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Validation of Finite Element Models for Puncture of Al7075 Plates of Various Thicknesses

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Introduction

Dynamic metallic plate puncture problems are of interest in many applications

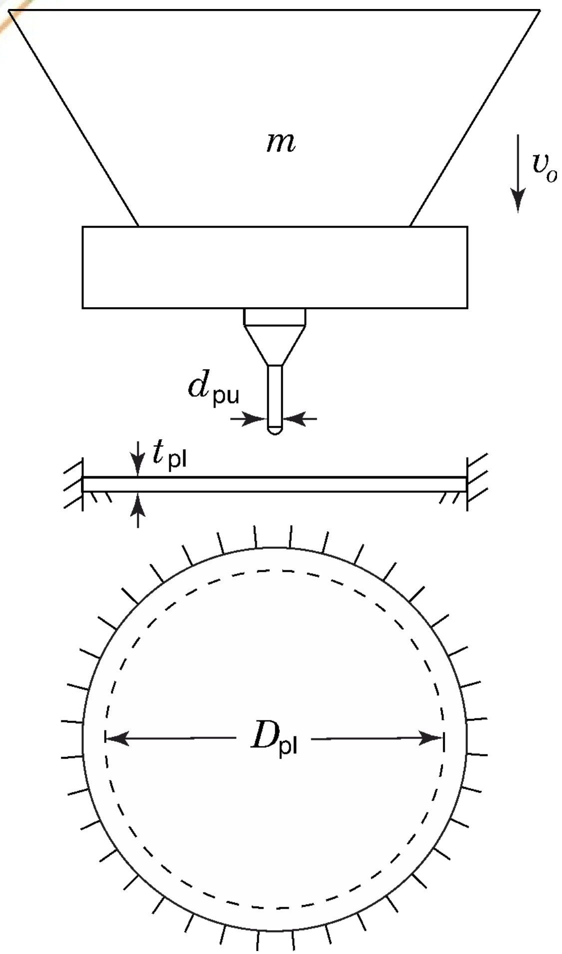
They are demanding on the elastic-plastic and ductile failure models in FEAs.

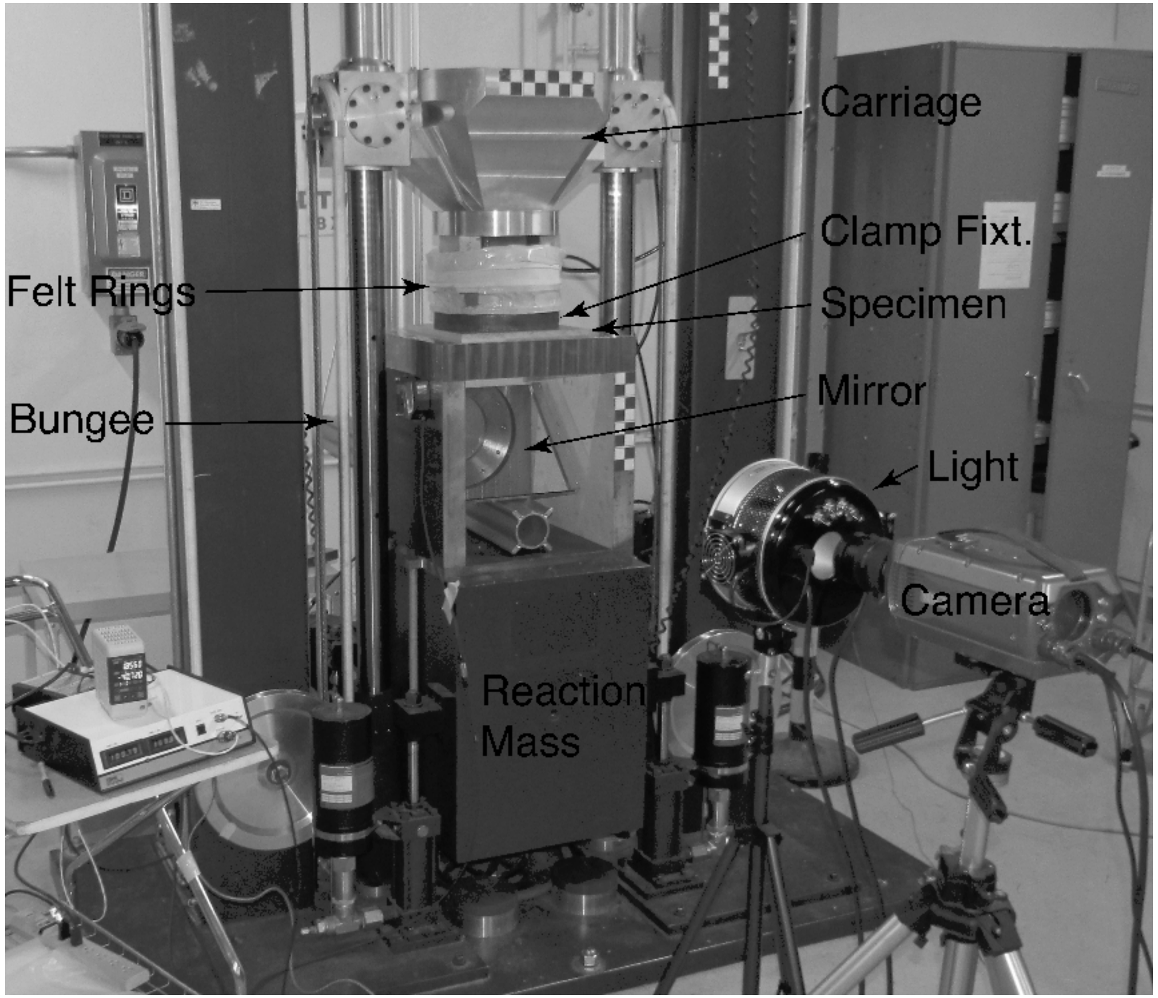
- Temperature and rate dependencies may need to be addressed
- Tensile-dominated and shear-dominated failure modes can be activated
- Possible sensitivity to element size

Objectives

- Conduct calibrations of thermal-mechanical material models
- Validate their application in FE simulations of plate puncture experiments:
  - Threshold puncture velocity (or energy)
  - Mode of puncture
  - Acceleration histories

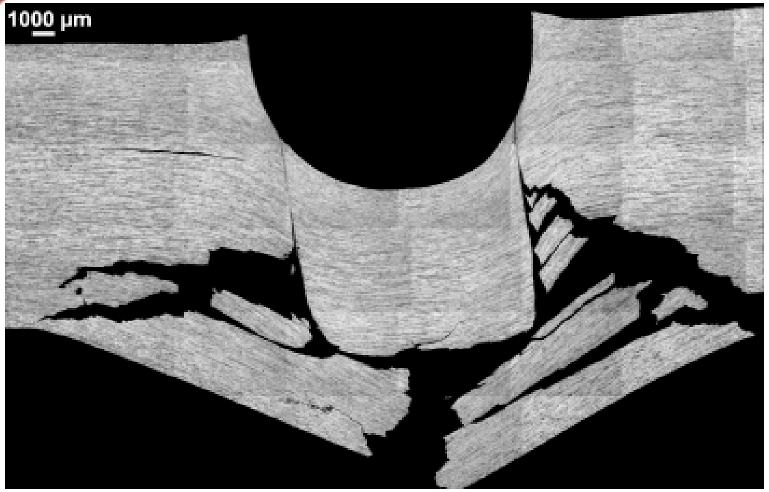
Al 7075-T651Plate Puncture Experiments

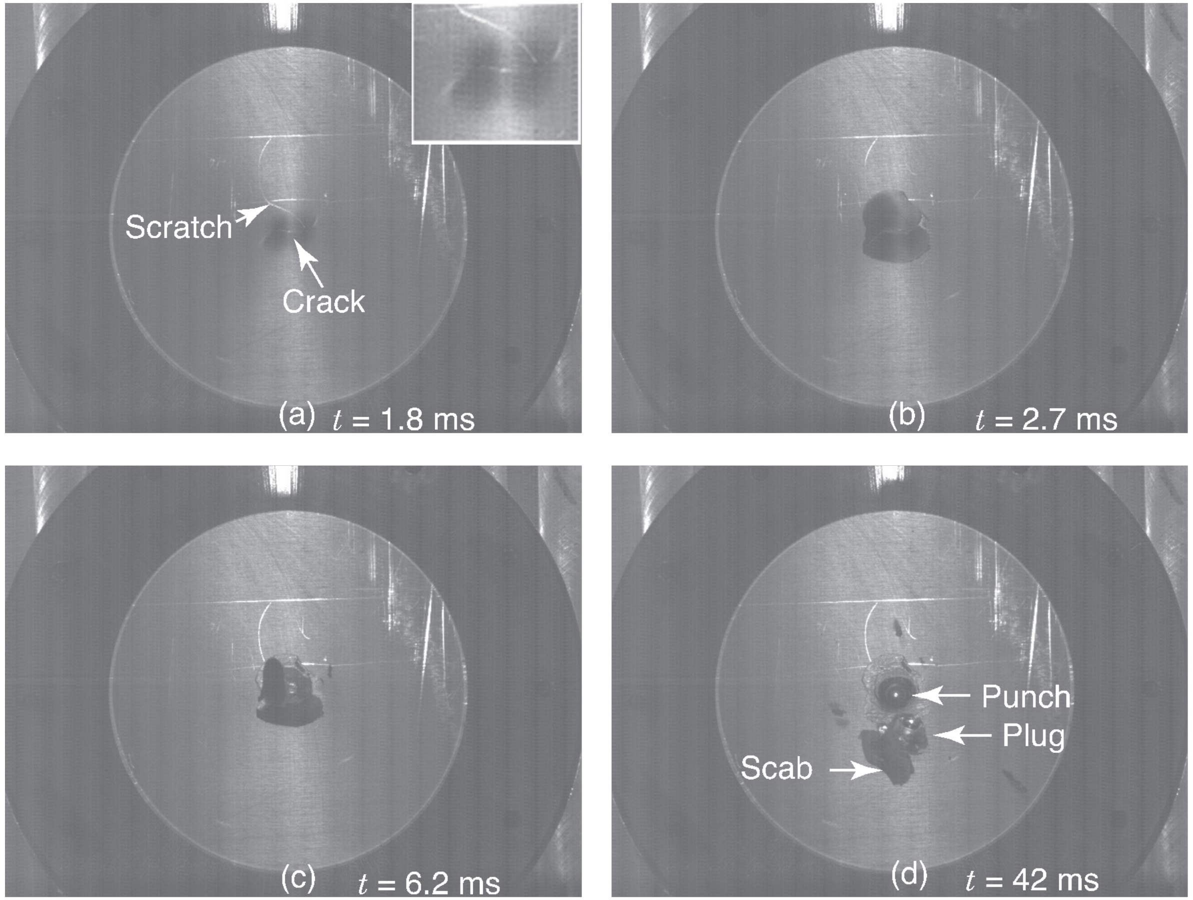


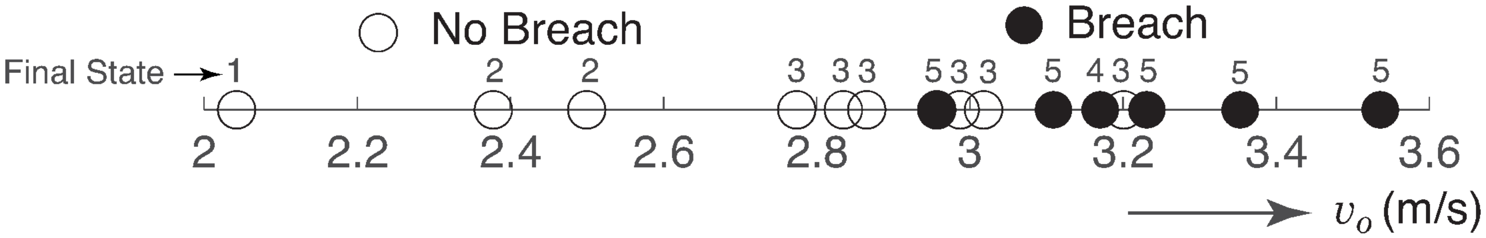


Fixed	Variable
$m = 139$ kg $D_{pl} = 171$ mm	$t_{pl} = 12.7$ mm, $d_{pu} = 12.7$ mm, hemispherical nose $t_{pl} = 1, 1.6, 2, 3.2, 4.8$ mm, $d_{pu} = 25.4$ mm, flat nose

Experimental Puncture Results (12.7 mm plate)







Plasticity Model Calibration

J_2 Yield Function with Isotropic Hardening:

$$f\left(\sigma_{ij}, \bar{\varepsilon}^p, T, \dot{\bar{\varepsilon}}^p\right) = \phi\left(\sigma_{ij}\right) - \sigma_y\left(\bar{\varepsilon}^p, T, \dot{\bar{\varepsilon}}^p\right) \qquad \phi(\sigma_{ij}) = \sqrt{\frac{3}{2} s_{ij} s_{ij}}$$

Flow Rule:

$$\dot{\varepsilon}_{ij}^p = \lambda \frac{\partial \phi}{\partial \varepsilon_{ij}^p}$$

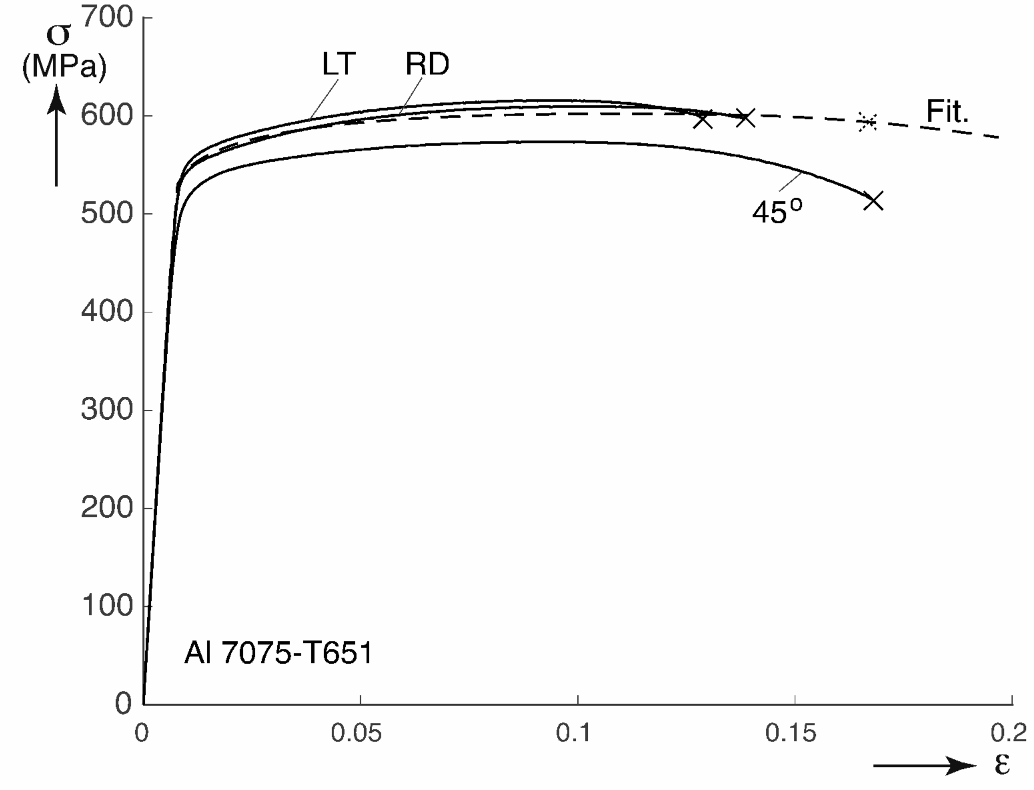
Hardening Function:

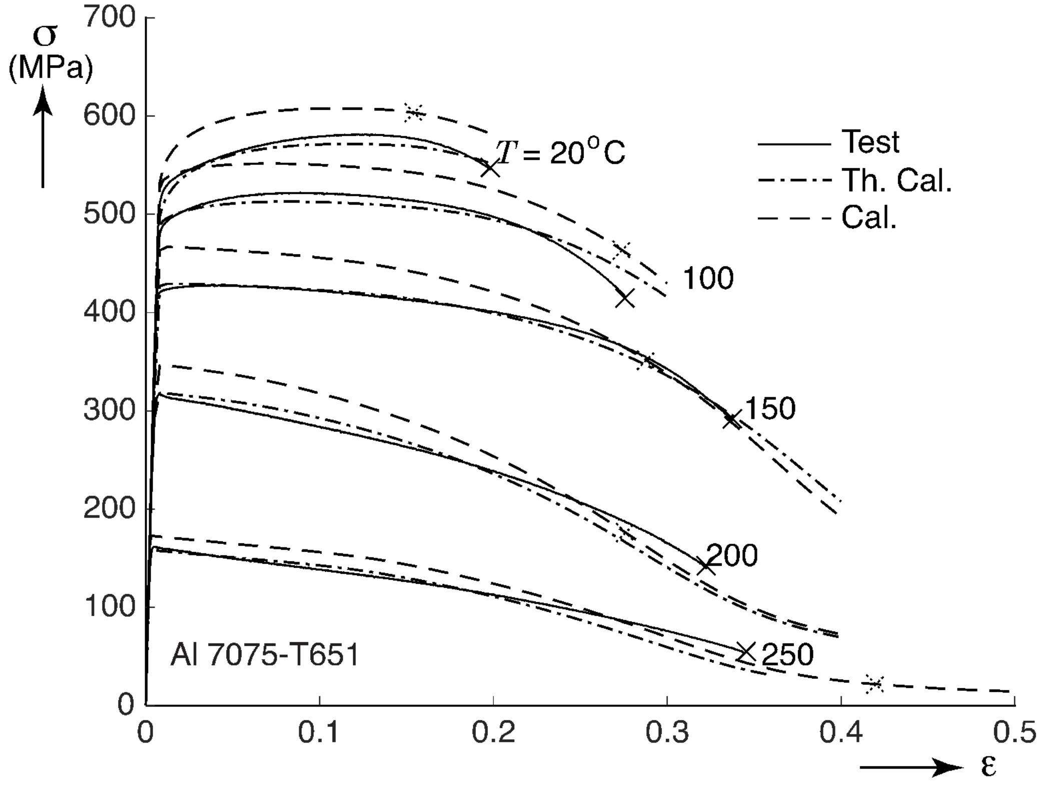
$$\sigma_y\left(\bar{\varepsilon}^p, T, \dot{\bar{\varepsilon}}^p\right) = \left[\sigma_y^o\left(T\right) + A\left(T\right)\left(\bar{\varepsilon}^p\right)^{n(T)}\right]\left[1 + C\left(T\right)\ln\left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}_o}\right)\right]$$

Adiabatic Heating:

$$T\left(t\right) = T(0) + \frac{\beta^{\mathrm{TQ}}}{\rho c_{\mathrm{p}}} \int_0^t \phi \frac{\partial \bar{\varepsilon}^{\mathrm{p}}}{\partial \tau} d\tau$$

Plasticity Calibration: Effect of Temperature





Values at 20 °C

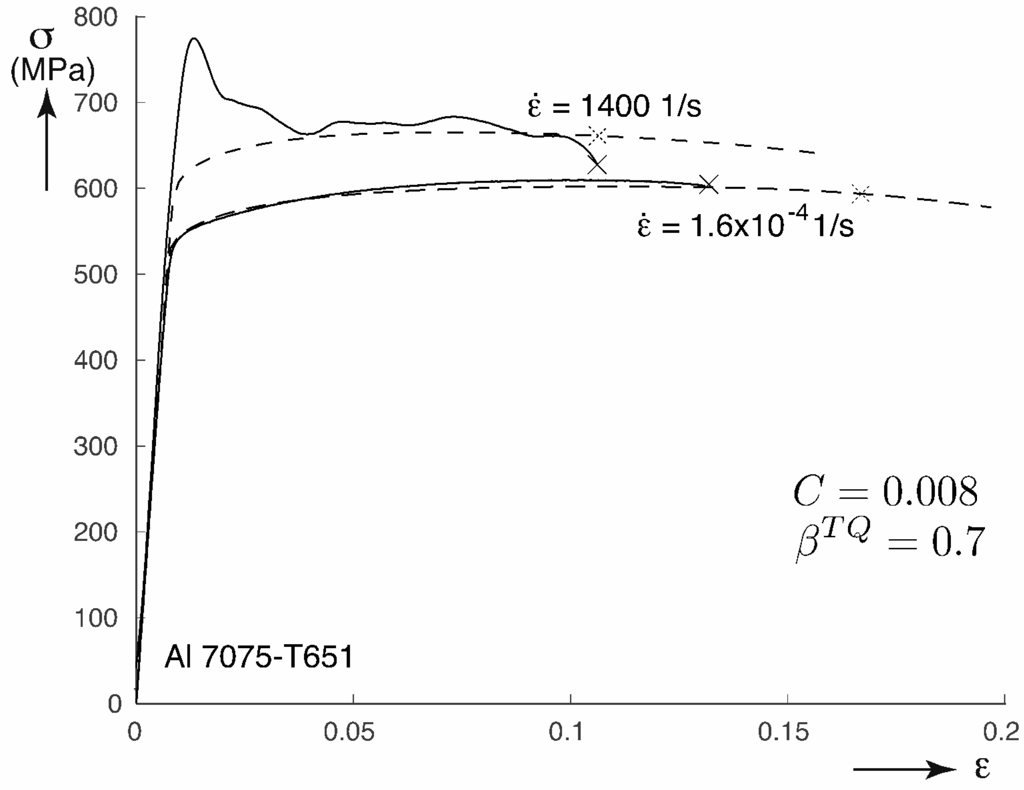
ρ, kg/m ^{3}	E, GPa	ν	c_p, J/kg-K	β^{TQ}
2810	71.7	0.33	960	0.7

σ_y, MPa	A, MPa	n	C,	$\dot{\varepsilon}_o$, 1/s
517	405	0.41	0.008	1.6×10^{-4}

Table of Function Values

T, °C	$\frac{\sigma_y^0(T)}{\sigma_y^0(20)}$	$\frac{A(T)}{A(20)}$	$\frac{n(T)}{n(20)}$	$\frac{C(T)}{C(20)}$
20	1.0	1.0	1.0	1.0
100	1.01	0.8	1.5	1.0
150	0.89	0.75	2.2	1.0
200	0.66	0.3	2.44	1.33
250	0.32	0.0	2.44	4.0
750	0.0	0.0	2.44	13.3

Plasticity Calibration: Effect of Strain Rate



Ductile Failure Model (One-way coupling to plasticity)

$$D = \frac{1}{D^{\mathrm{cr}}} \int_0^{\bar{\varepsilon}^p} w_1\left(\sigma_m\right) w_2\left(\theta\right) w_3\left(\dot{\bar{\varepsilon}}^p\right) w_4\left(T\right) d\hat{\varepsilon}^p$$

$$w_1 = \left(\frac{1}{1 - \frac{\sigma_m}{B}}\right)^{\alpha}$$

$$w_2 = \left(2 - \mathcal{A}\right)^{\beta}, \quad \mathcal{A} = \max\left(\frac{s_2}{s_3}, \frac{s_2}{s_1}\right)$$

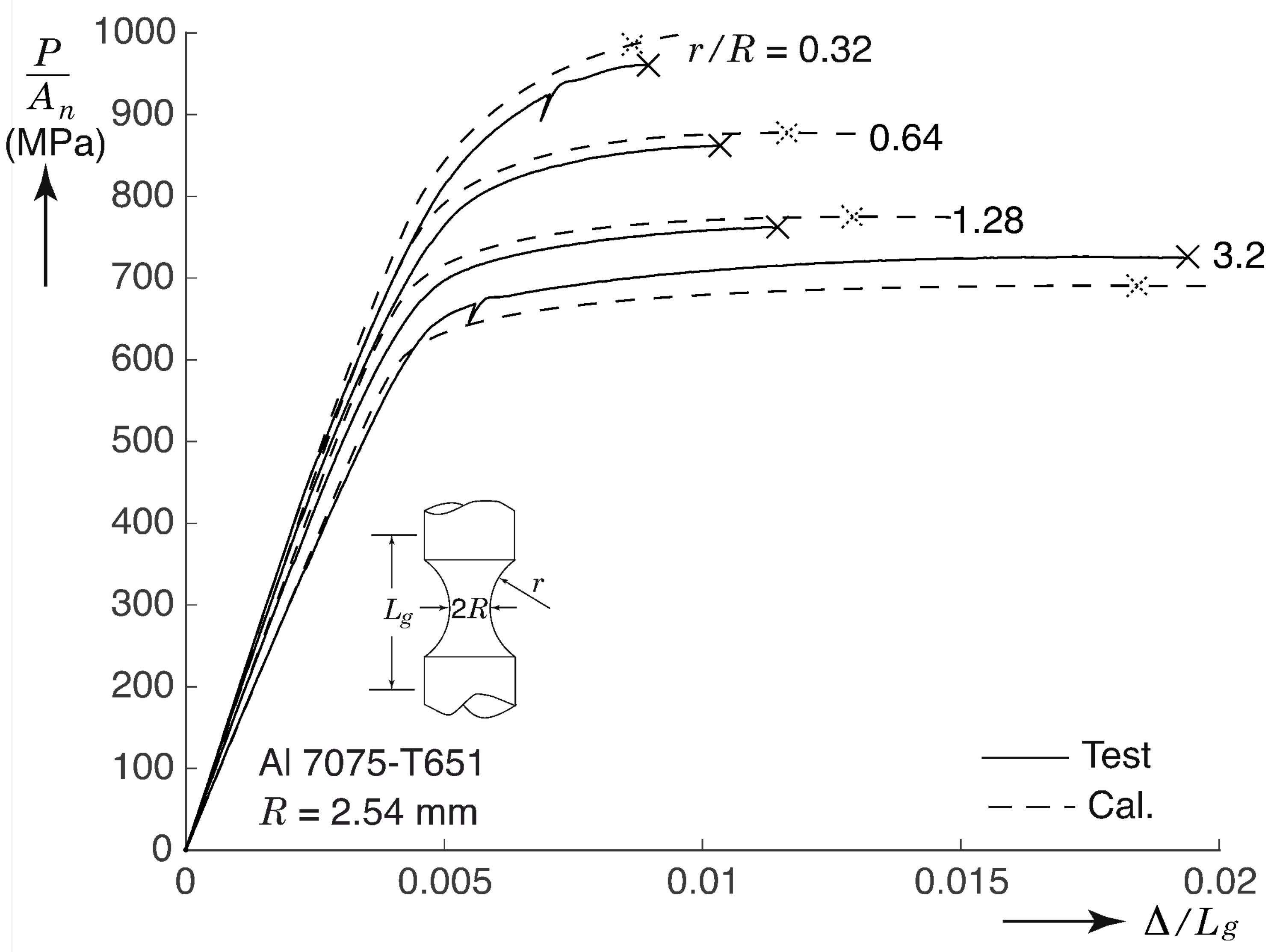
Wilkins Model

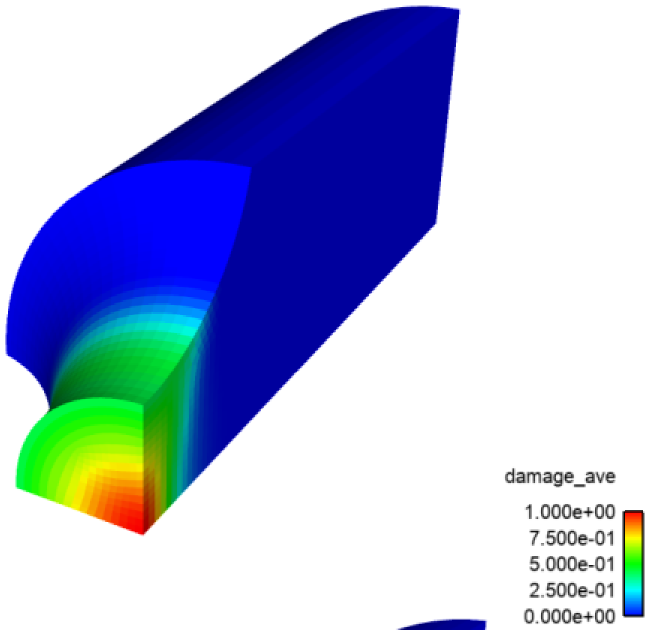
$$w_3\left(\dot{\bar{\varepsilon}}^p\right) = \frac{1}{1 + D_4 \ln \frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}_0}}$$

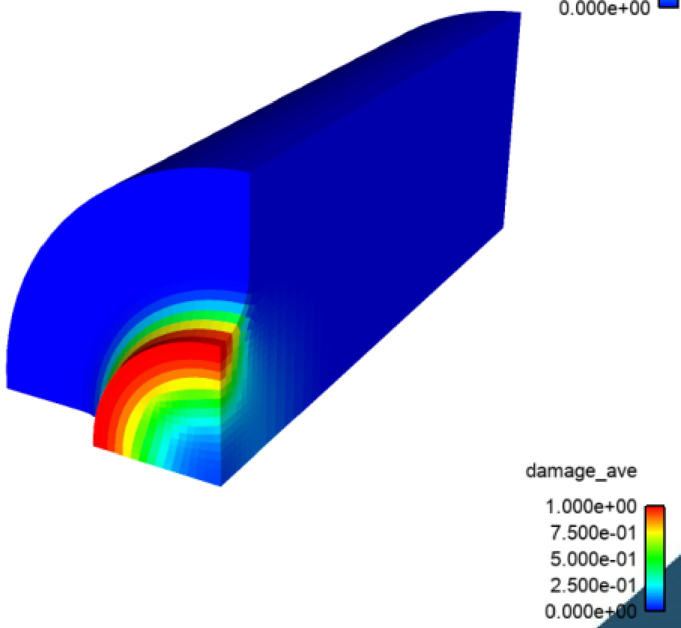
$$w_4\left(T\right) = \frac{1}{1 + D_5 \frac{T - T_{\mathrm{ref}}}{T_{\mathrm{melt}} - T_{\mathrm{ref}}}}$$

B, GPa	α	β	D^{cr}	D_4	D_5	T_{melt}, $^\circ$ C	T_{ref}, $^\circ$ C
2.07	4.1	0.6	0.3	-0.039	22.6	750	20

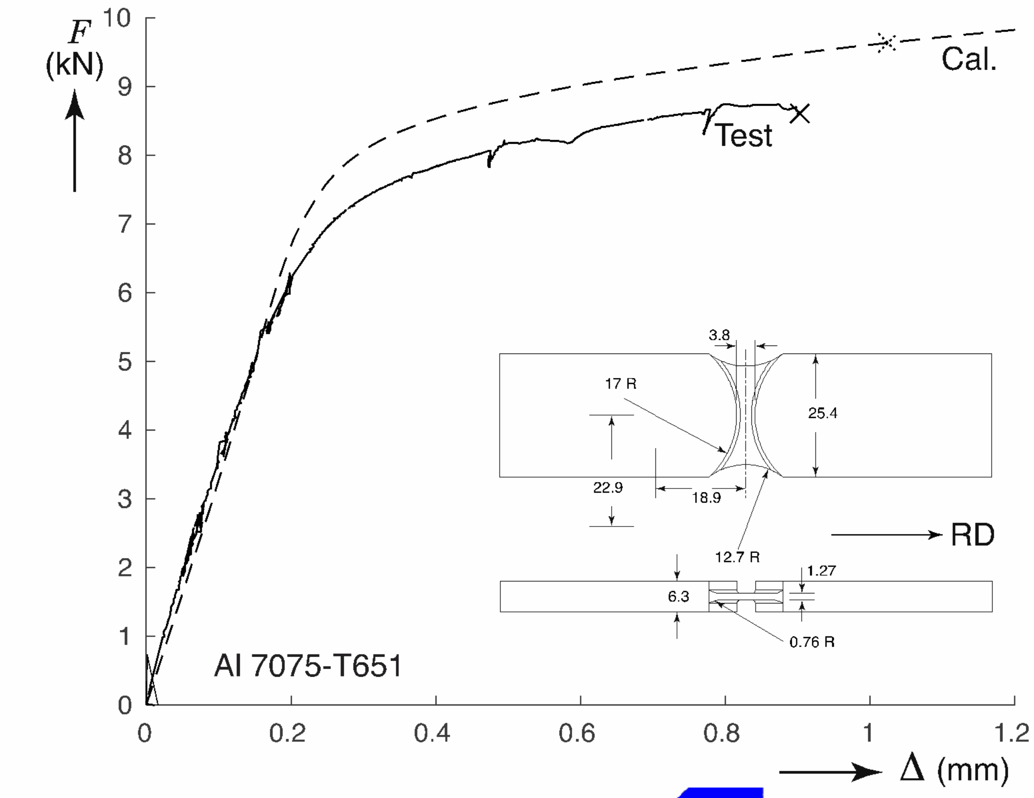
Ductile Failure Model Calibration: QS Notched Tension Tests

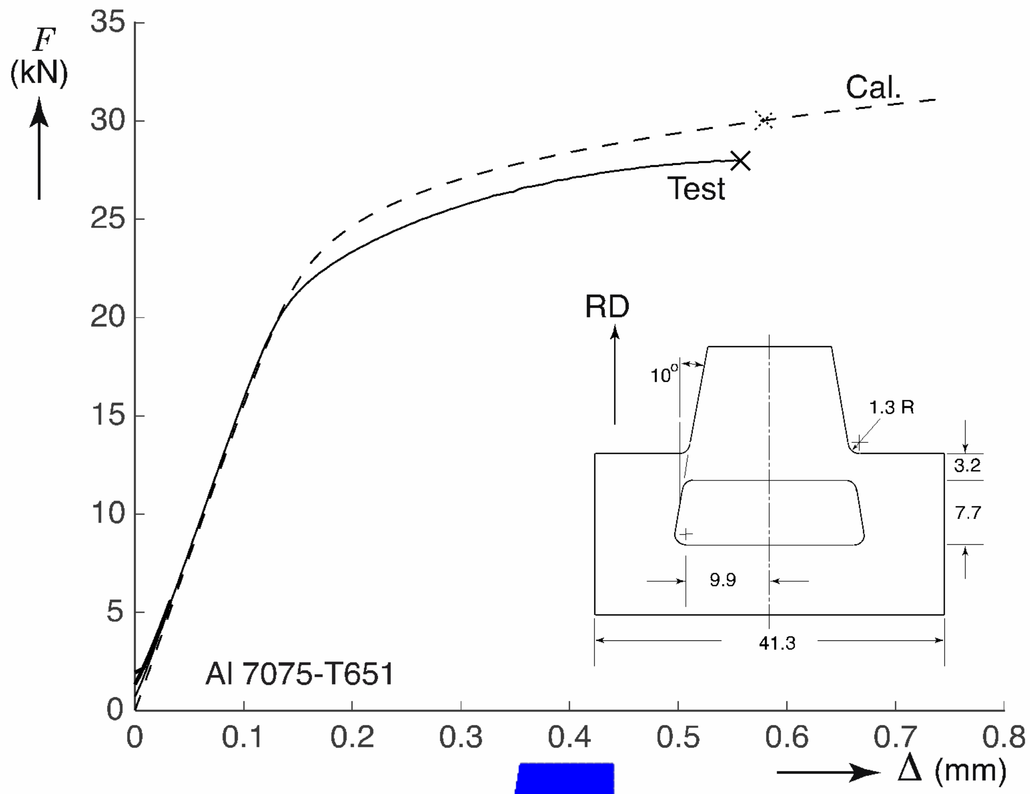


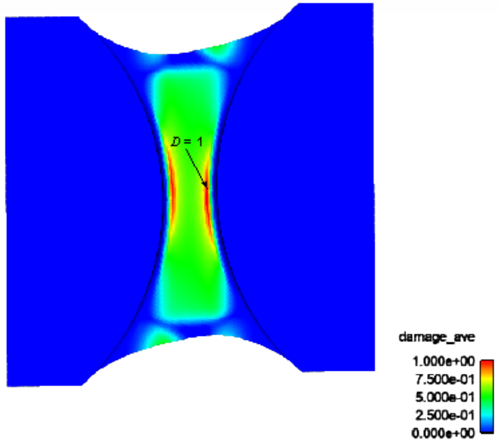


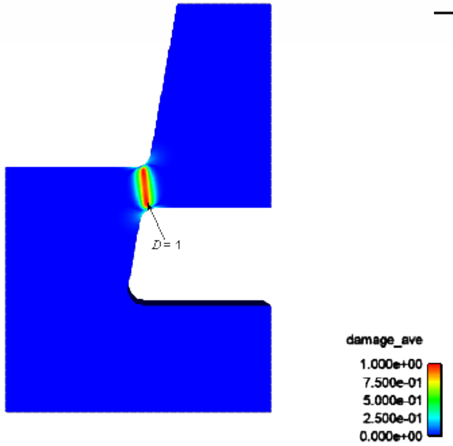


Ductile Failure Model Calibration: QS Shear Dominated Tests

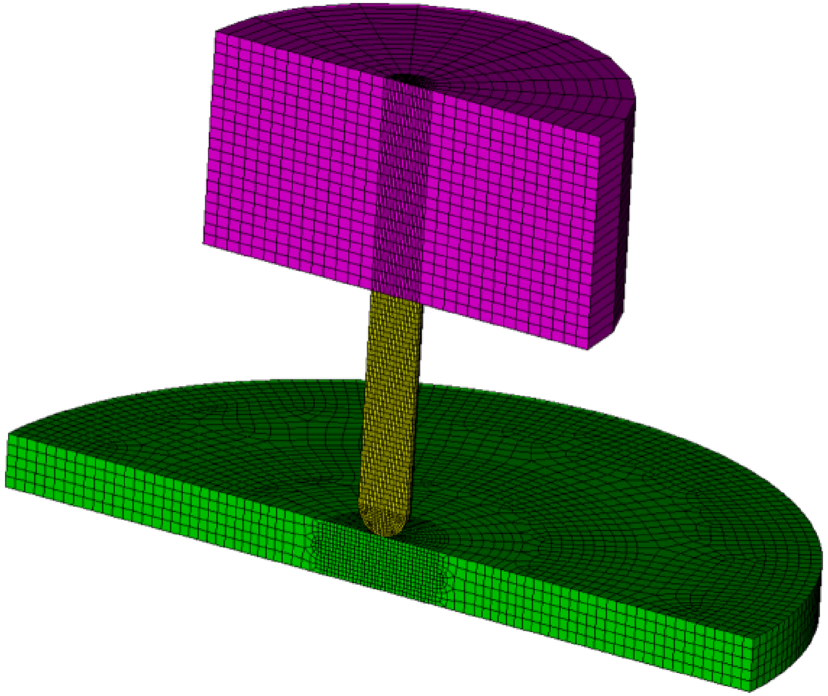


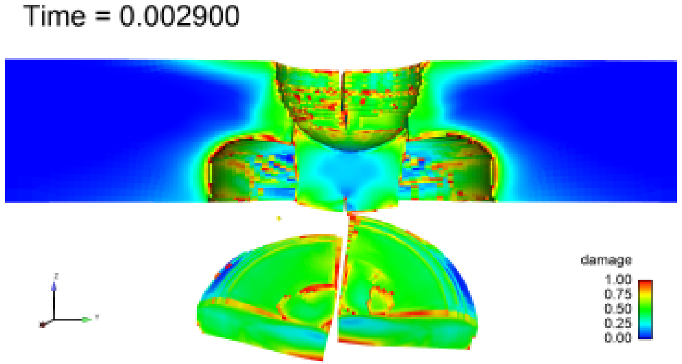


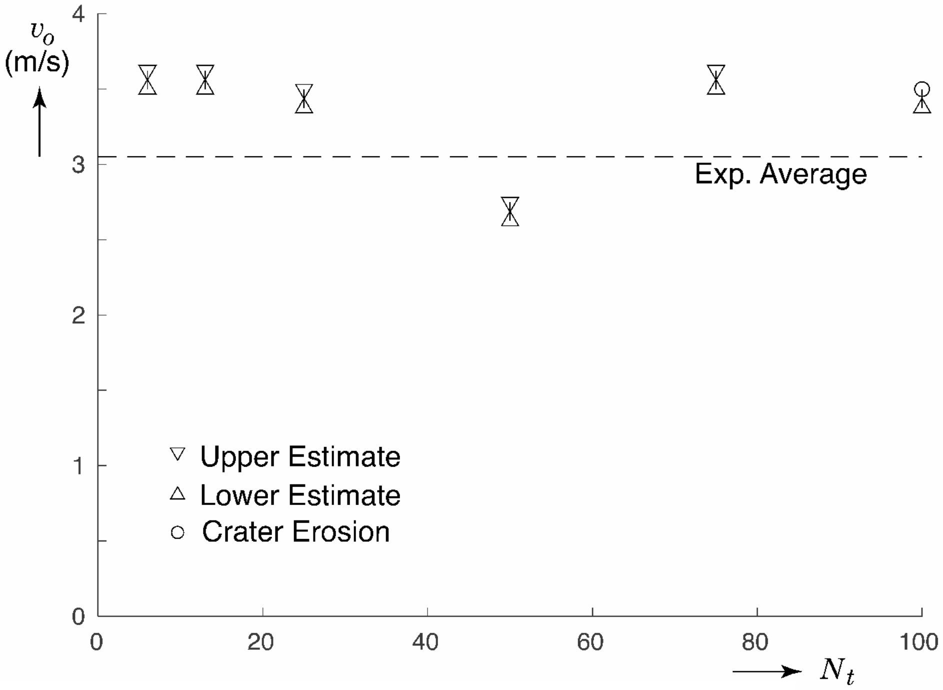


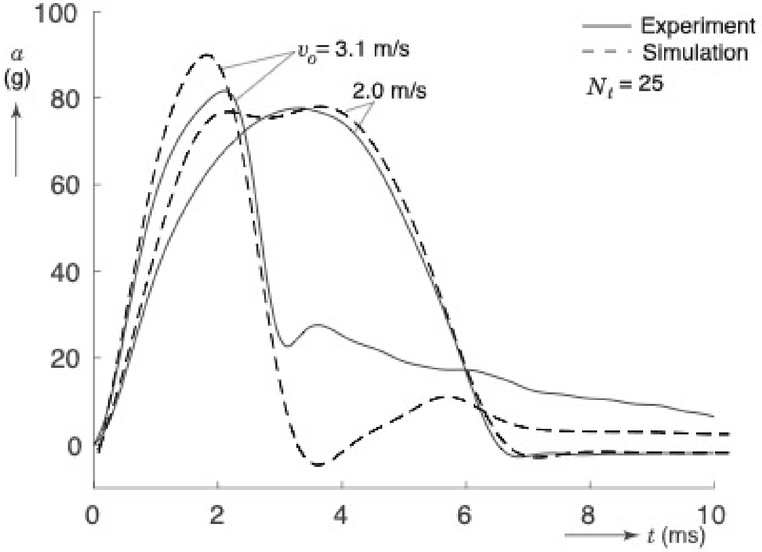


Results (12.7 mm Plates)





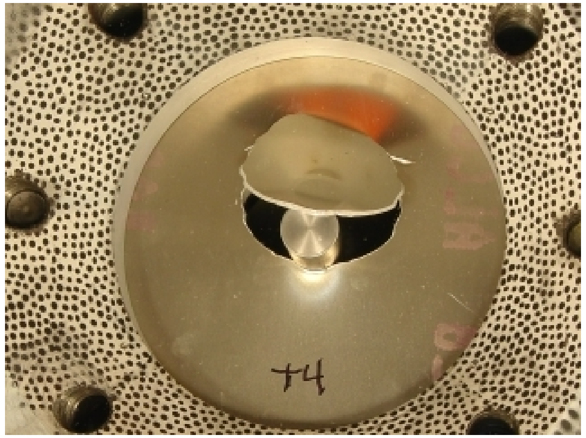




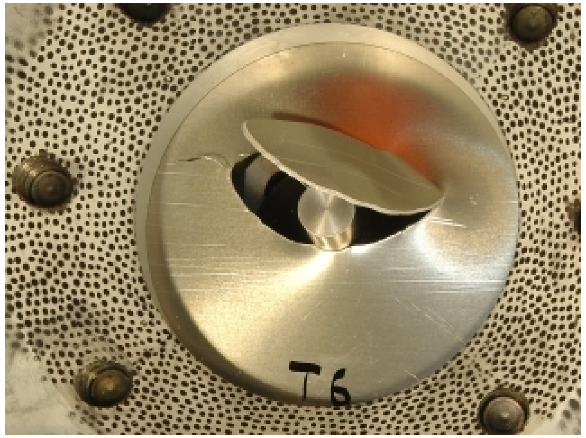
Thin Plates – Failure Configurations

4.8 mm

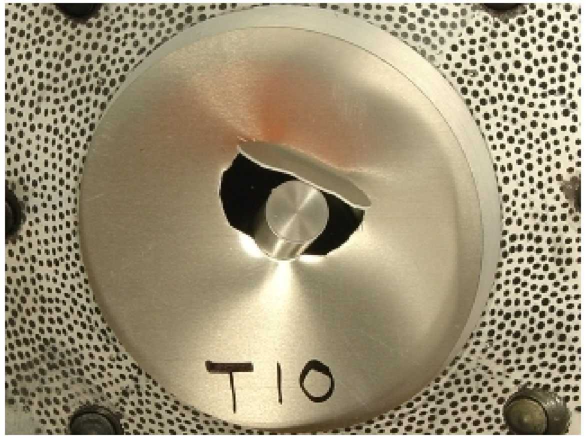
3.2 mm



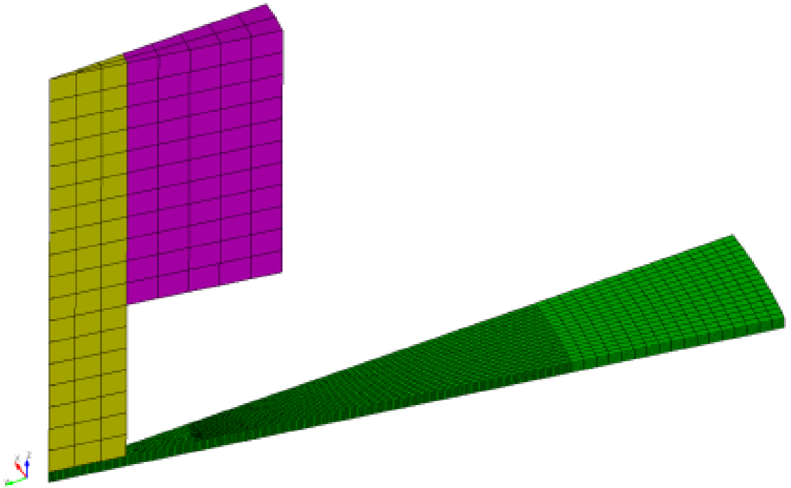
2.0 mm



1.7 mm



1.0 mm



10^o Wedge Model

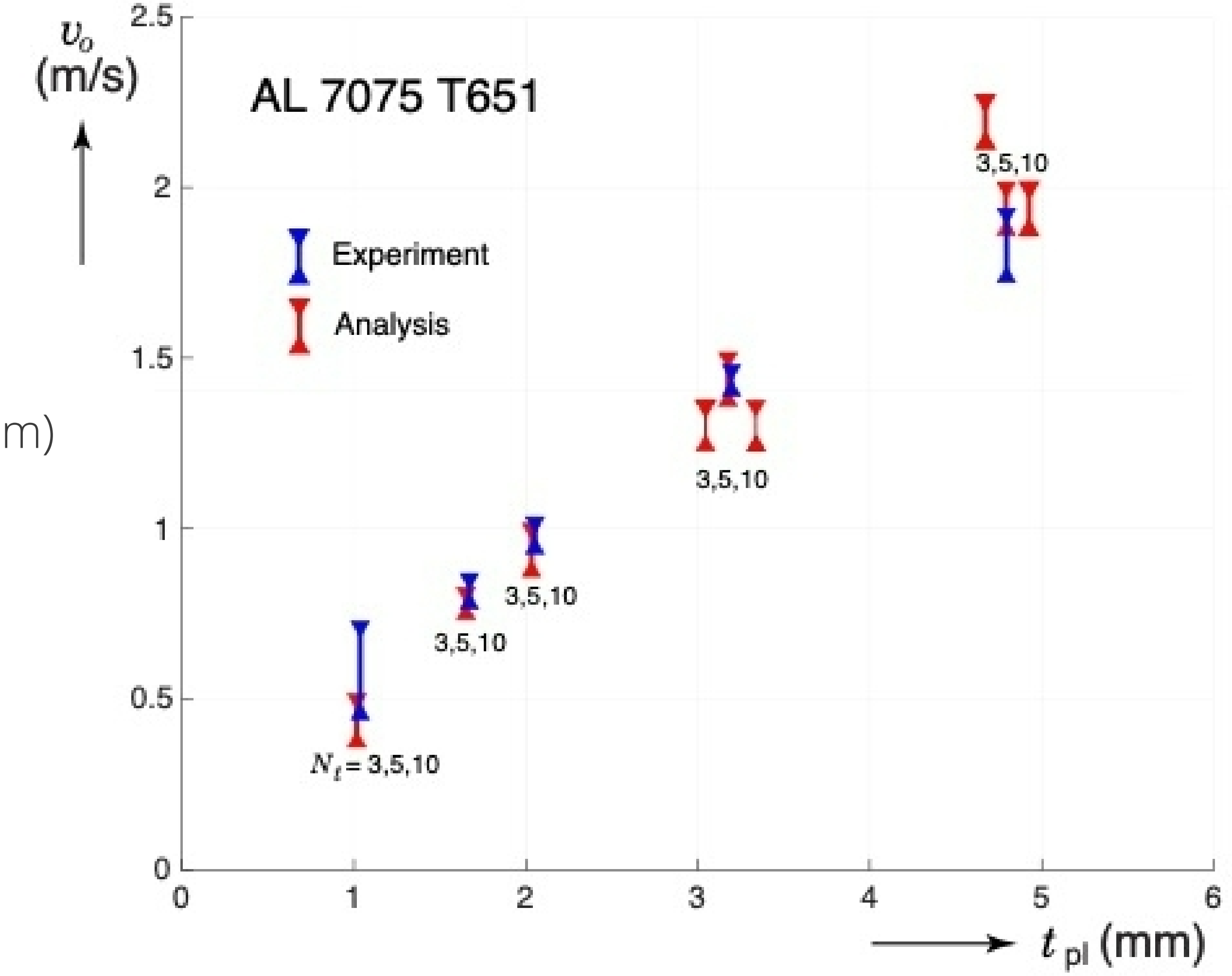
Assume axisymmetry up to failure. In-plane crack propagation not considered

Thin Plates – Comparison of Measured and Predicted Puncture Speed Brackets

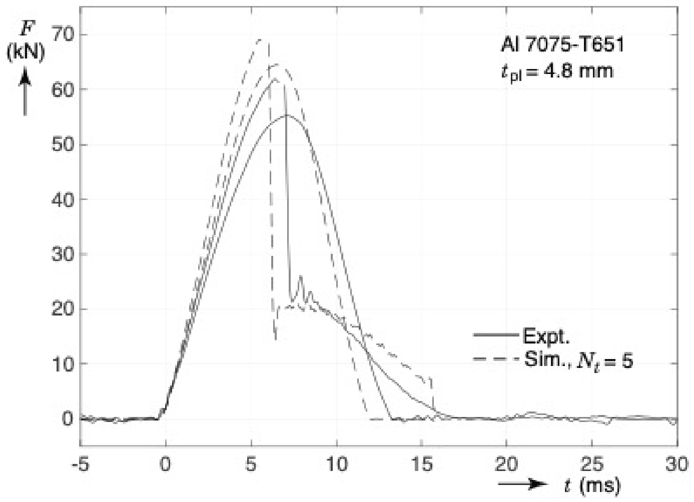
180º wedge for 4.8, 3.2 and **2.0** mm thick
10º wedge for **2.0** 1.7 1.0 thick

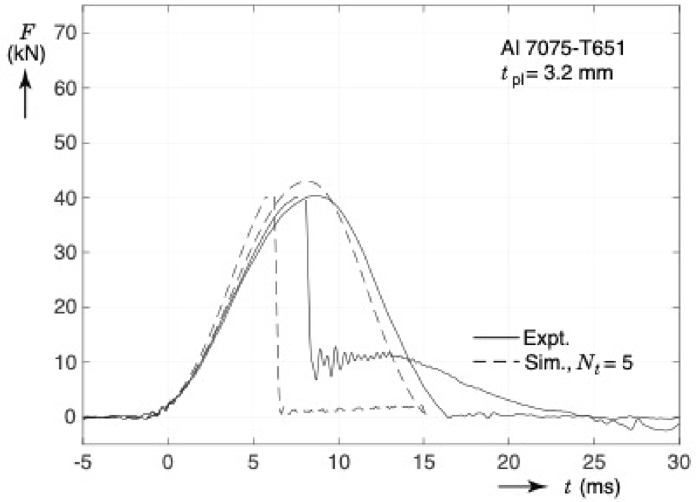
Basic Plastic Properties (% difference wrt 12.7 mm)

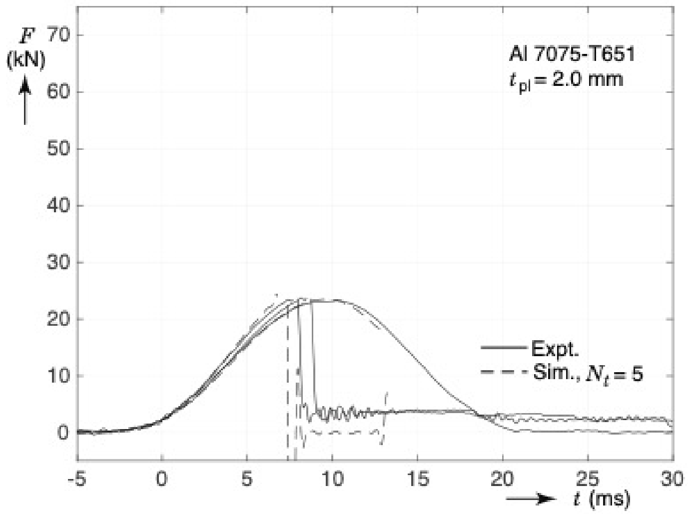
t, mm	σ_o, MPa	σ_u, MPa	ε_f (%)
1	490 (-11)	564(-9)	12 (1)
1.6	517 (-6)	588 (-5)	12.7 (5)
2	518 (-6)	583 (-6)	11.4 (-6)
3.2	501 (-9)	571 (-8)	12.9 (7)
4.8	495 (-10)	571 (-8)	12.3 (2)
12.7	**551**	**618**	**12.1**

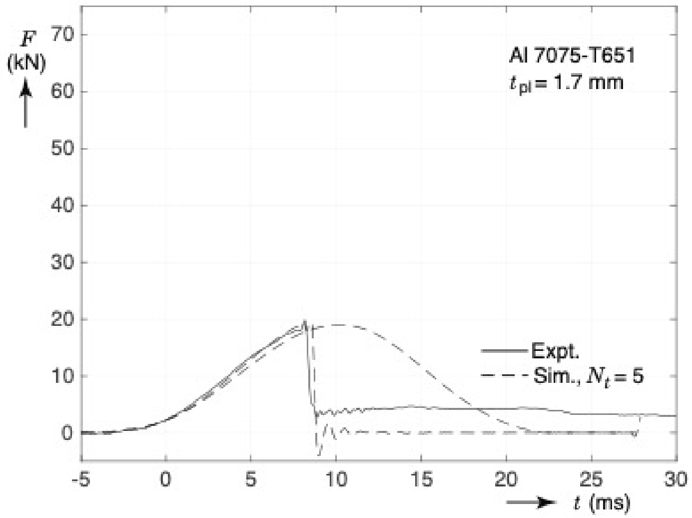


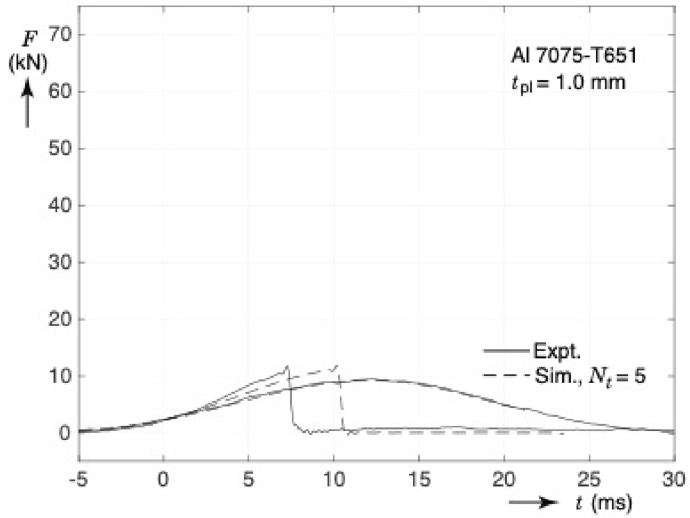
Thin Plates - Acceleration Histories Comparisons



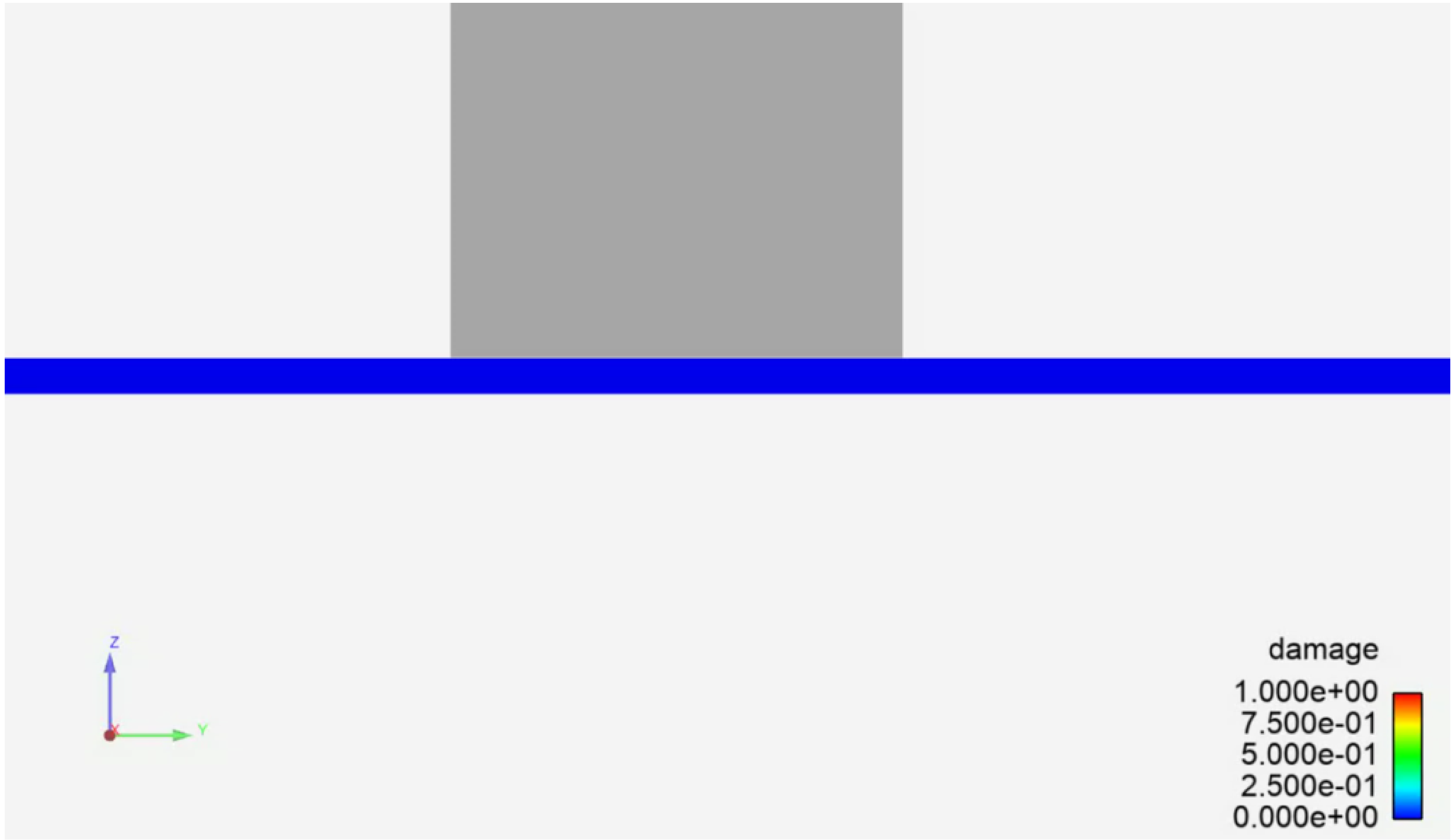




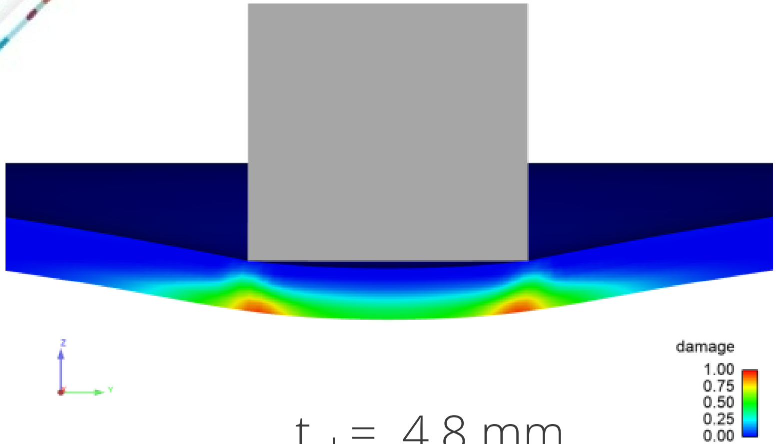




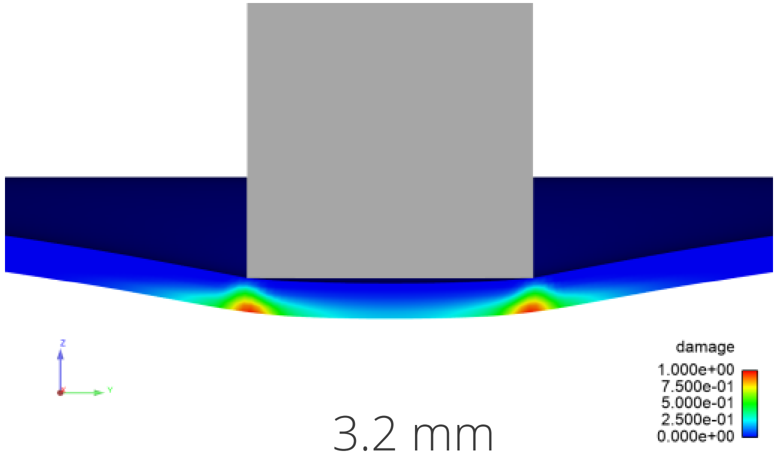
Progression of Damage t = 2 mm



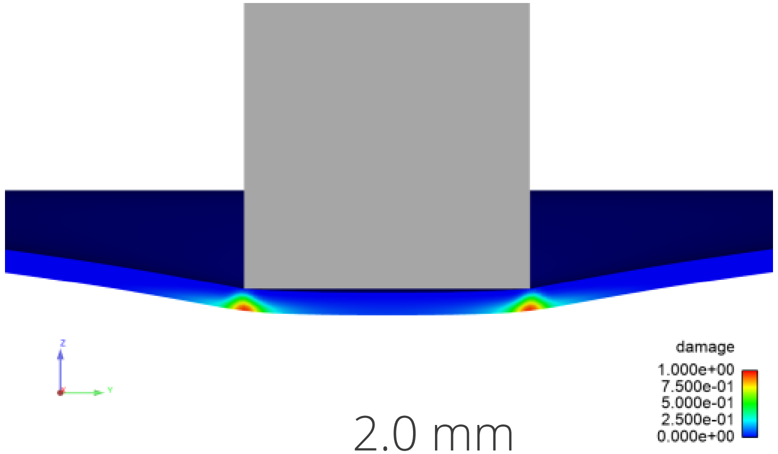
Thin Plates: Damage at Failure (N_t = 5)



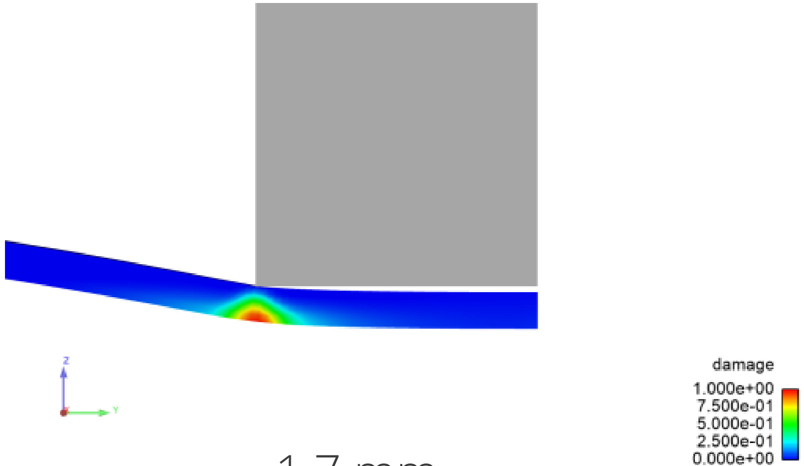
t_{pl} = 4.8 mm



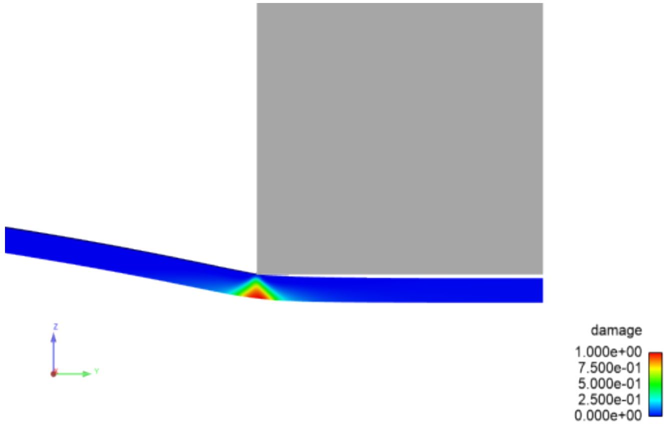
3.2 mm



2.0 mm



1.7 mm



1.0 mm

Conclusions

- Thermal-mechanical plasticity and ductile failure model calibrations for finite element simulation of Al 7075-T651 plate puncture of various thicknesses

- Assumption of axisymmetry was not representative for thick plates, but it was so for thinner plates

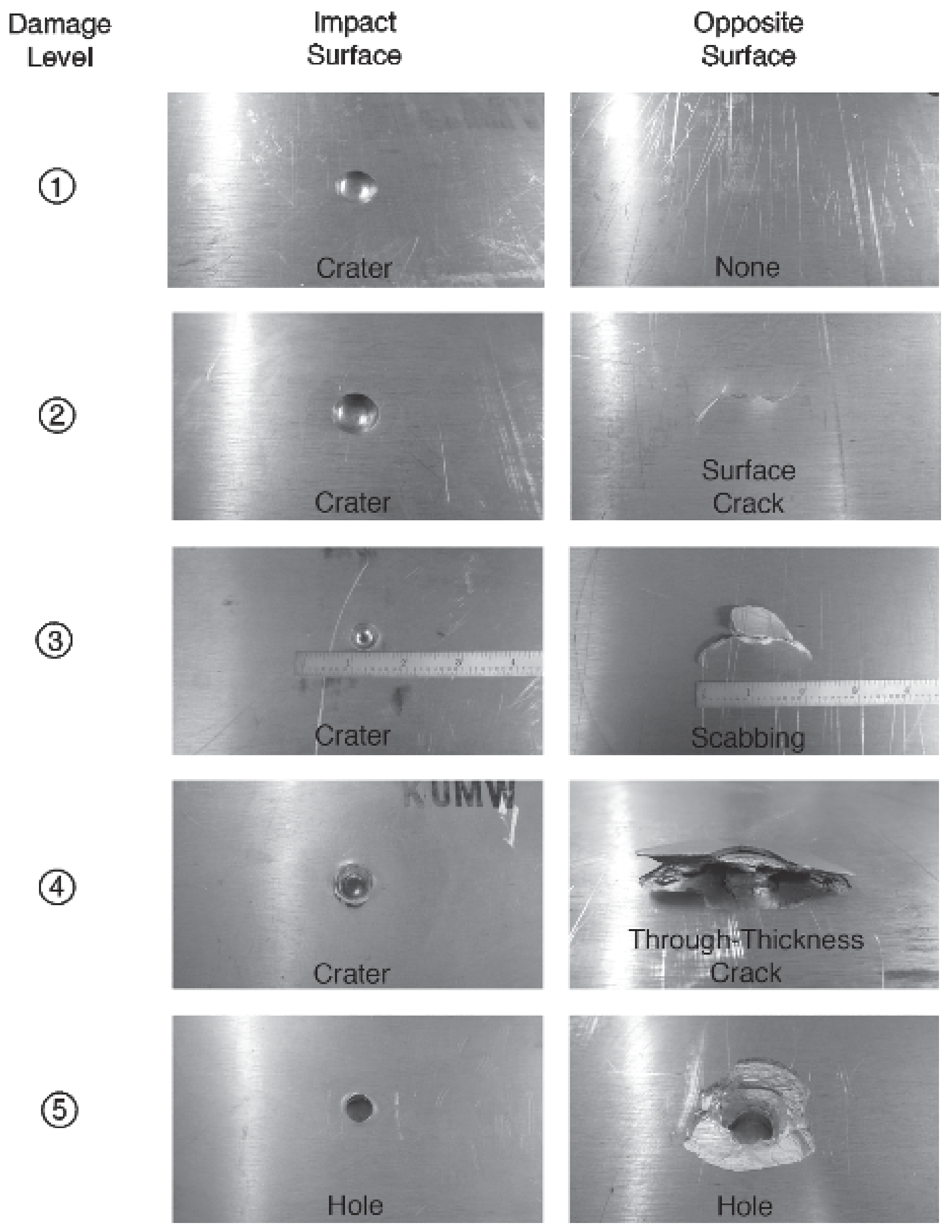
- Predictions for the threshold puncture punch velocity and punch acceleration histories agree reasonably well with experiments

- Not very strong element size sensitivity within the ranges studied, especially for thinner plates

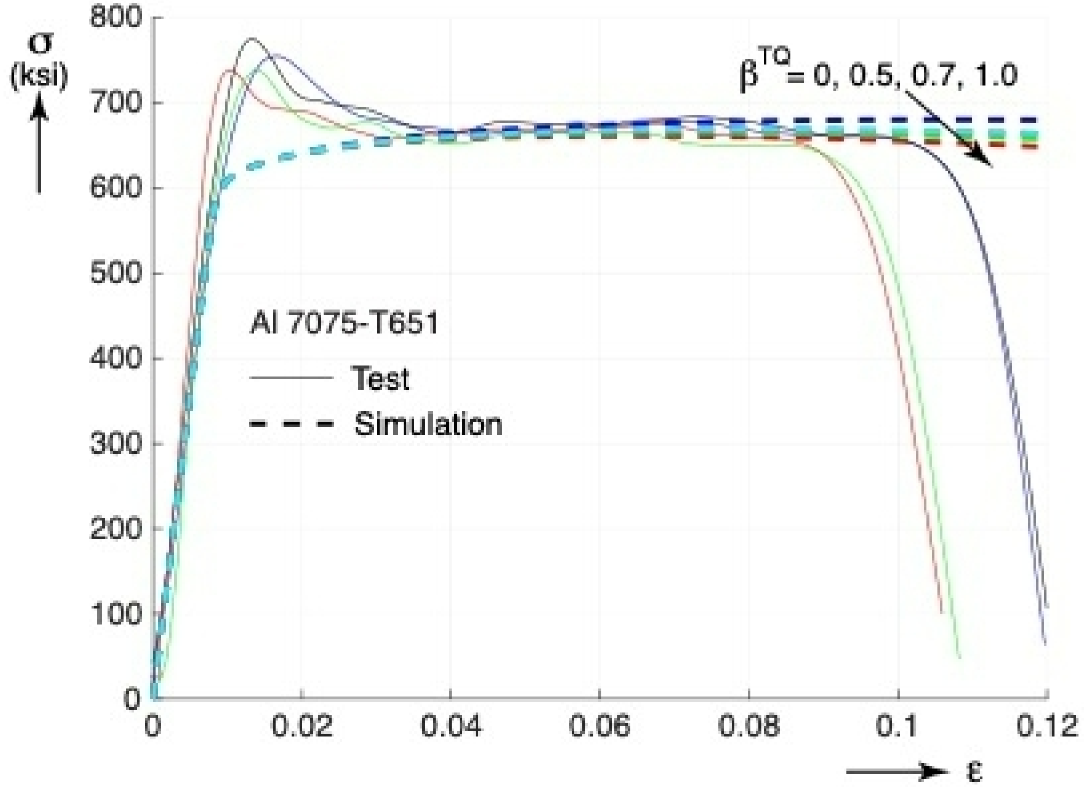
- Thick plates that fail by plugging suffer from considerable temperature increases and high strain rates, not so thinner plates

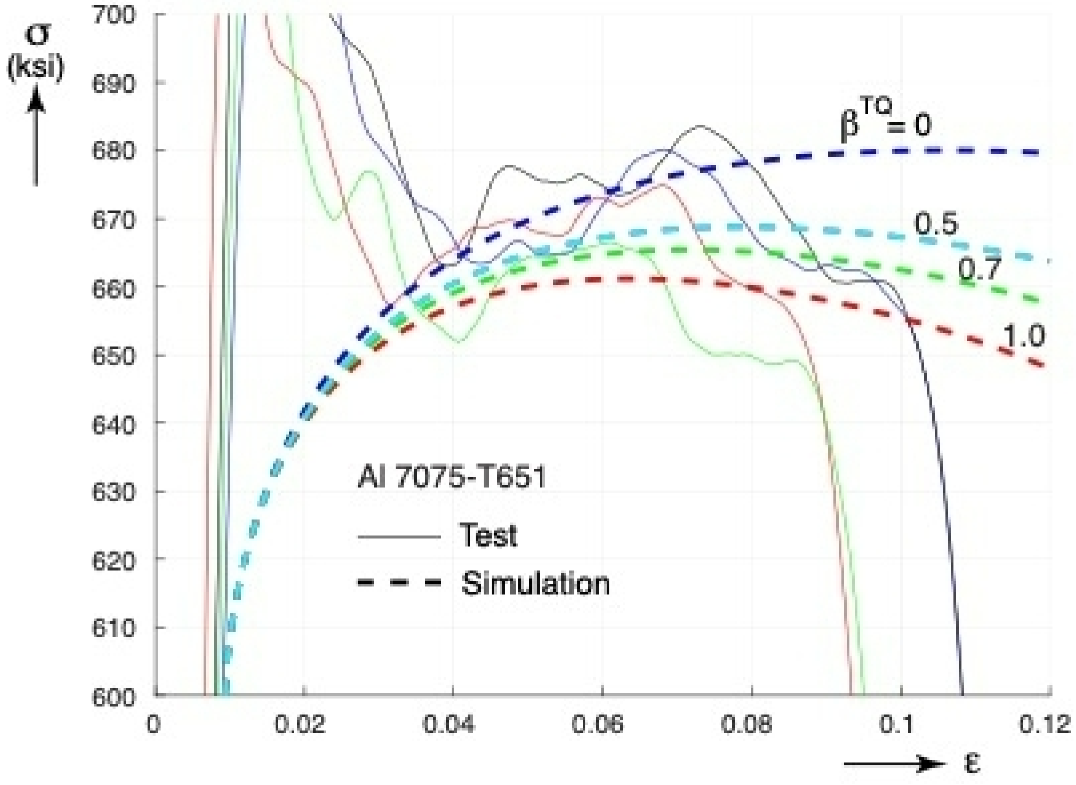
- Calibrated plasticity and ductile failure models were appropriate for the applications at hand.

Damage Levels



Calibration of β^{TQ}





Failure Model Calibration procedure

INPUT

Experiment	Simulations	Calibration Parameters
$d_i,\ i=1,6$	$\{\bar{\varepsilon}^p, \sigma_1, \sigma_2, \sigma_3\}_i,\ i=1,6$	$\{e_1, \ldots, e_N\}_i,\ i=1,6$
		B
		$\{\alpha_{\min}, \alpha_{\max}, \Delta\alpha\}$
		$\{\beta_{\min}, \beta_{\max}, \Delta\beta\}$
		$\{D^{cr}_{\min}, D^{cr}_{\max}, \Delta D\}$

PREREQUISITE CALCULATIONS

$$\sigma_m = \frac{1}{3}\sum_{j=1}^{3}\sigma_j \qquad s_j = \sigma_j - \sigma_m,\ j=1,2,3 \qquad A = \max\left(\frac{s_2}{s_3}, \frac{s_2}{s_1}\right)$$

TABULATION

for $\alpha = \alpha_{\min}$ to $\alpha_{\max}$ increment $\Delta\alpha$ do:

for $\beta = \beta_{\min}$ to $\beta_{\max}$ increment $\Delta\beta$ do:

for $D^{cr} = D^{cr}_{\min}$ to $D^{cr}_{\max}$ increment ΔD^{cr} do:

for $i = 1$ to 6 increment 1 do:

for $k = 1$ to N increment 1 do:

$$D_k = \frac{1}{D^{cr}}\int_0^{\bar{\varepsilon}^p} w_1 w_2 \, d\hat{\varepsilon}^p$$

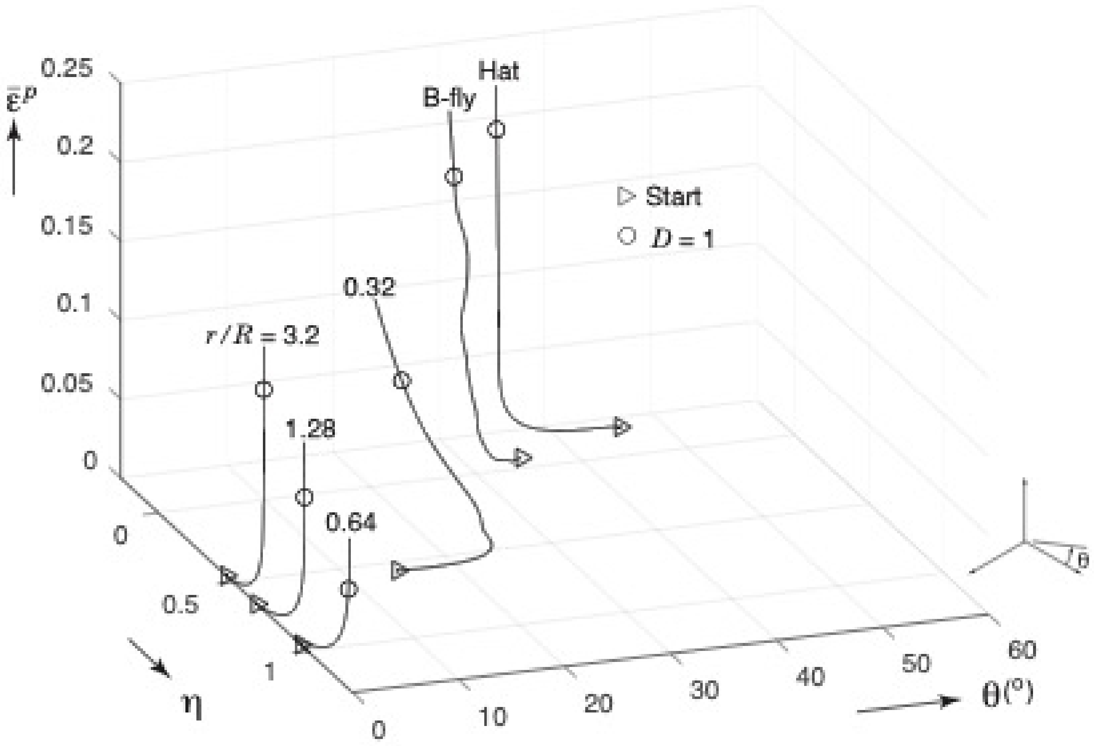
Find e_i with lowest $\bar{d}_k$ when $D_k = 1$

$$E_i = \bar{d}_i - d_i$$

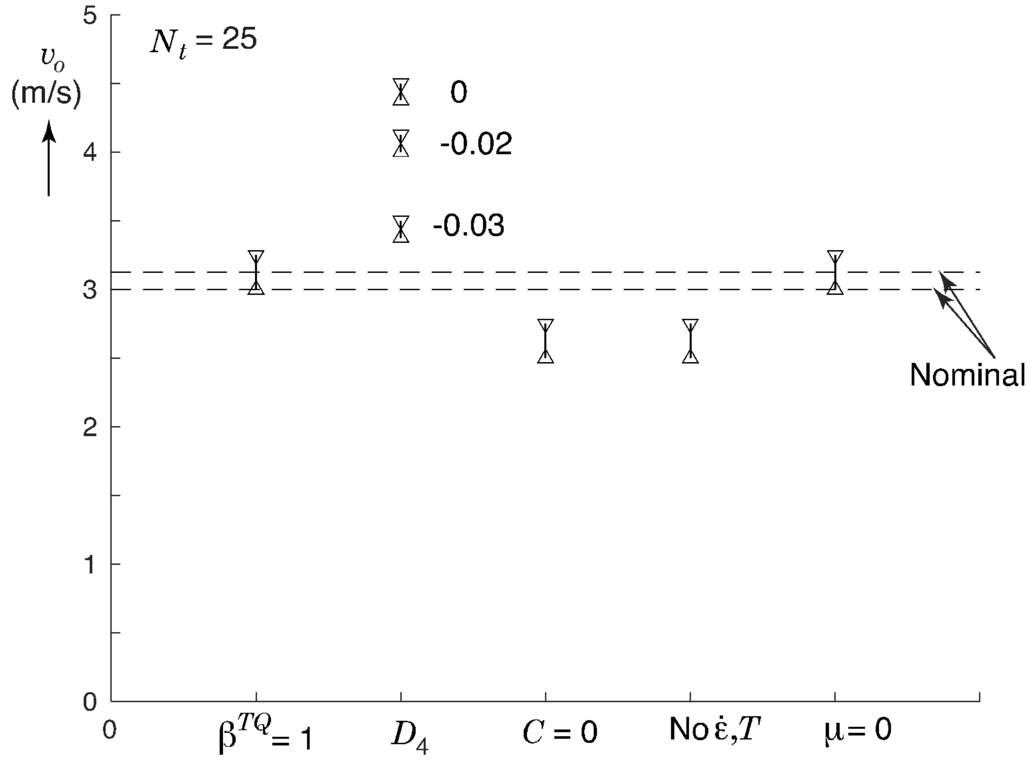
$$E = \sum_{i=1}^{6} E_i^2$$

Tabulate $\{E, \alpha, \beta, D^{\mathrm{cr}}, \text{other diagnostics}\}$

Histories at First Failure Location



Effects of Selected Parameters



State Variables Just Prior to Failure (12.7 and 4.8 mm)