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Puncture of Thin Aluminum 7075-T651 Plates

Experiments and Simulations

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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

- Identify if calibrations of thermal-mechanical material models made from one lot can accurately predict puncture of plates from a different lot.

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**

← Stock used for calibrations

- Compare FE predictions of plate puncture experiments to experimentally identified:
  - Minimum punch velocity to cause puncture
  - Force-time histories
  - Failure mode

Material Model Calibration

Plasticity Model Calibration

J_2 Yield Function with Isotropic Hardening:

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

Associated Flow Rule:

$$\dot{\bar{\varepsilon}}^p_{ij}=\lambda\frac{\partial\phi}{\partial\varepsilon^p_{ij}}$$

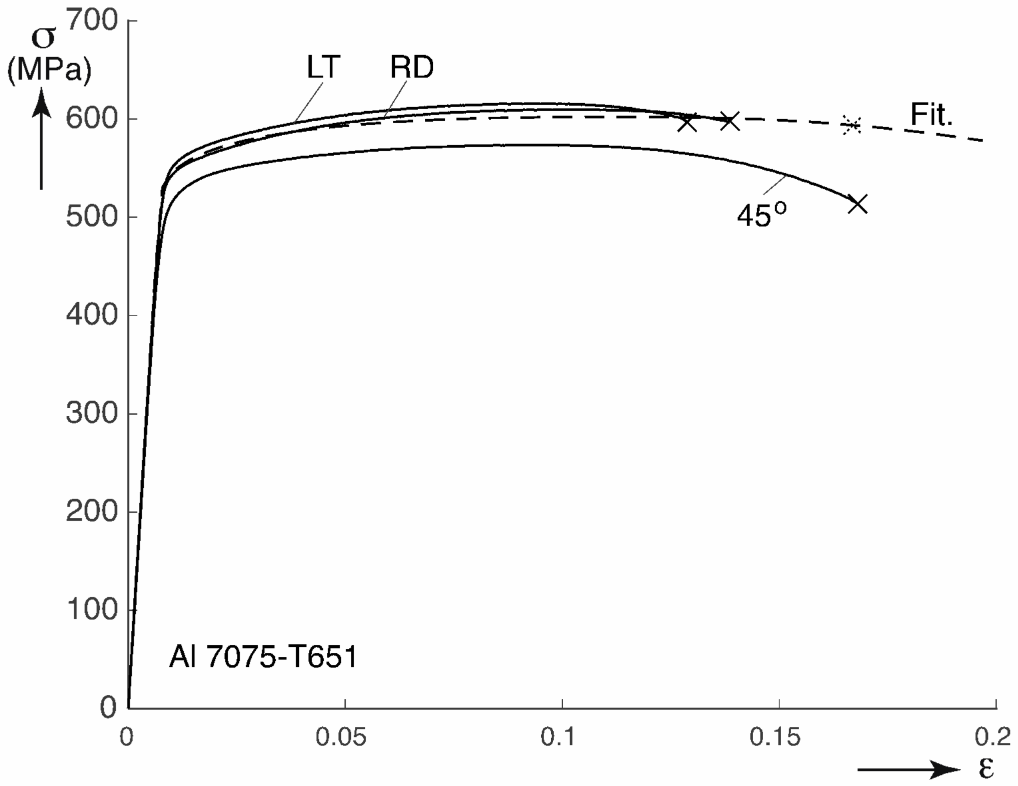
Hardening Function:

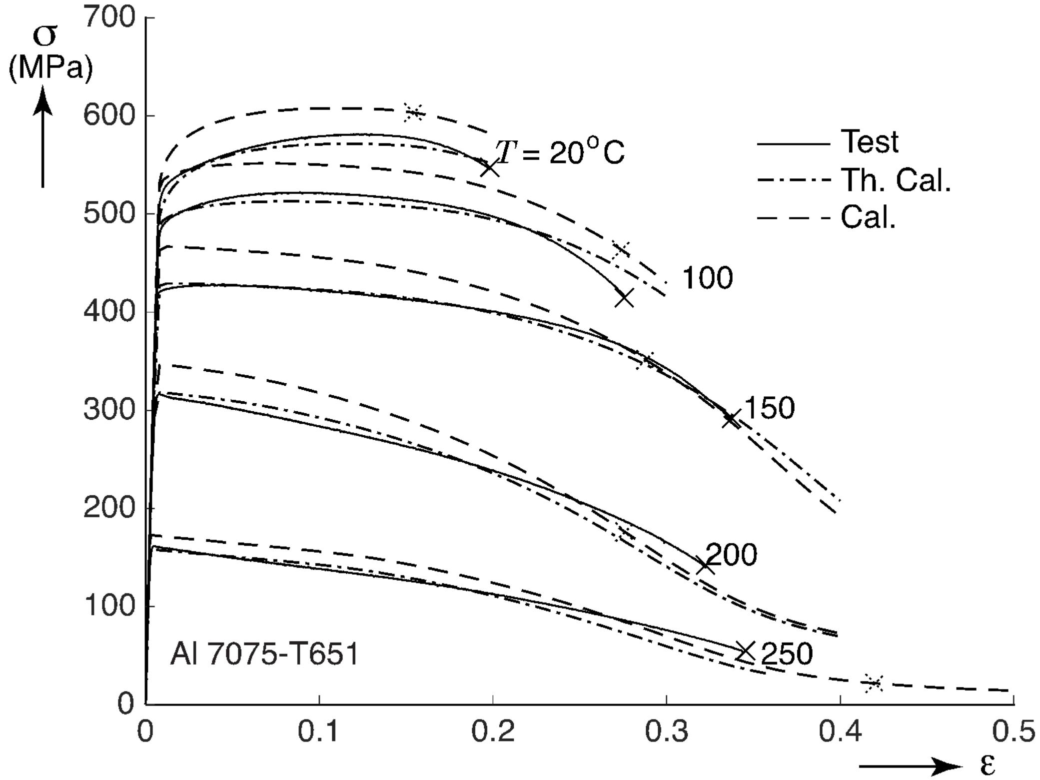
$$\sigma_y\left(\bar{\varepsilon}^p,T,\dot{\bar{\varepsilon}}^p\right)=\left[\sigma_y^o\left(T\right)+A\left(T\right)\left(\bar{\varepsilon}^p\right)^{n(T)}\right]\left[1+C\left(T\right)\ln\left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}_o}\right)\right]$$

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

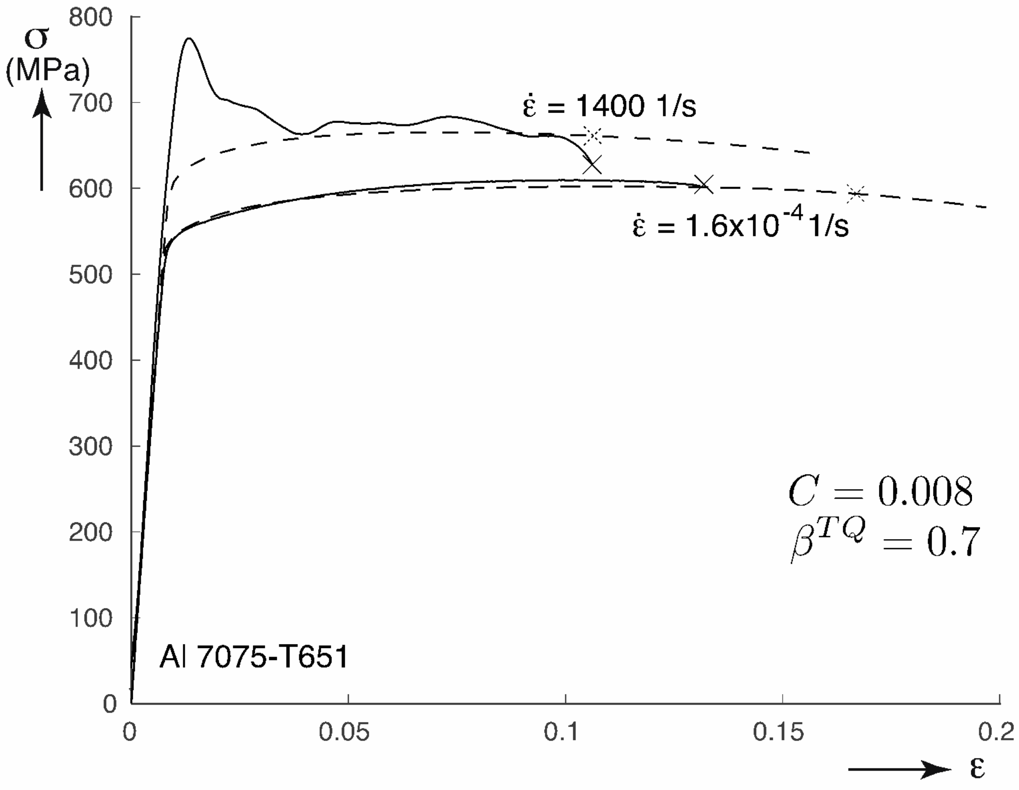
ρ, kg/m ^{3}	E, GPa	ν	c_p, J/kg-K	β^{TQ}
2810	71.7	0.33	960	0.7

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)

Wilkins Model

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

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

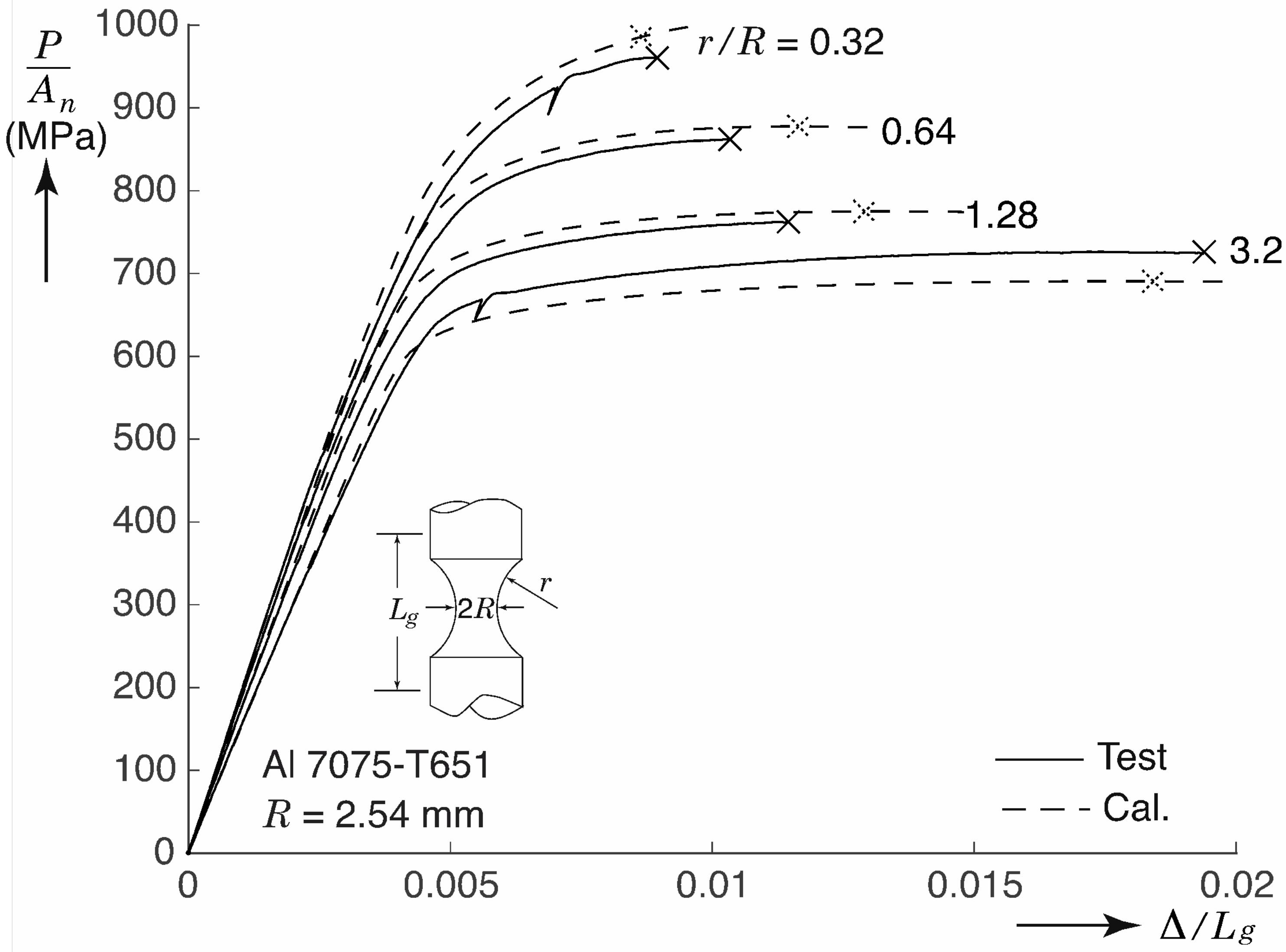
$$w_2 = (2 - \mathcal{A})^{\beta}\,, \quad \mathcal{A} = \max\left(\frac{s_2}{s_3}, \frac{s_2}{s_1} \right)$$

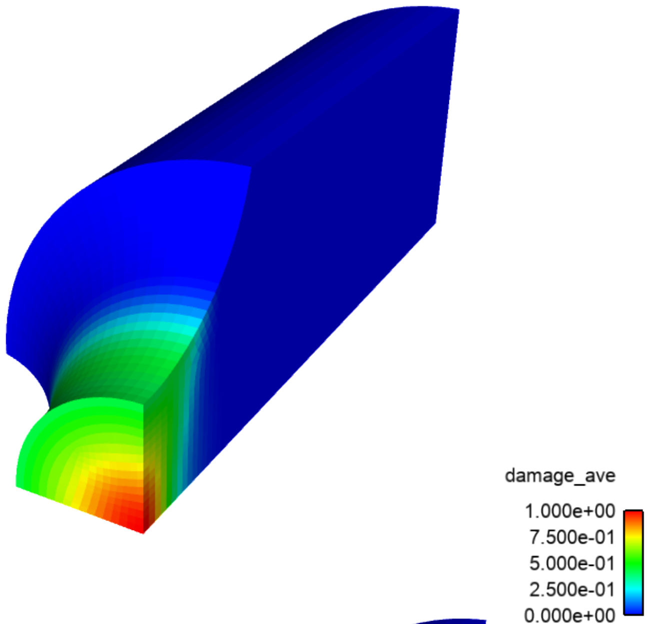
$$w_3(\dot{\bar{\varepsilon}}^p) = \frac{1}{1 + D_4 \ln \frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}_0}}$$

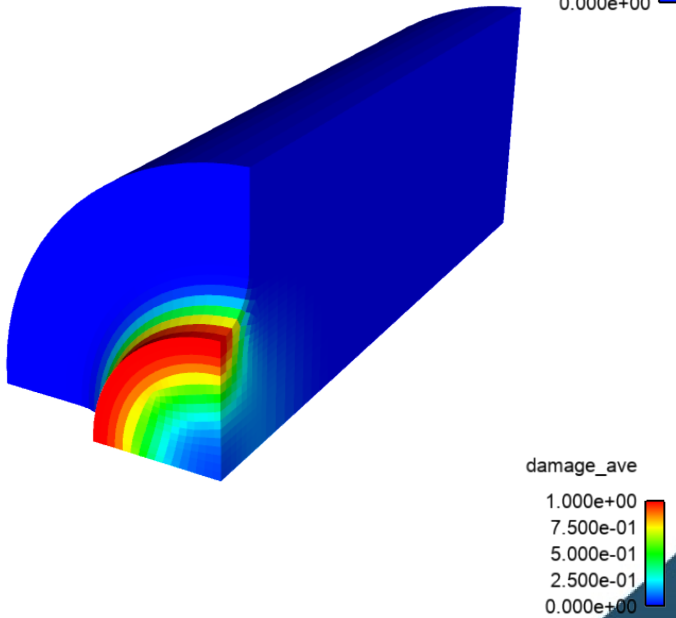
$$w_4(T) = \frac{1}{1 + D_5 \frac{T - T_{\mathrm{ref}}}{T_{\mathrm{melt}} - T_{\mathrm{ref}}}}$$

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

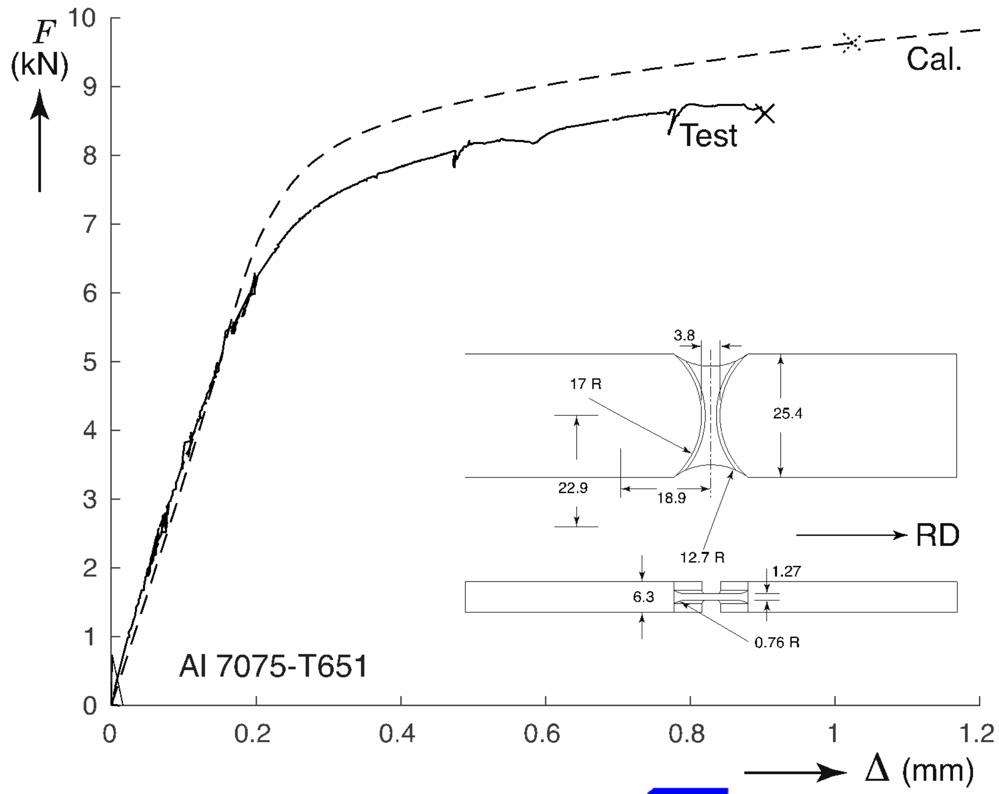
Ductile Failure Model Calibration: QS Notched Tension Tests

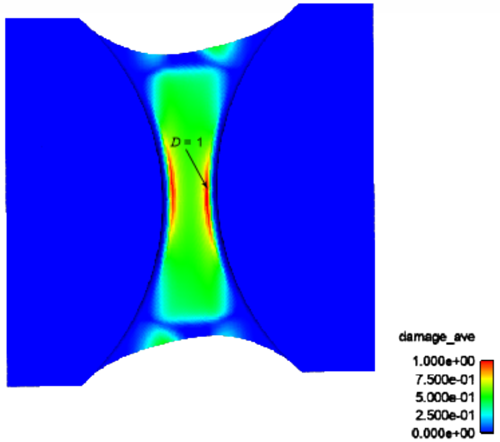


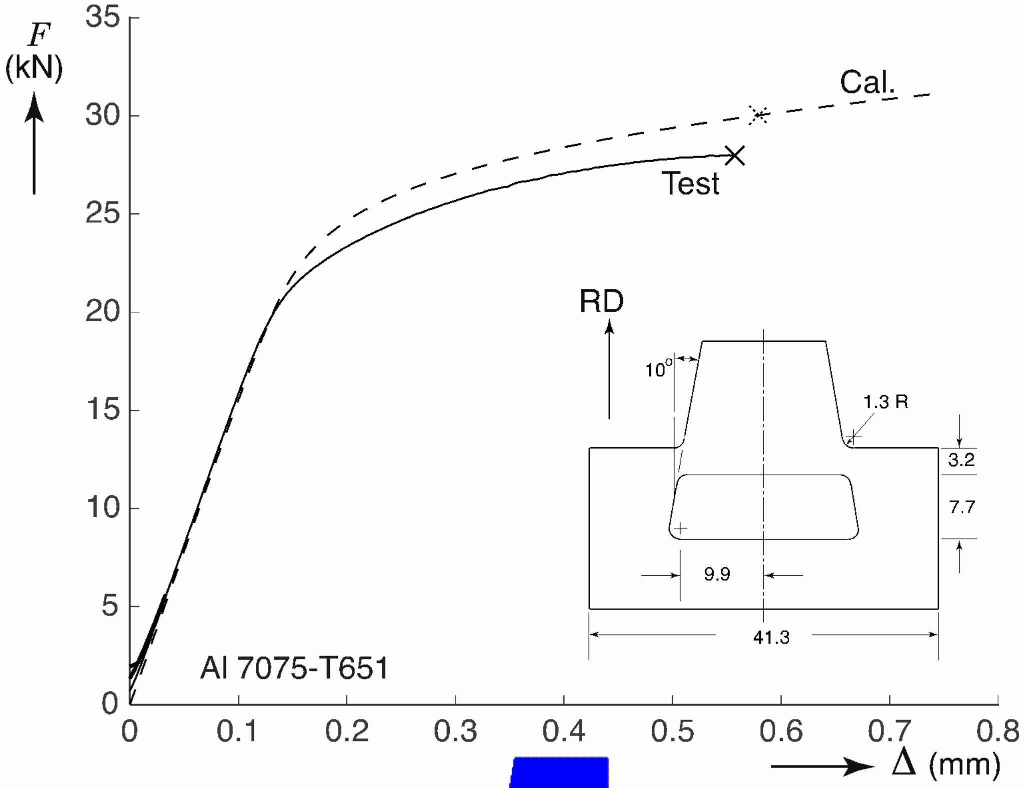




Ductile Failure Model Calibration: QS Shear Dominated Tests







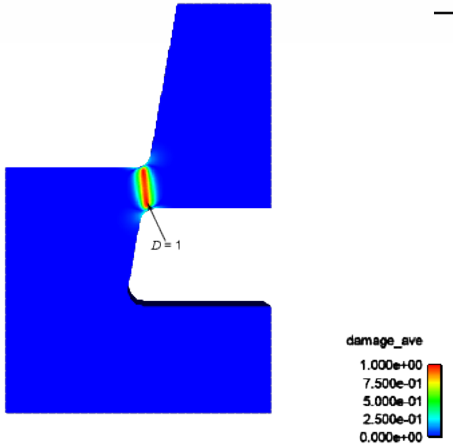
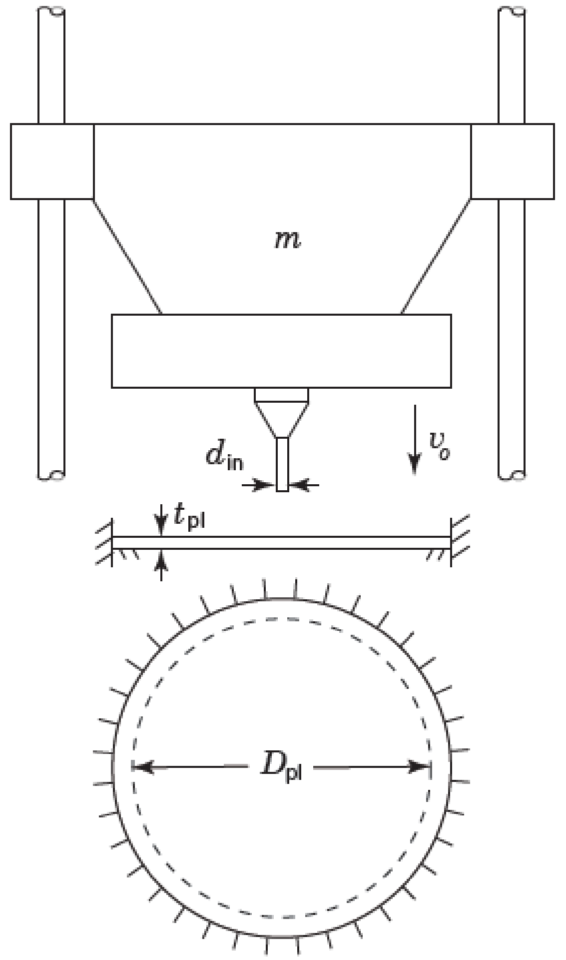
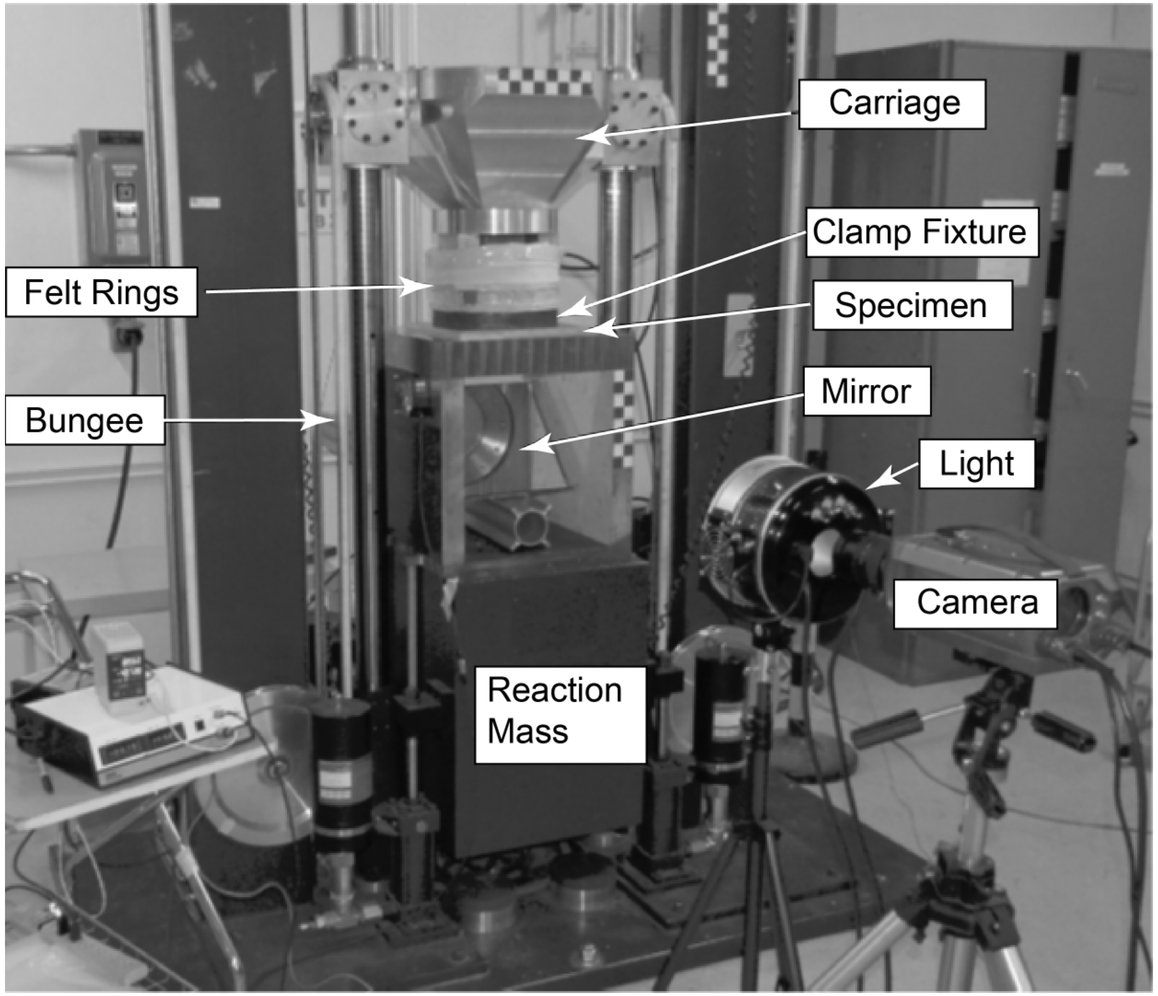


Plate Puncture

Experimental Setup





$D_{pl} =$

$m = 1$

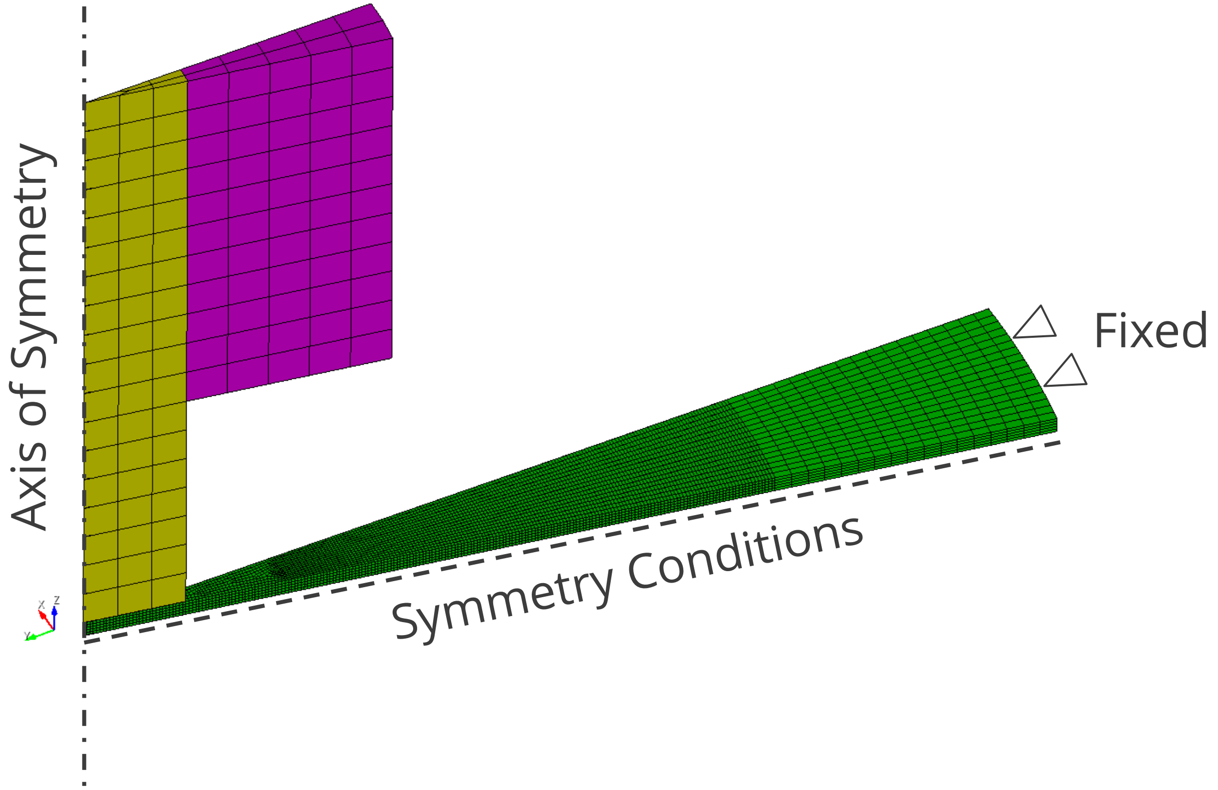
$t_{pl} = 1, 1.6, 2, 3.2, 4.8$ mm, $d_{in} = 25.4$ mm

Finite Element Numerical Modeling

- Explicit, transient-dynamic finite element model.
- Reduced-integration 8-node hexahedral elements
- Frictional hard contact between punch and plate
- Punch is rigid, plate is elastic-plastic.
- Failure propagation modeled via element deletion.

- Simulations conducted with 3, 5 and 10 elements through the plate thickness.

- 180^{o} wedge for 4.8, 3.2 and 2.0 mm thick
- 10^{o} wedge for 2.0, 1.7, 1.0 mm thick



Comparison of Measured and Predicted Puncture Speed Brackets

Basic Plastic Properties (% difference wrt 12.7 mm)

t, mm	σ_o, MPa	σ_u, MPa	ε_f (%)
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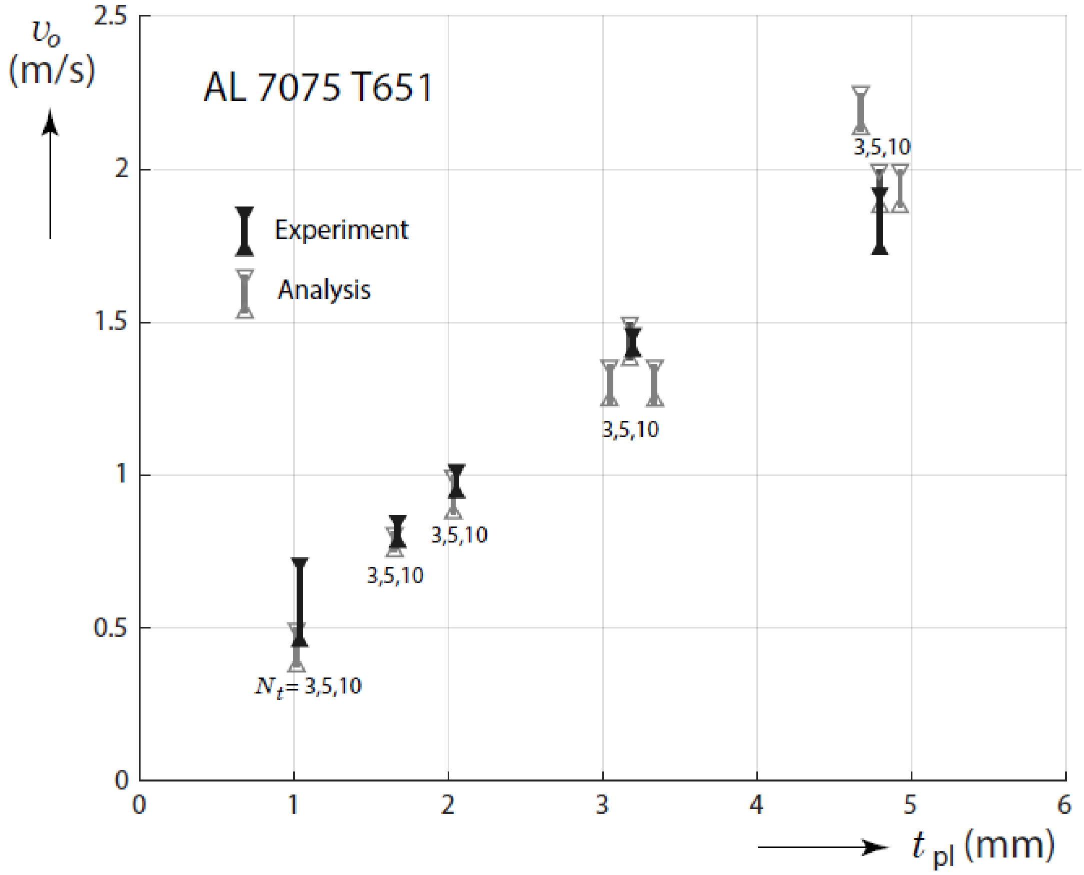
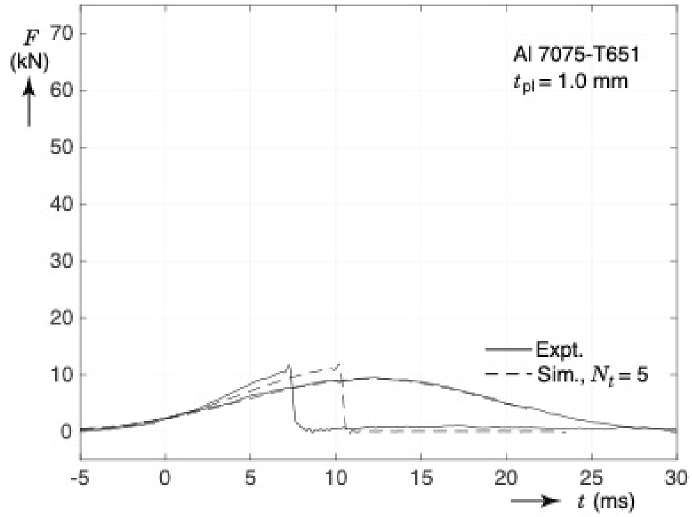
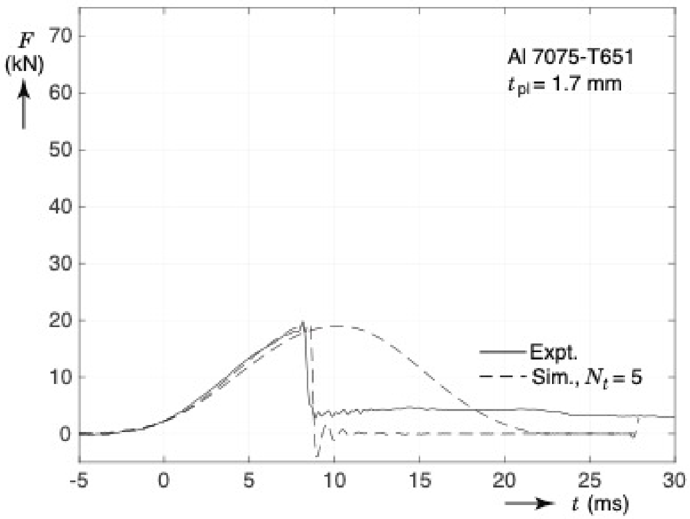
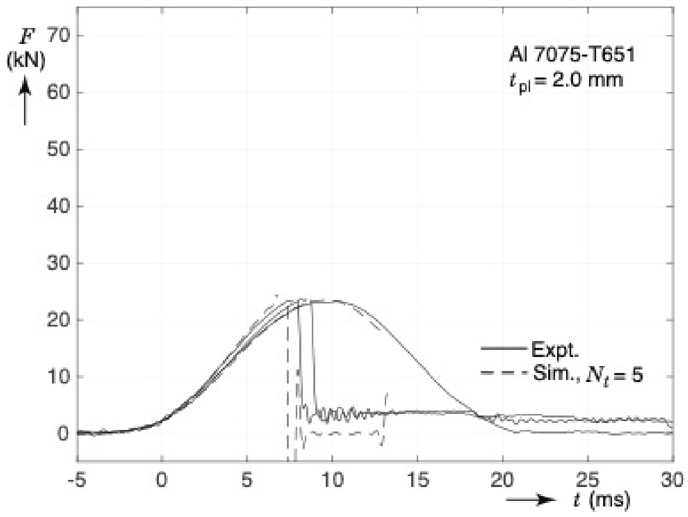
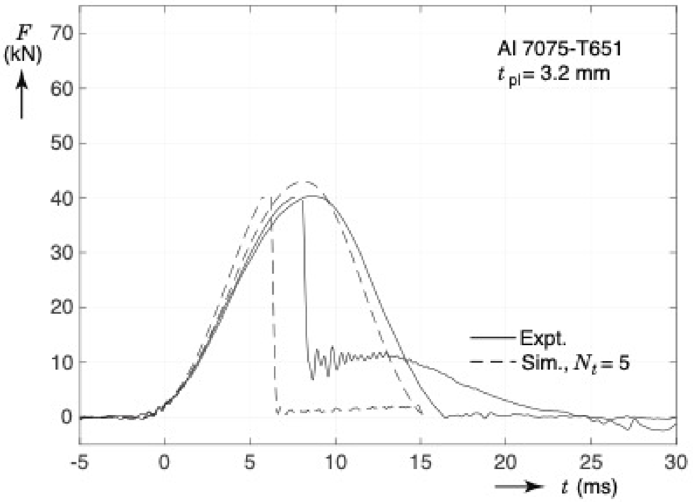


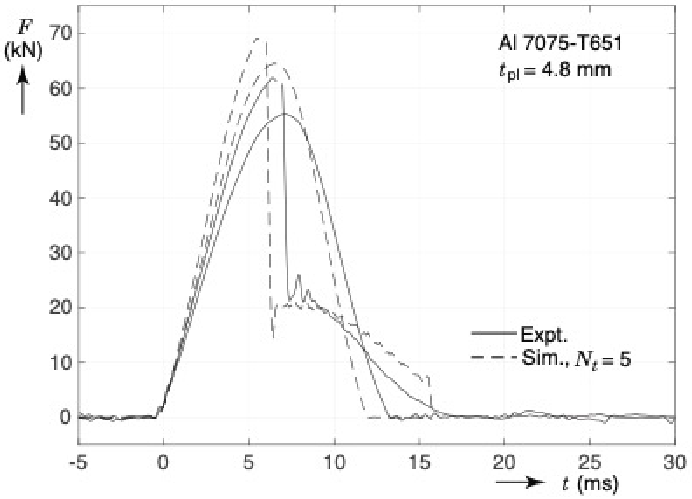
Force-Time History Comparisons











Basic Material Properties

t, mm	σ_o, MPa	σ_u, MPa	ε_f (%)
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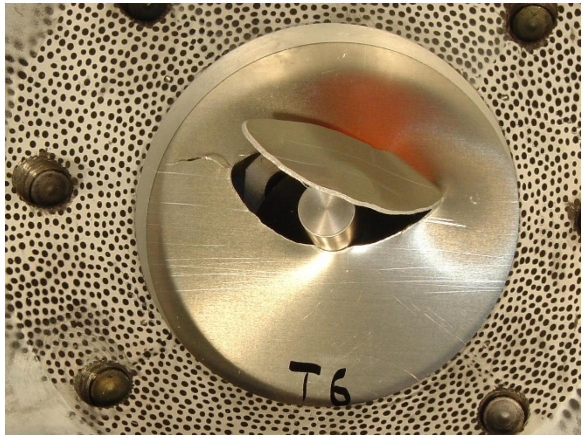
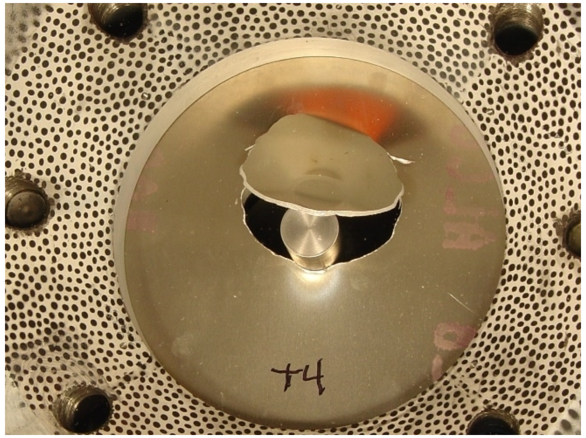
Experimental Failure Configurations

1.0 mm

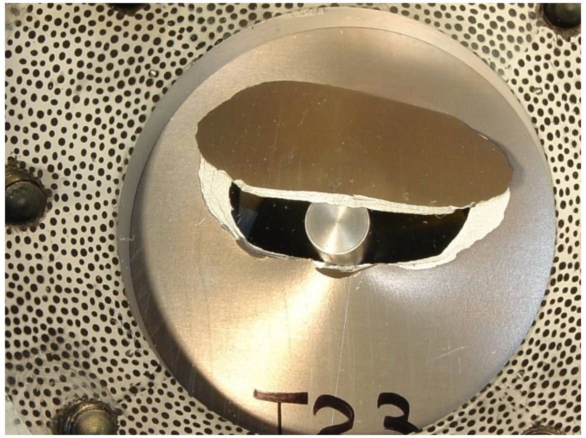


1.7 mm



2.0 mm

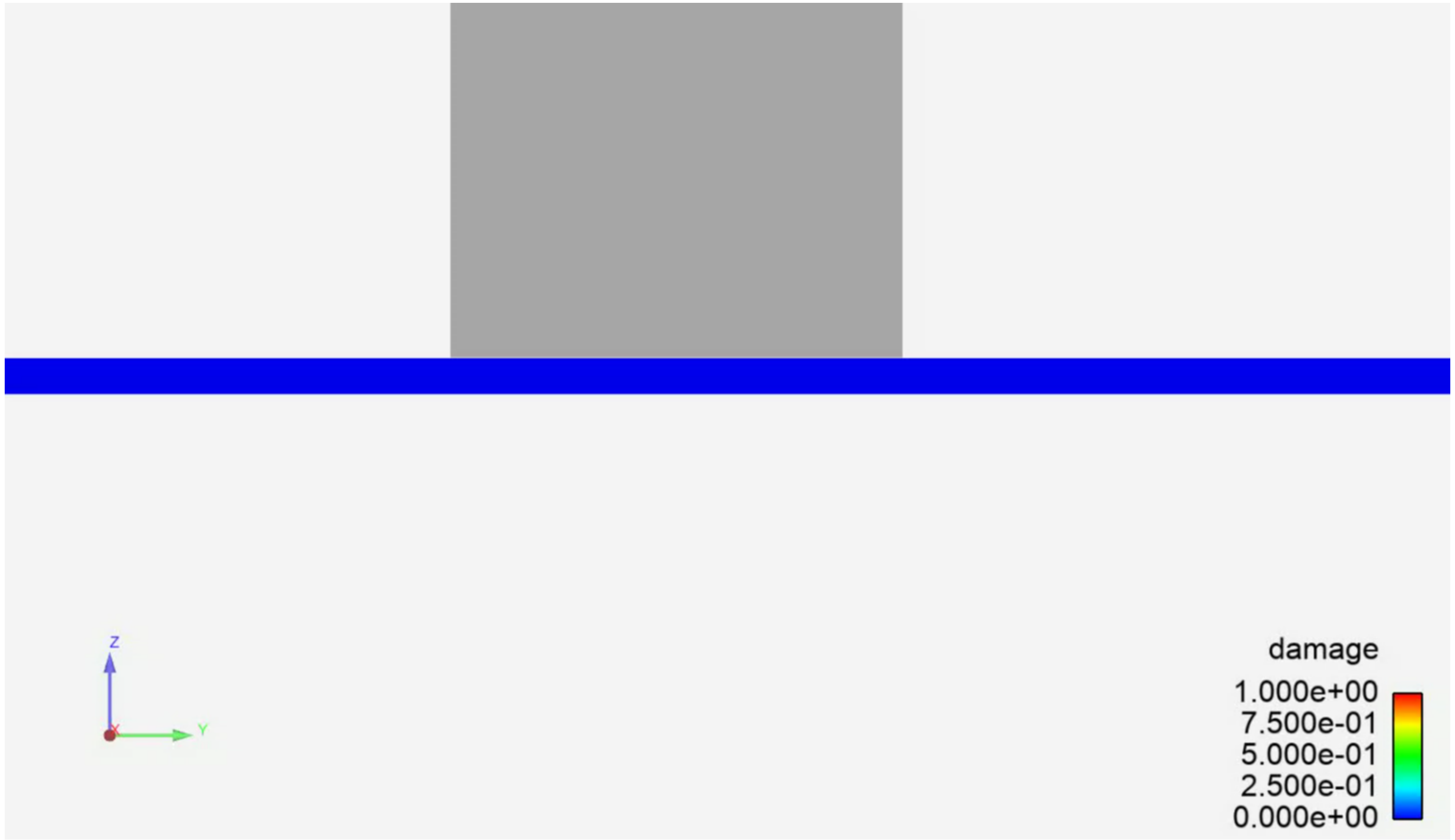
3.2 mm



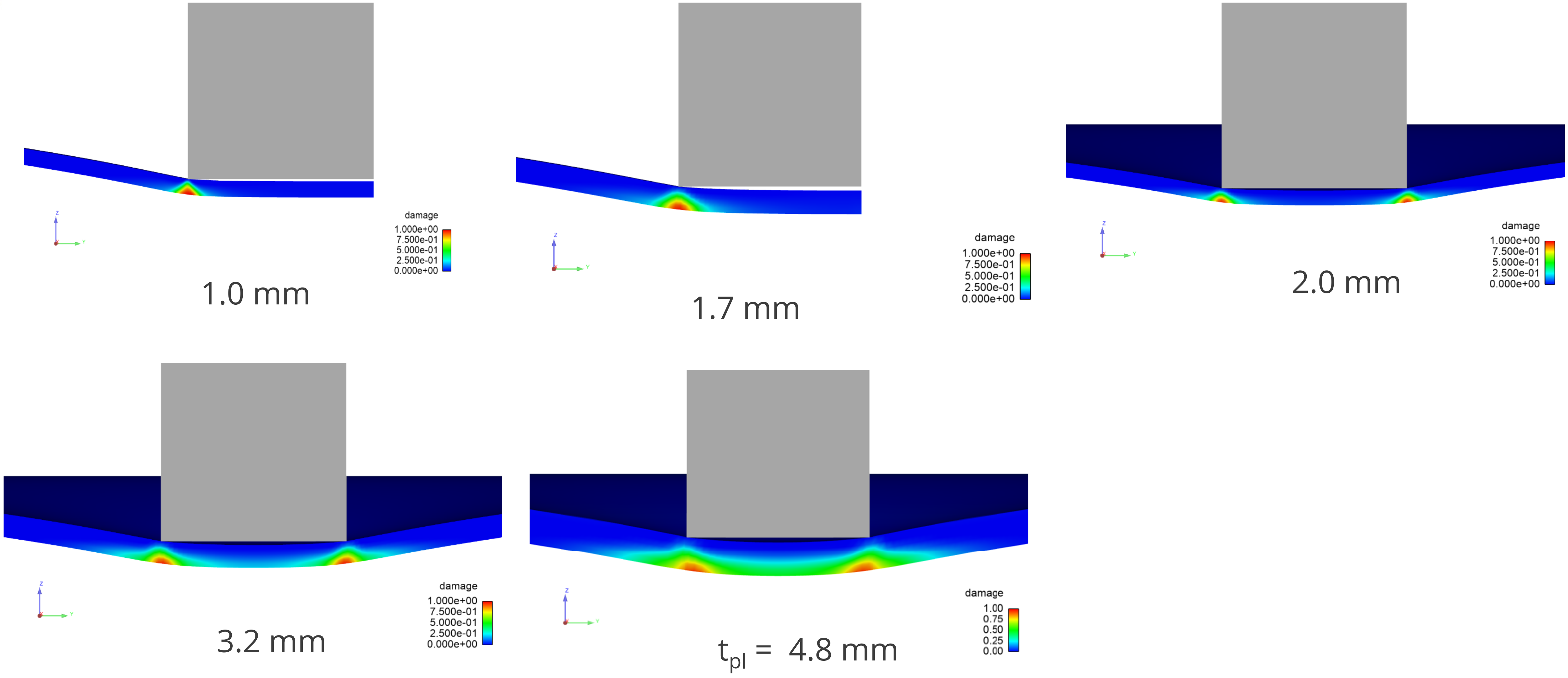
4.8 mm

Failure initiates under edge of punch and propagates outwards.

Progression of Damage t = 2 mm



Damage at Failure ($N_t = 5$)



Conclusions

- Thermal-mechanical plasticity and ductile failure model calibrations were made from one lot of 7075 for finite element simulation of Al 7075-T651 plate puncture tests of different lots.

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

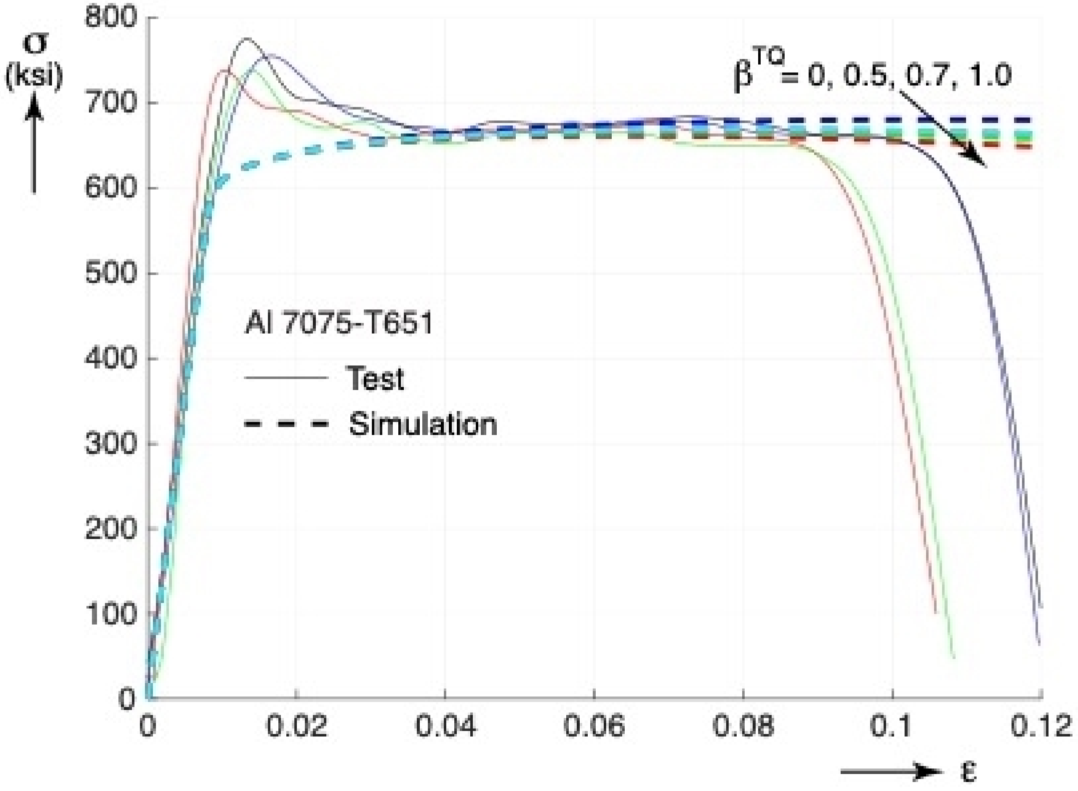
- Not very strong element size sensitivity within the ranges studied

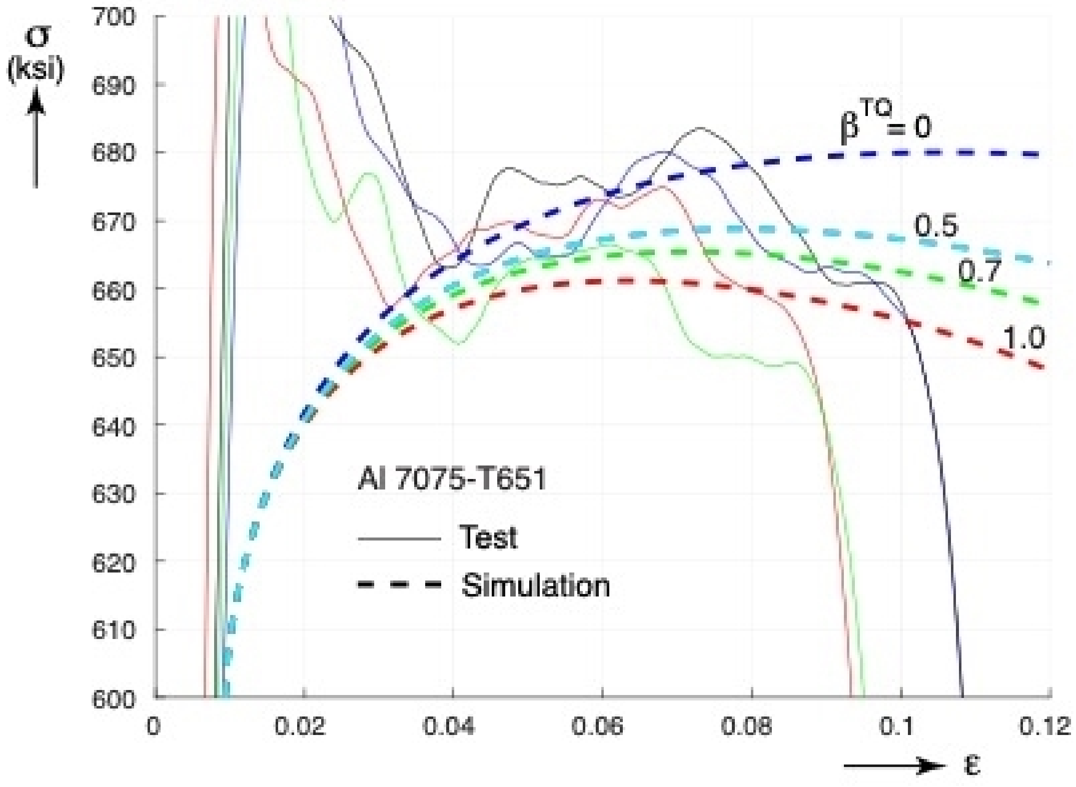
- Calibrated plasticity and ductile failure models were appropriate for predictions on puncture velocity, and Force-time histories but not for predicting final flap shape.

Thank you for your Attention

Questions?

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