Coupon, BCJ

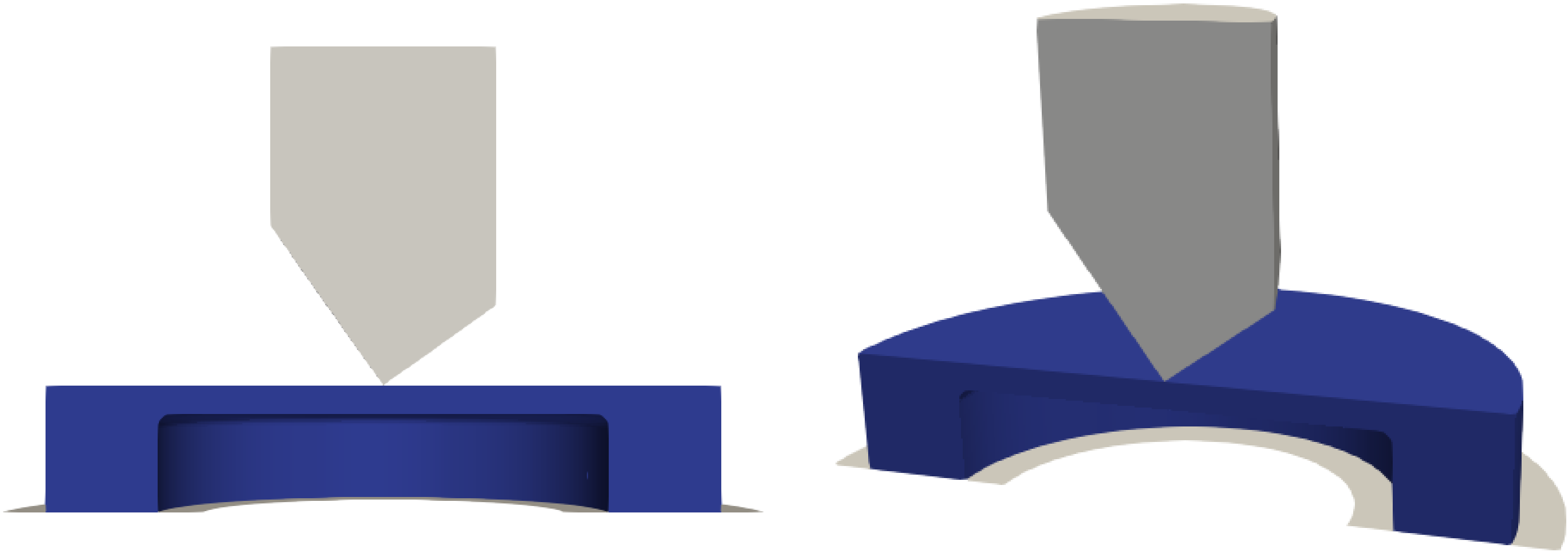


Mesh refinement results in a **212 % increase** in energy



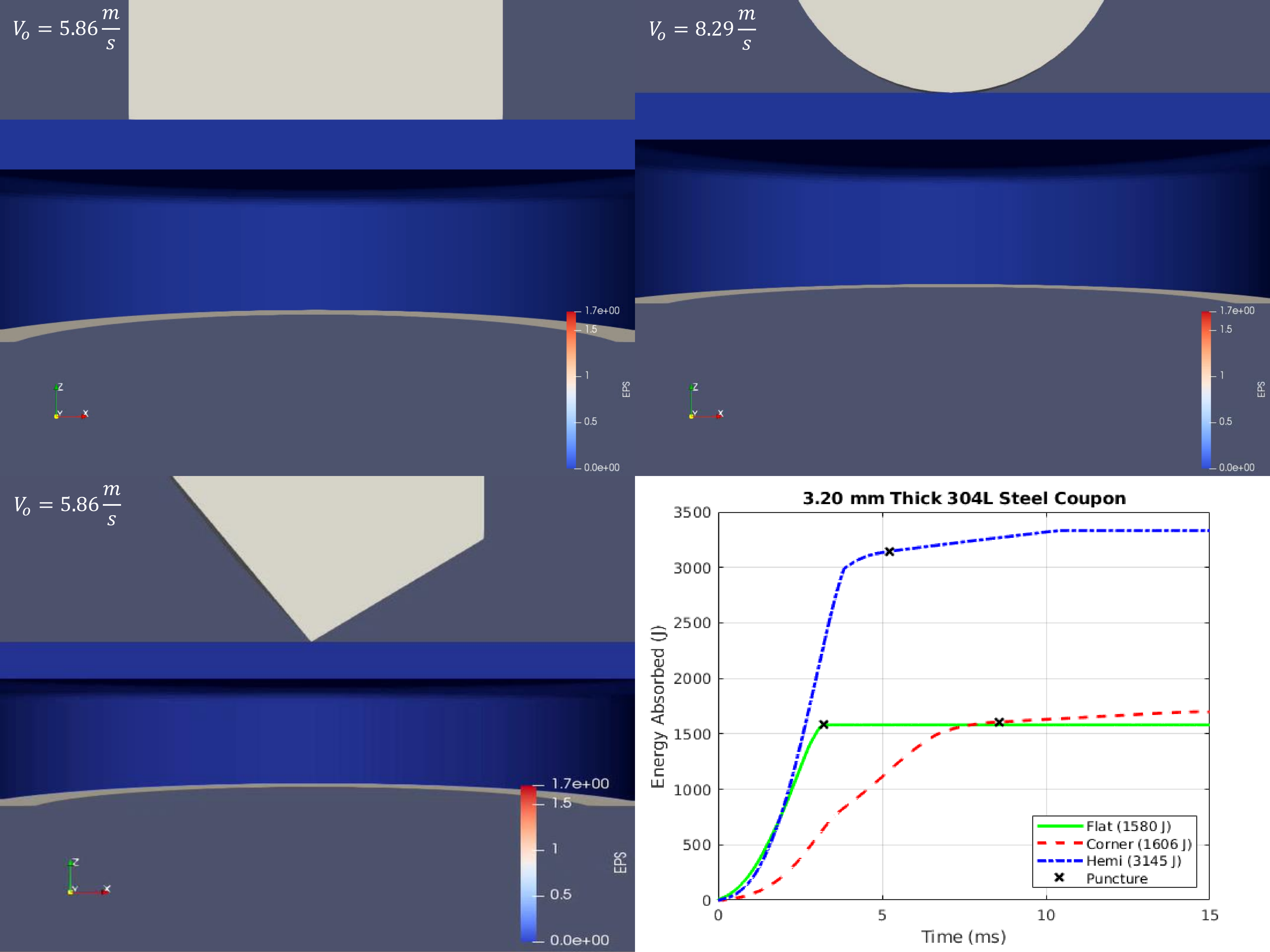
$V_o = 3.78\frac{m}{s}$
$V_o = 5.35\frac{m}{s}$
$V_o = 3.78\frac{m}{s}$
EPS
1.7e+00
1.5
1
0.5
0.0e+00
Z
X
1.60 mm Thick 304L Steel Coupon
Energy Absorbed (J)
Time (ms)
0
200
400
600
800
1000
1200
5
10
15
Flat (670 J)
Corner (504 J)
Hemi (1154 J)
Puncture

3.20 mm Thick SS304L Coupon



- Plasticity Model: BCJ (Horstemeyer et al)
- Damage Model: Max eqps (Blandford et al)
- Coupon Mesh Quality: 0.85
- Flat Probe Initial KE: 2400 J
- Corner Probe Initial KE: 2400 J
- Hemi Probe Initial KE: 4800 J

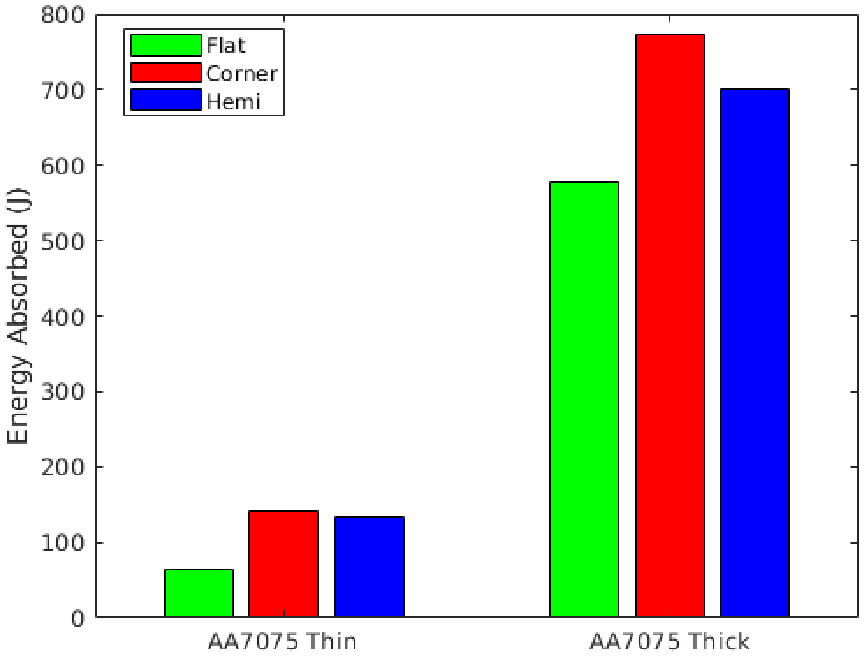
Horstemeyer et al, "Micromechanical Finite Element Calculations of Temperature and Void Configuration Effects on Void Growth and Coalescence," Int J. Plasticity, Vol. 16, 2000.
Blandford et al, “Tensile Stress-Strain Results for 304L and 316L Steel Plate at Temperature,” ASME. Pressure Vessels and Piping Conference, *Volume 6: Materials and Fabrication* ():617-628. doi:10.1115/PVP2007-26096.



$V_o = 5.86\frac{m}{s}$
$V_o = 8.29\frac{m}{s}$
$V_o = 5.86\frac{m}{s}$
EPS
1.7e+00
1.5
1
0.5
0.0e+00
3.20 mm Thick 304L Steel Coupon
Energy Absorbed (J)
Time (ms)
Flat (1580 J)
Corner (1606 J)
Hemi (3145 J)
Puncture

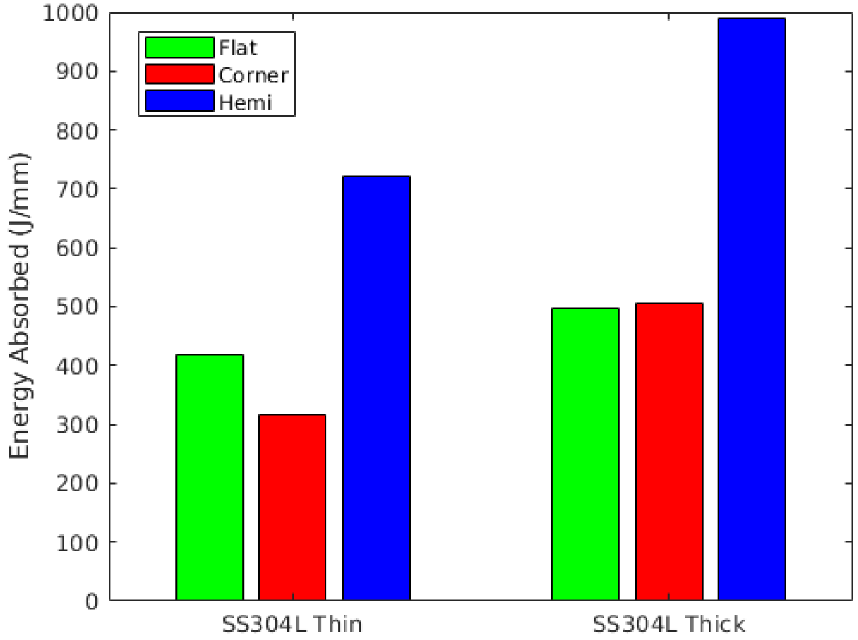
Conclusion AA7075-T651

- Johnson-Cook plasticity and failure models were used to simulate puncture of various Al 7075-T651 coupons
- Simulations consistently over-predict energy absorbed when compared to experimental results, most notably for corner-probe geometry
- Regardless of thickness, simulations consistently show the following trend in energy absorbed:
  - High -> Corner Probe
  - Medium -> Hemi Probe
  - Low -> Flat Probe



Conclusion SS304L

- BCJ plasticity model with eqps failure criteria was used
- Hemispherical probe absorbs **much** more energy due to high ductility of steel and few areas of stress concentration
- Dominating failure modes change with coupon thickness
- For 304L Steel, primary mechanism of energy absorption for each probe are as follows:
  - Flat -> Plastic Strain Energy
  - Corner -> Fracture Energy
  - Hemi -> Plastic Strain Energy



Future Work

- Calibrate failure model for SS304L
- Compare SS304L models to experimentation
- Further evaluate the role that thickness of the coupon has on energy absorption for each probe
- Evaluate probe orientation's affect on puncture energy

Acknowledgements

- Non-Linear Mechanics and Dynamics (NOMAD) managers and Staff:
  - Rob Kuether
  - Brooke Allensworth
- Team 7 Mentors:
  - Neal Hubbard (Sandia National Laboratories)
  - Emily Miller (Sandia National Laboratories)
  - Edmundo Corona (Sandia National Laboratories)
  - Yu-Lin Shen (University of New Mexico)
- Sandia National Laboratories*

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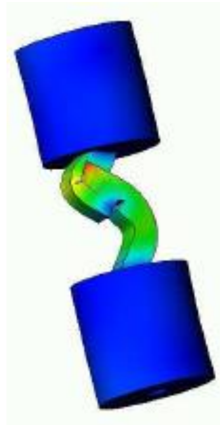
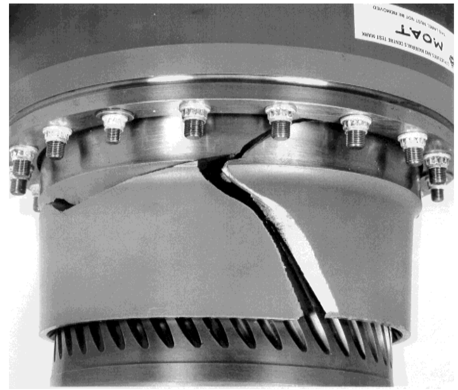
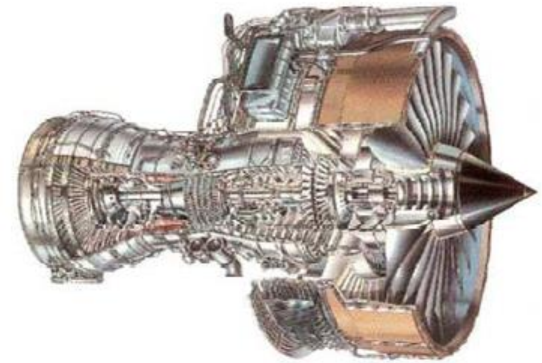
Sandia National Laboratories

N-O-MAD Research Institute







Validation of Puncture Simulations with Various Probe Geometries

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U.S. DEPARTMENT OF ENERGY

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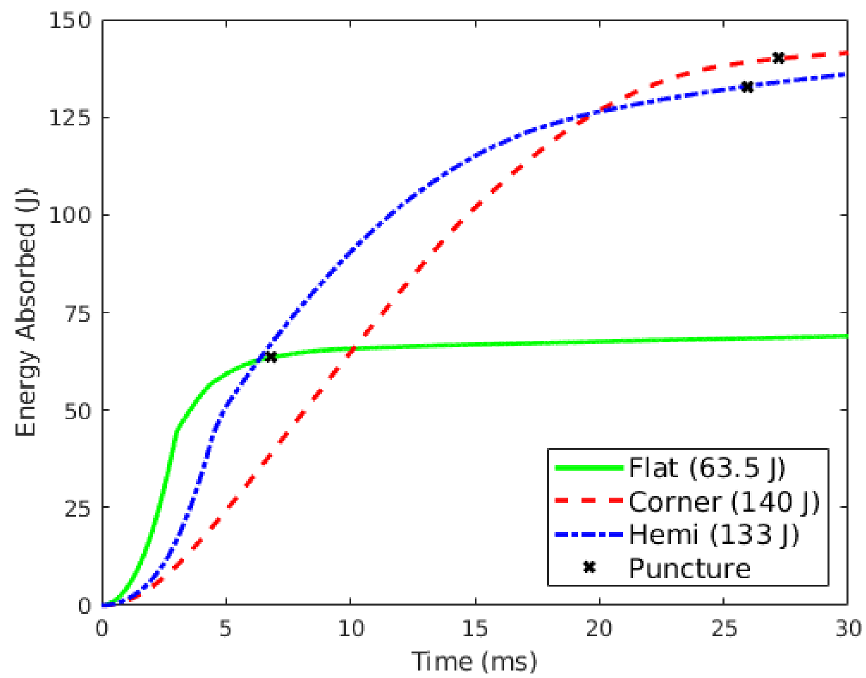
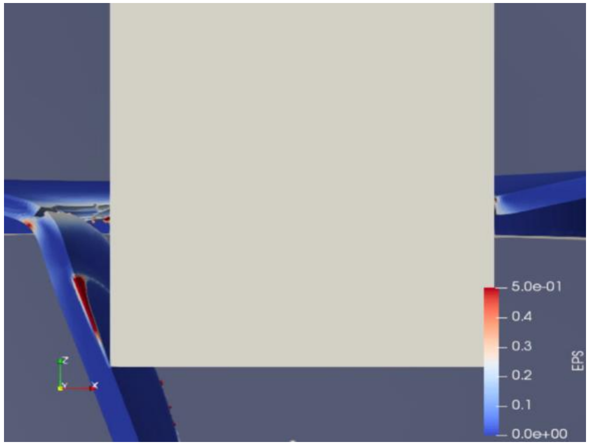
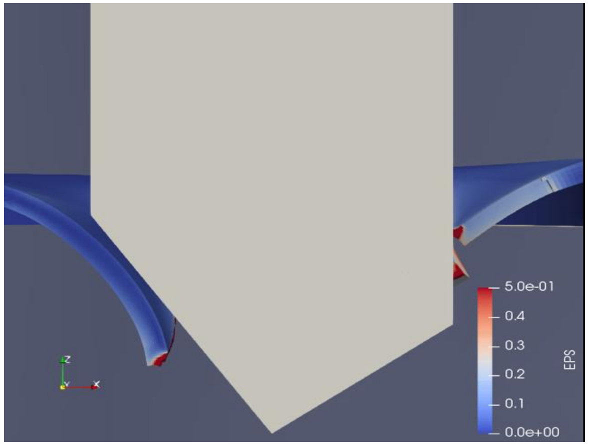
Corner Probe Requires Highest Energy for Fracture

- Corner Probe and Hemispherical Probe requires largest energy for fracture
  - Due to increase contact surface
- Flat Probe requires least energy input for fracture

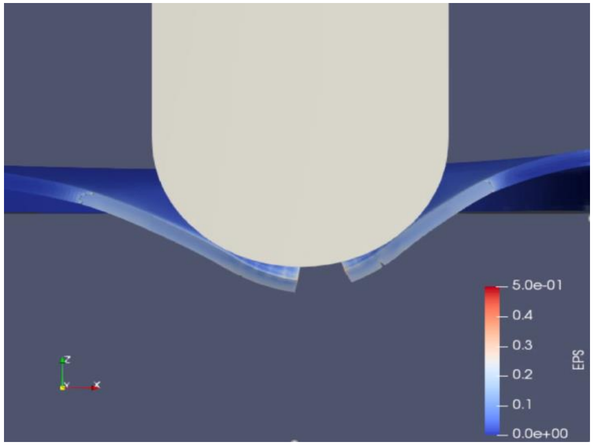




Flat Probe



Corner Probe



Hemispherical Probe