Numerical simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

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Introduction

Federal Aviation Administration

- **Part of a research program conducted by FAA William J Hughes Technical Center (NJ)**

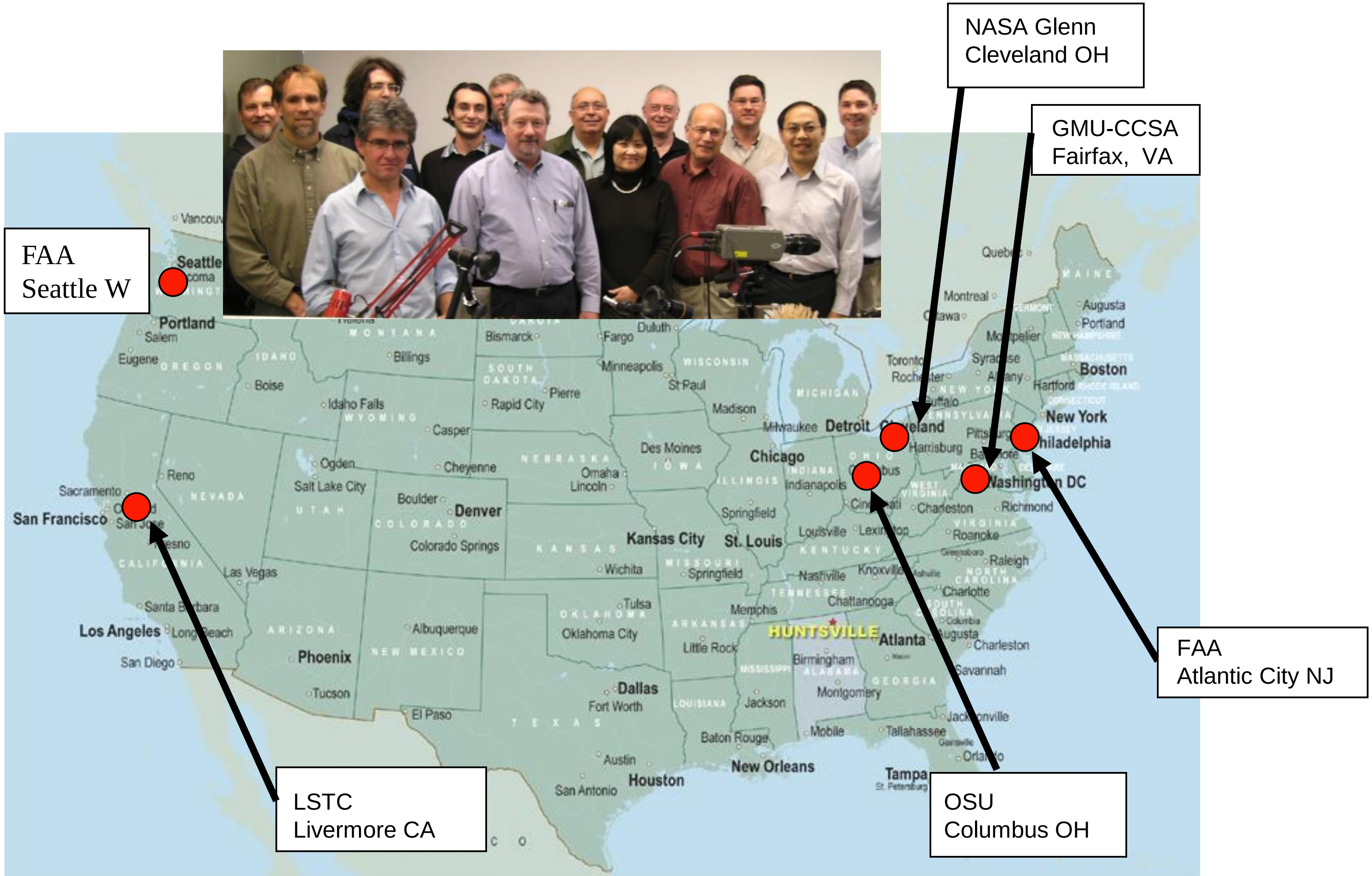
- **material testing performed by OSU**
- **ballistic testing performed by NASA/GRC**
- **numerical simulations performed by GMU-CCSA**

- **involved the implementation in LS-DYNA of a tabulated generalisation of the Johnson-Cook material law with regularisation to accommodate simulation of failure in ductile materials : MAT_224 or MAT_TABULATED_JOHNSON_COOK**

- **previously published results in :**

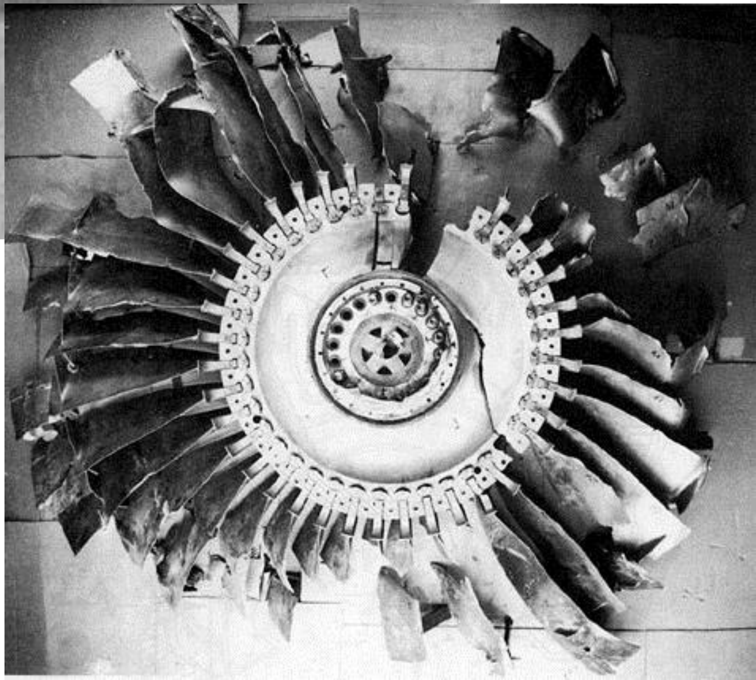
▪ **A Generalized, Three Dimensional Definition, Description and Derived Limits of the Triaxial Failure of Metals, Carney, DuBois, Buyuk, Kan, Earth&Sky, march 2008**

FAA engine safety working group



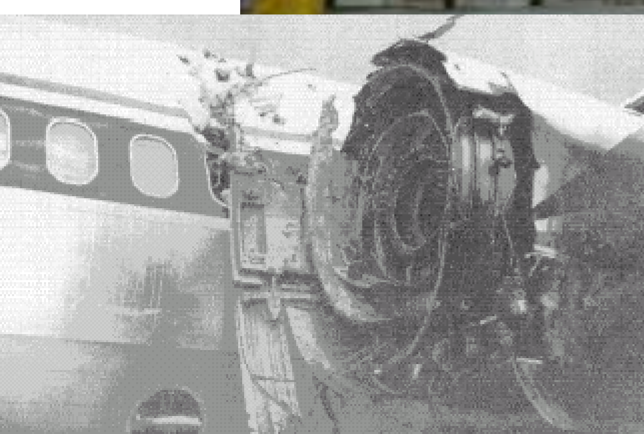
Background : blade-out events

- Aircraft Safety depends upon sound engine containment designs, and upon realistic evaluation of the damage from uncontained engine debris.
- The program addresses the modeling of impact between the blades and case, or between the fragments and non-engine aircraft structure
- The program has developed an extensive material test database and has modeled many different tests to evaluate the overall applicability of a single material model to the larger overall problem



Sioux City, 1989

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V



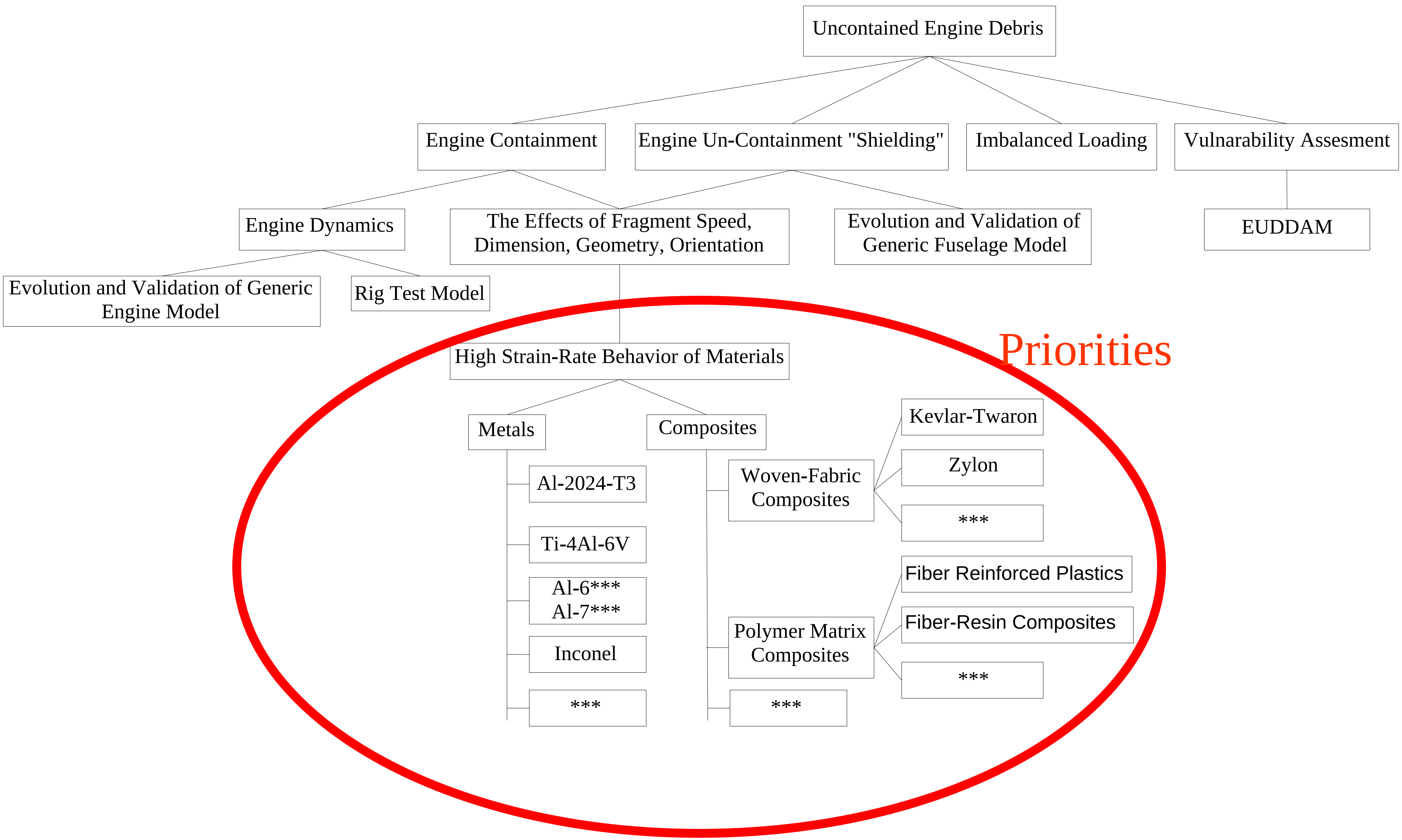
Pensacola RTO, 1996

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

Mandatory full scale engine containment test

Fan blades of Trent

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V



References

- Ravi Shriram Yatnalkar*, Experimental Investigation of Plastic Deformation of Ti-6Al-4V under Various Loading Conditions*, B.E, Thesis, The Ohio State University, 2010
- Jeremy Daniel Seidt, Plastic *Deformation and Ductile Fracture of 2024-T351 Aluminum under Various Loading Conditions, Dissertation*, The Ohio State University, 2010
- Jeremiah Thomas Hammer, *Plastic Deformation and Ductile fracture of Ti-6Al-4V under Various loading Conditions, Dissertation*, The Ohio State University, 2012
- Murat Buyuk, *Development of a tabulated thermo-viscoplastic material model with regularized failure for dynamic ductile failure prediction of structures under impact loading, Dissertation*, The George Washington University, 2013

Development of MAT_224 in LS-DYNA

- started development in november 2006
- production version available in ls971-R4.2
- current presentation is based on implementation in ls971-R6.1
- developed on the basis of MAT_024 with VP=1
- available for fully and underintegrated shell and solid elements
- full keyword code : *MAT_TABULATED_JOHNSON_COOK

Development history of MAT_224

- R4-52798 (june 2009) had the first official release of MAT_224, load curve driven failure only
- R4-54523 : implementation of the NUMINP option by Tobias Erhardt from Dynamore
- R4-54921 : implementation of tabulated failure by Paul Du Bois and Murat Buyuk
- R5-59419 : (july 2010) QA at LSTC by Gunther Blankenhorn

- Further development driven by demand from industrial users :

- R5-63444 : (april 2011) optional coupling with EOS
- R6-68028 : E-modulus can be a function of temperature
- R6-68055 : (july 2011) MAT_224 is coupled with type 13 tetrahedrons
- R6-70523 : (december 2011) tabulated regularisation
- R6-71932 : coupled with *CONSTRAINED_TIED_NODES_FAILURE
- R6-72543 : (february 2012) NUMINT=-200 means no erosion will occur if d=1
- Dev-87525 : (february 2014) BETA<0 refers to a load curve in function of strain rate

Development of a material and failure model for Ti-6-4

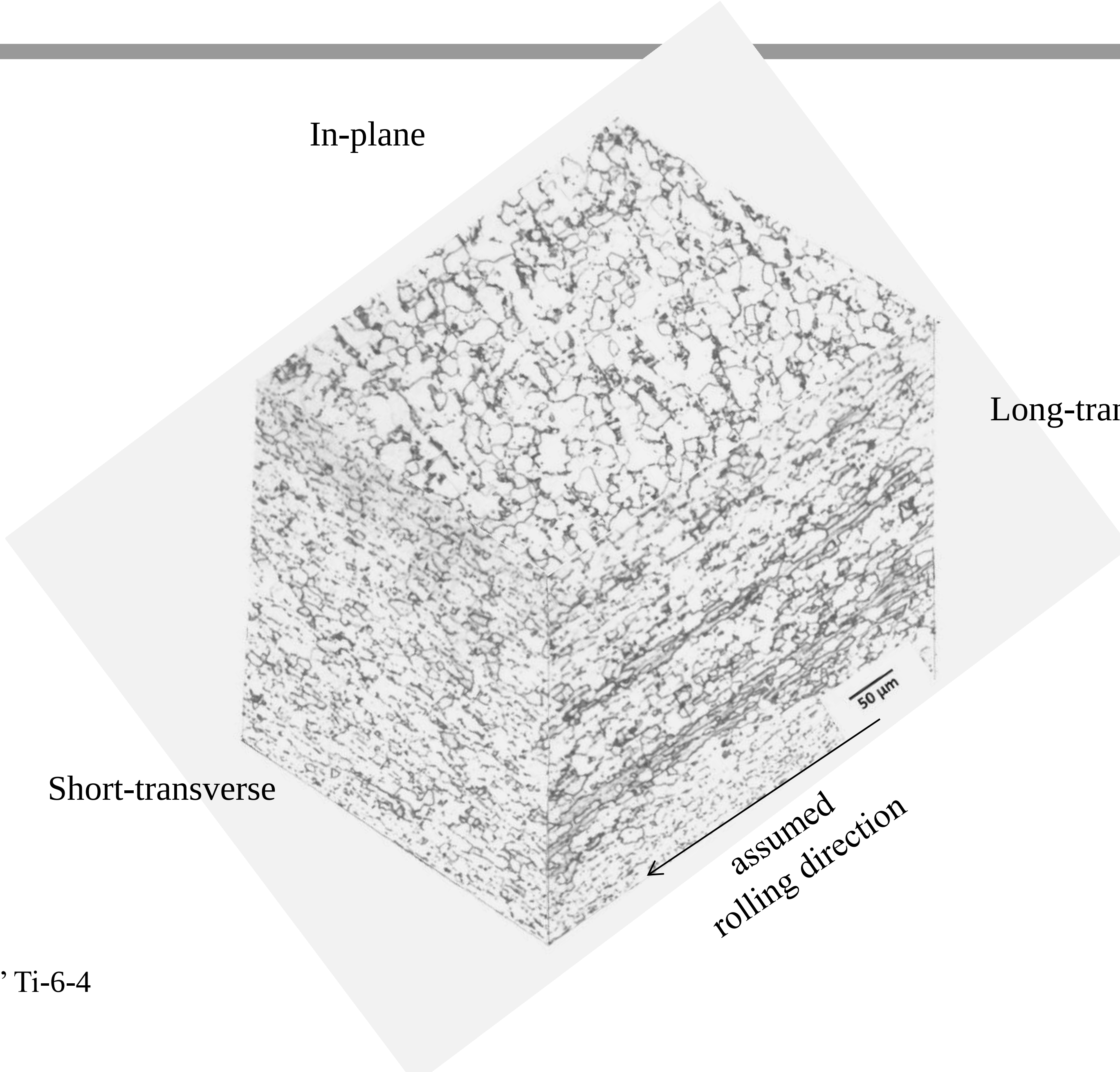
FAA-OSU-GWU-NASA Columbus 2007

Part 1 : material model

Careful material selection

- Material properties depend upon the microstructure : grain size, texture, orientation, surface quality…
- Manufacturing operations (rolling, annealing) influence the microstructure and therefore the material properties
- Specific material models may be needed for individual components
- Some microstructural aspects of the material can be studied under the electron-microscope

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V



BLM 45 0.530” Ti-6-4

Ti-6-4 Texture

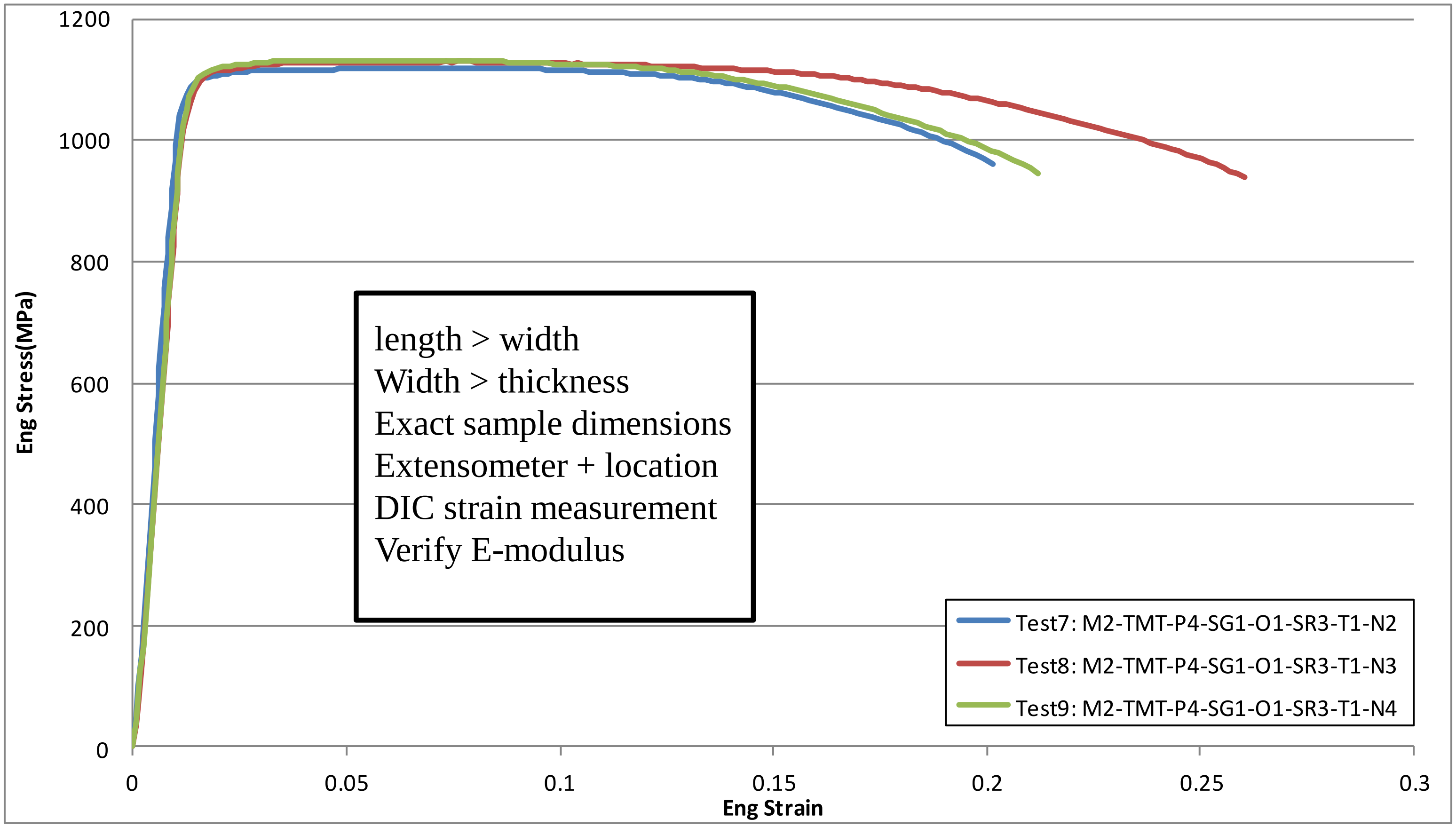
	Sample	Texture Index	Predominant Texture Type	Degrees off-center
Batch 2	BLM 45 0.270”	1.24	Transverse	31
	BLM 45 0.530”	1.13	Basal	27
	BLM 46 0.270”	1.33	Transverse	24
	BLM 47 0.425”	1.54	Transverse	-
Batch 1	0.09”	1.40	Transverse	-
	0.135”	1.17	Basal	30
	0.25”	1.48	Basal	18
	0.50”	1.03	Basal, Transverse	-

- **Texture index** denotes degree of anisotropy

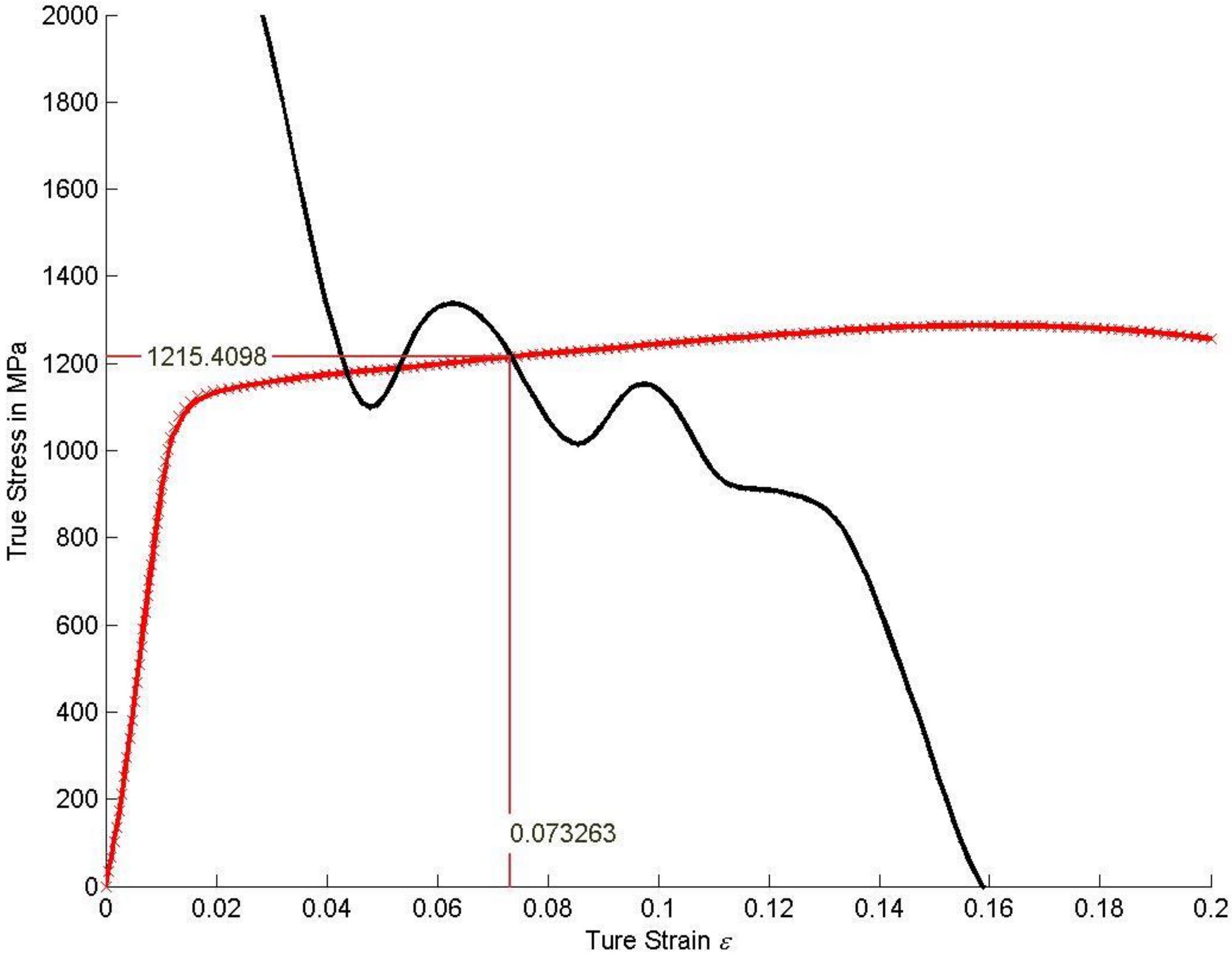
  Index ranges from 1 (isotropic) to ∞ (single crystal)

  Aluminum foil (highly textured) has an index of 4.14

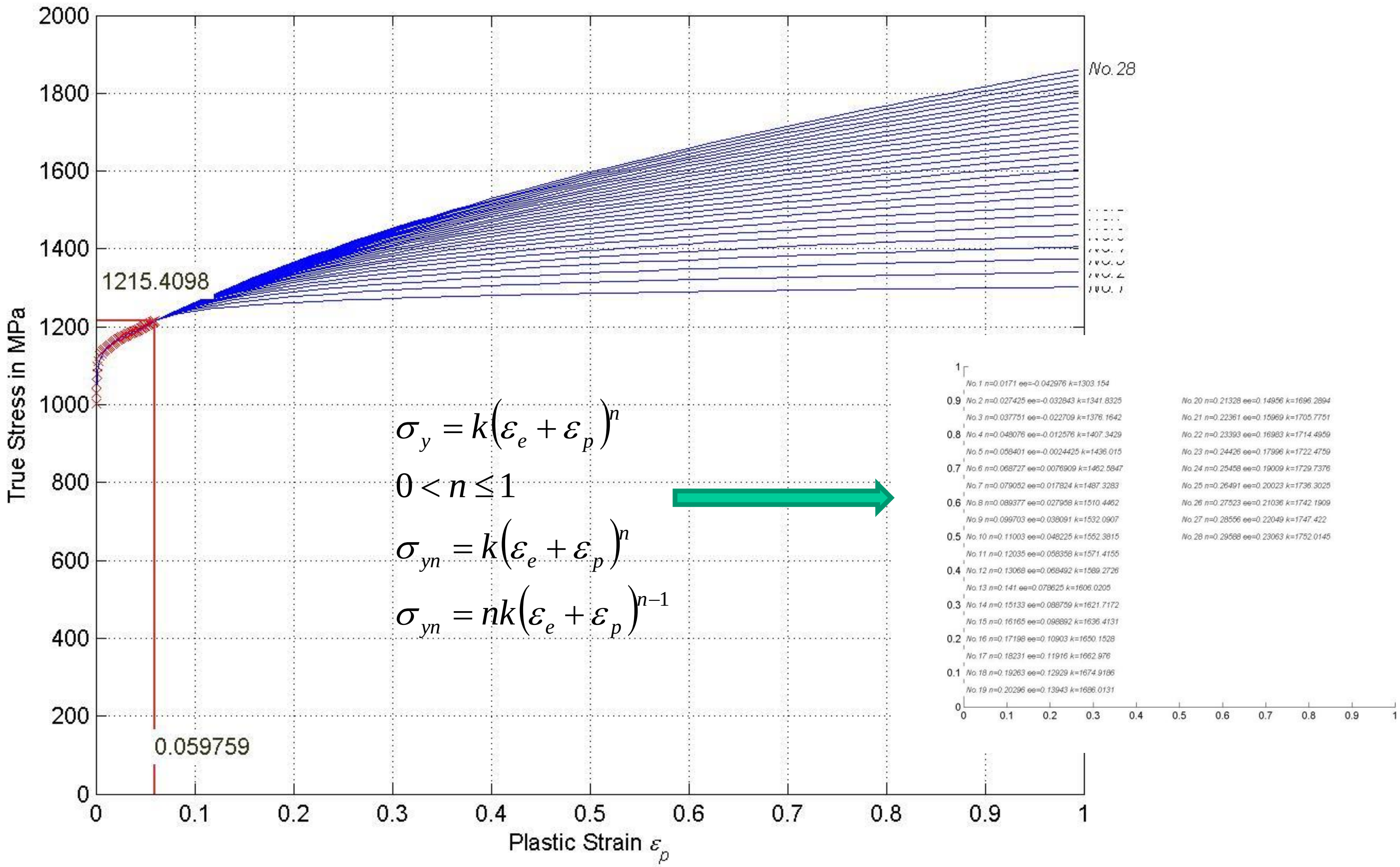
Example of Ti-6-4 0.5” plate stock at strain rate = 1/s



Example of Ti-6-4 at strain rate = 1/s



Example of Ti-6-4 at strain rate = 1/s



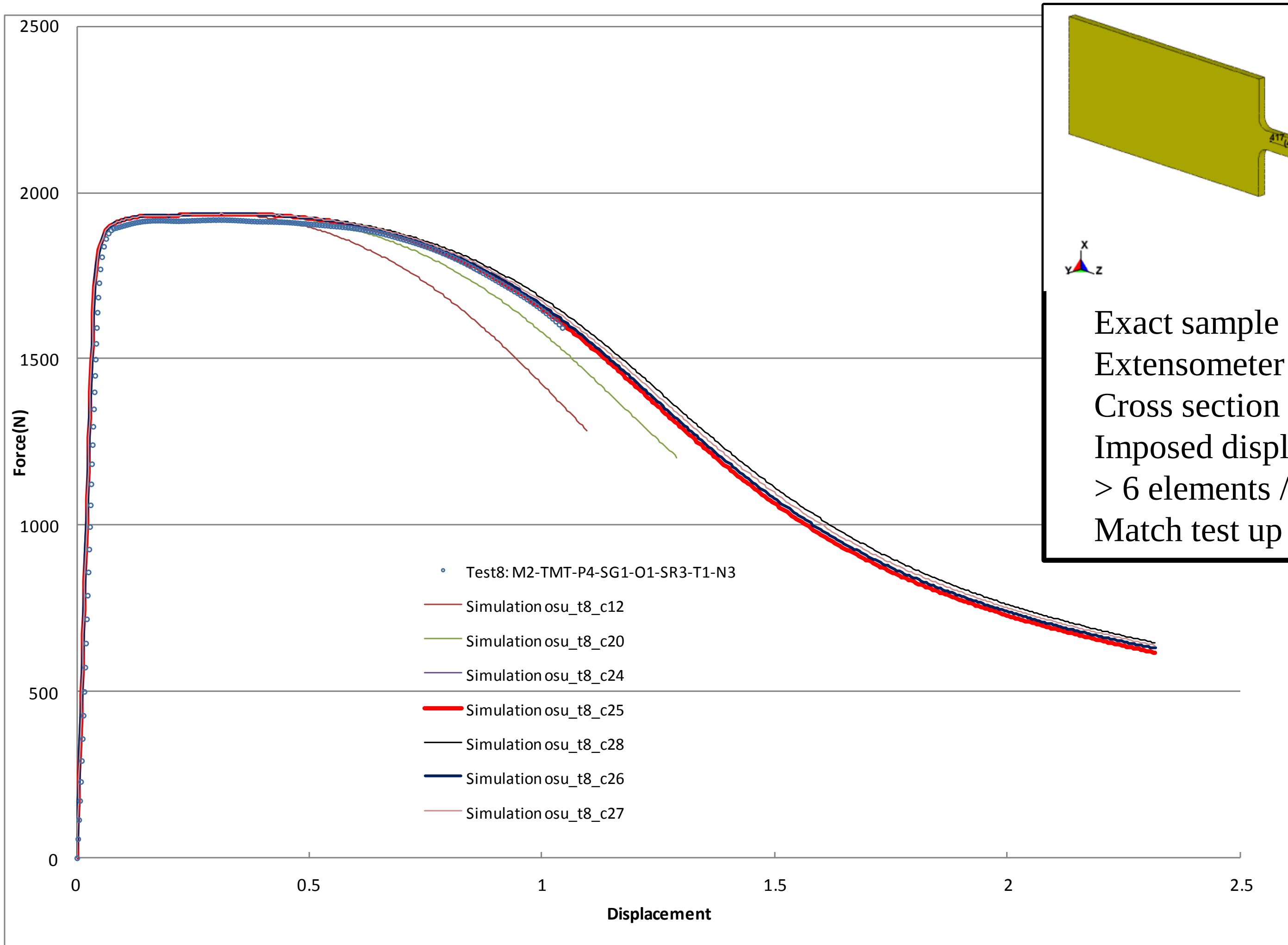
$$\sigma_y = k\left(\varepsilon_e + \varepsilon_p\right)^n$$

$$0 < n \leq 1$$

$$\sigma_{yn} = k\left(\varepsilon_e + \varepsilon_p\right)^n$$

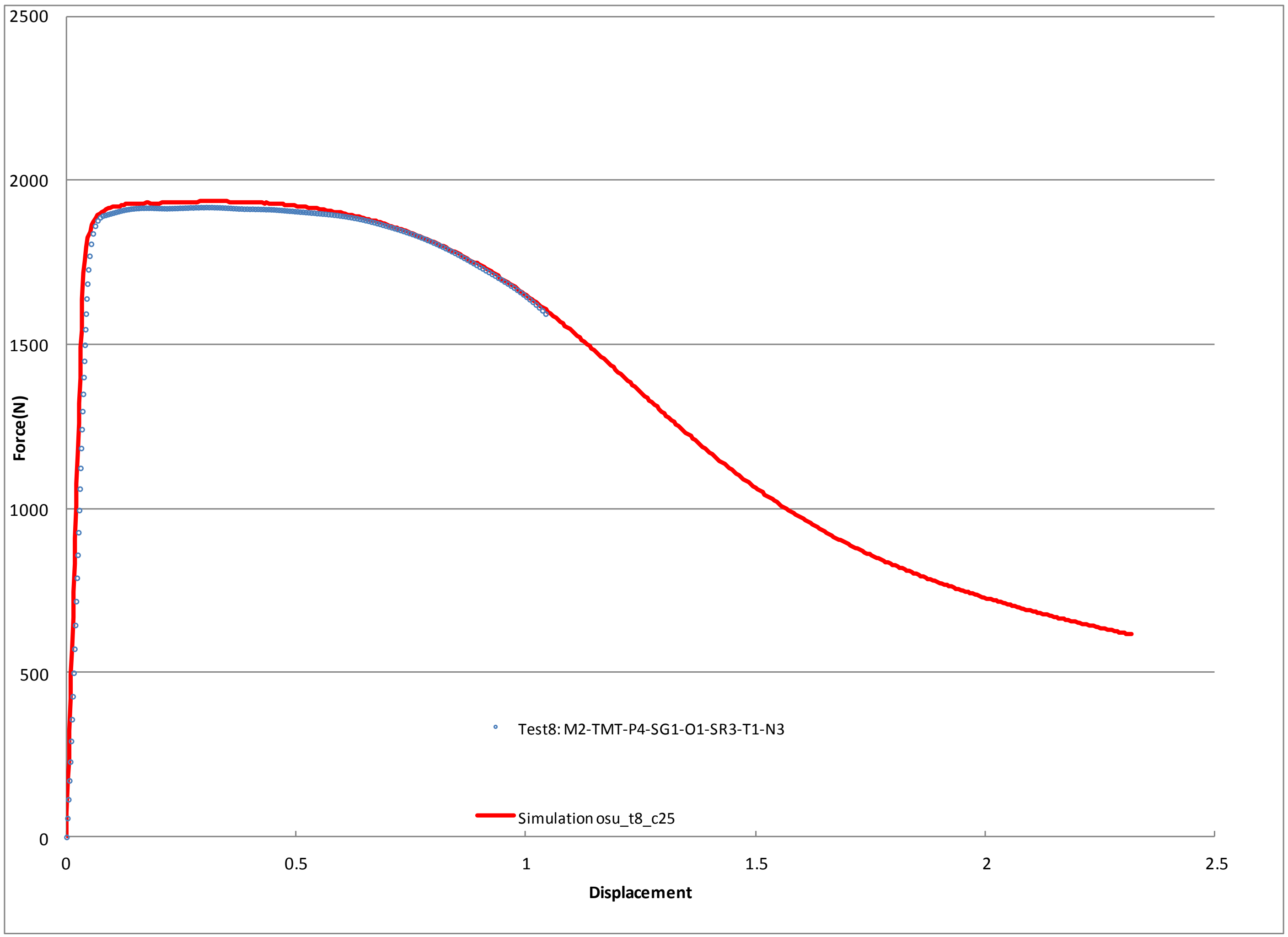
$$\sigma_{yn} = nk\left(\varepsilon_e + \varepsilon_p\right)^{n-1}$$

Example of Ti-6-4 at strain rate = 1/s

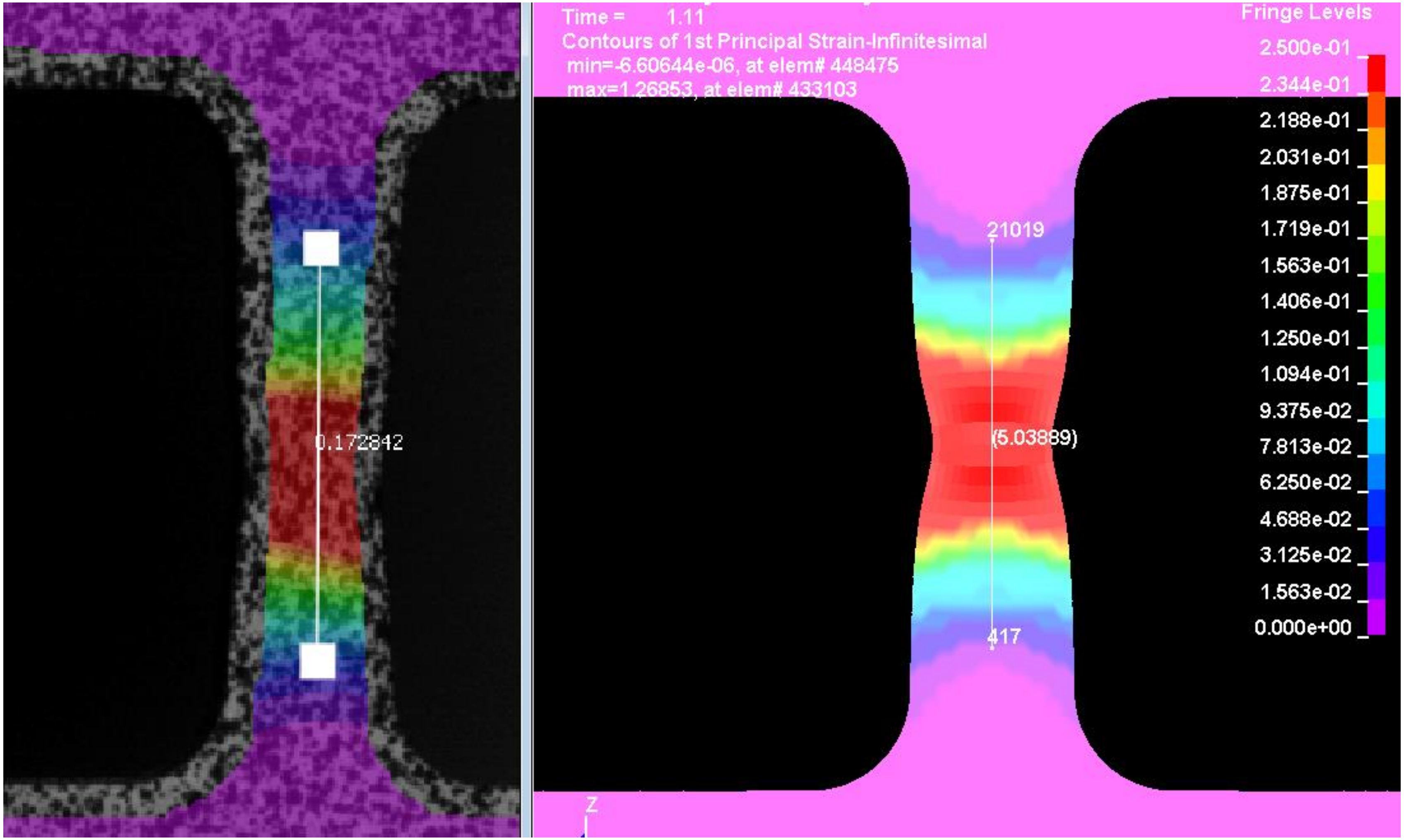


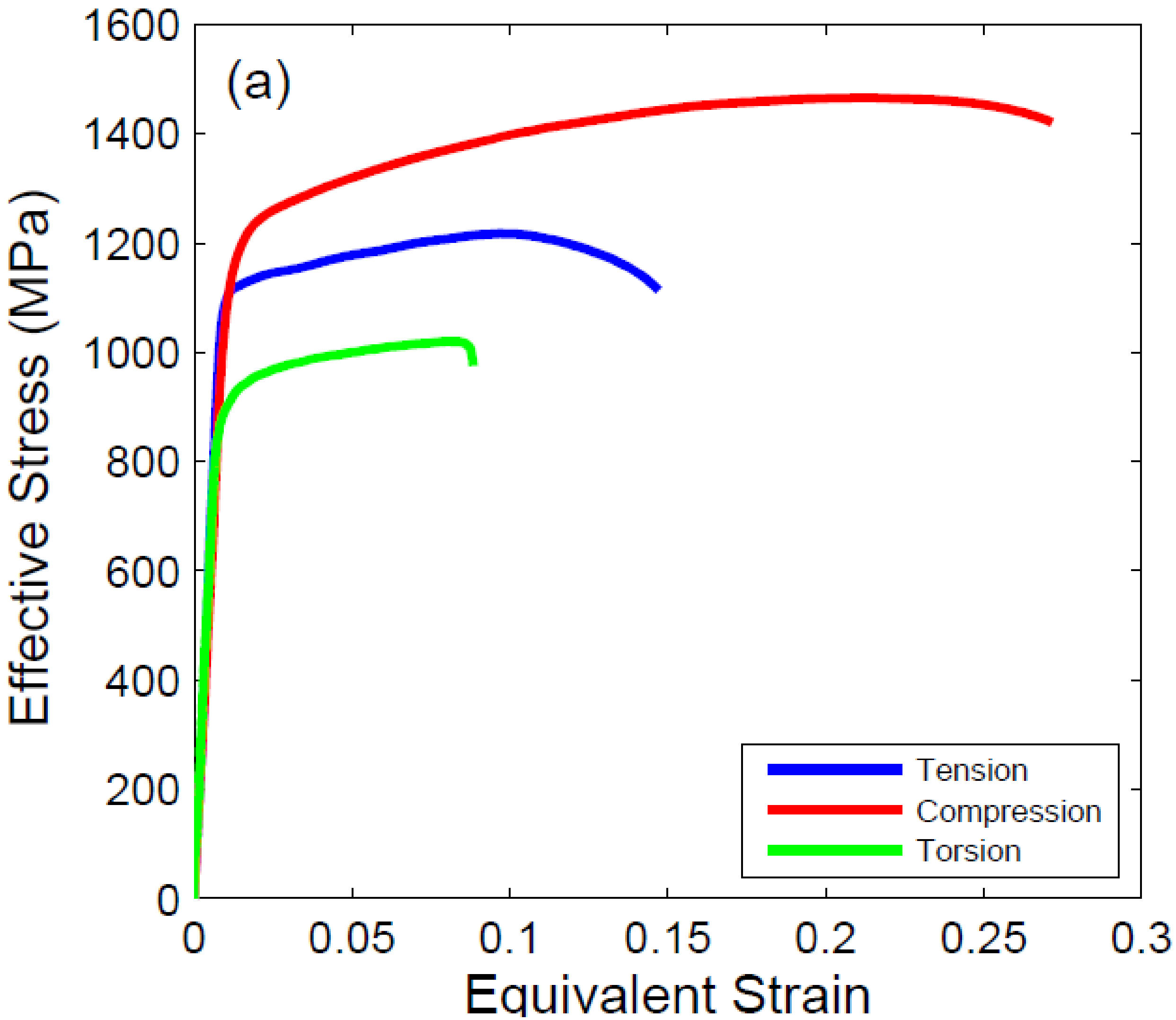
Exact sample dimensions
Extensometer base points
Cross section
Imposed displacement (speed)
> 6 elements / width
Match test up to necking

Example of Ti-6-4 at strain rate = 1/s



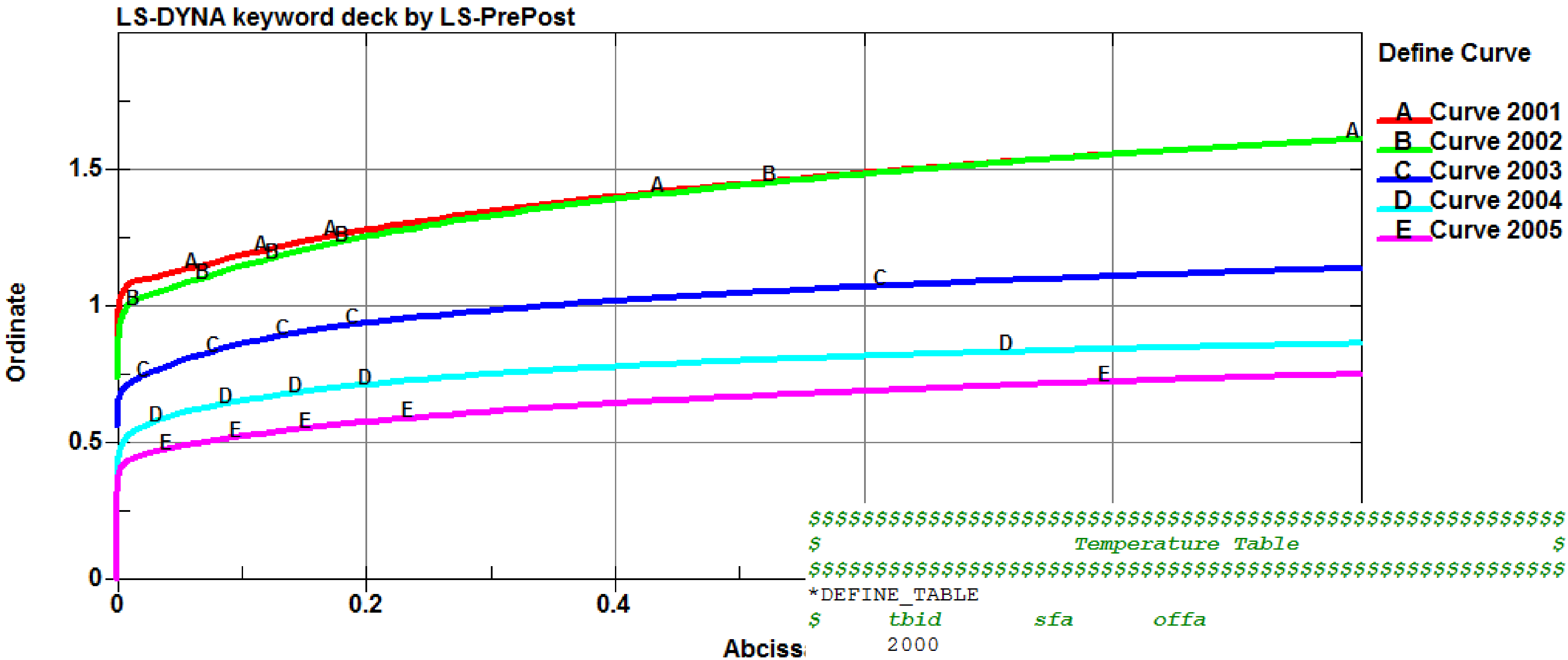
Example of Ti-6-4 at strain rate = 1/s





- Plate asymmetry
- MAT_224 uses tension data to generate yield curve
    - Tension/Torsion will be over estimated
    - Compression/Torsion will be under estimated
- MAT_224_GYS allows for asymmetrical input

Temperature Curves (table 2000)

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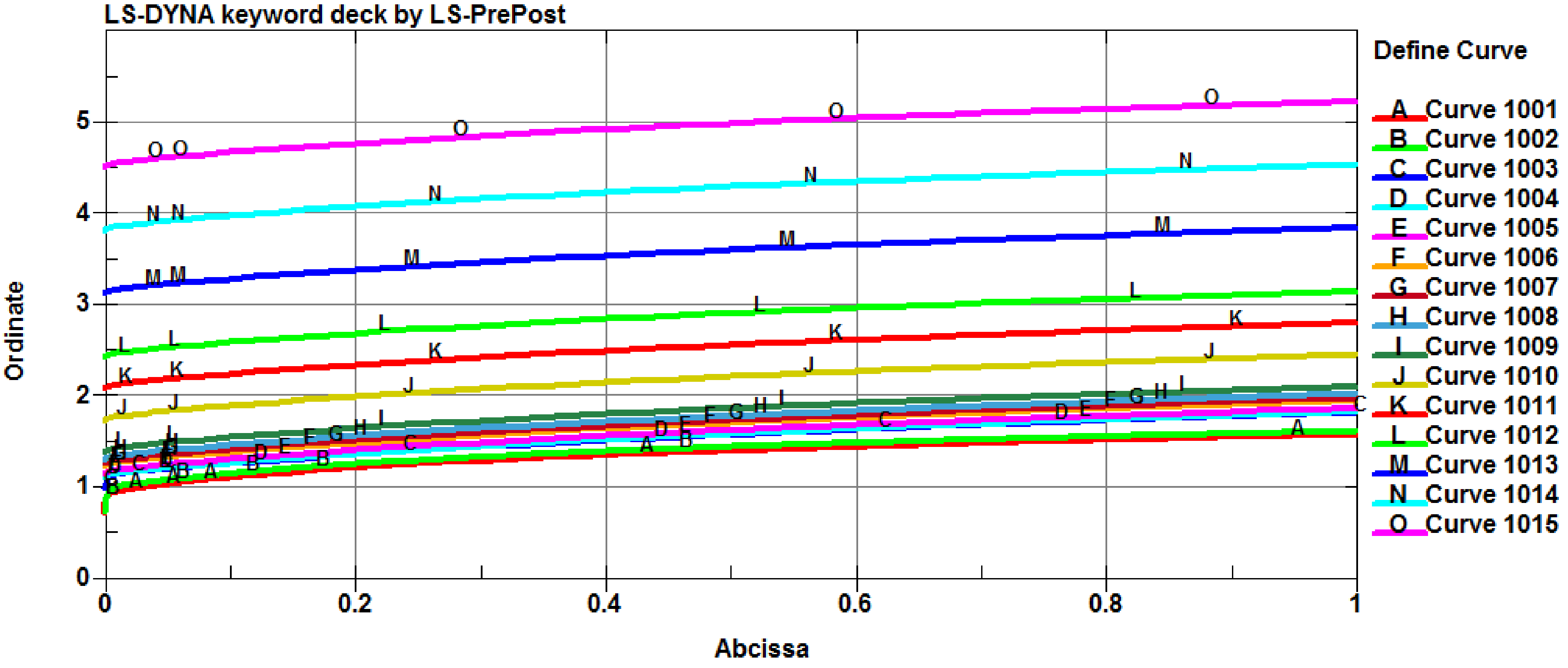
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$                         Temperature Table                                    $
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*DEFINE_TABLE
$      tbid       sfa      offa
       2000
$                 value              curveid
                 223.15                 2001
                 293.00                 2002
                 473.15                 2003
                 673.15                 2004
                 873.15                 2005
                1877.00                 2006
                2500.00                 2007
```

Zero curve (melt) ←

Strain Rate Curves (table 1000)



Covered the range from 0.0001/s to 50000/s

conclusion

- Realistic material data are needed beyond necking (localisation) and up to failure if a predictive simulation with respect to failure is to be achieved
- A procedure was established allowing for reasonable accuracy as well as cost efficiency
- Value of DIC cannot be overestimated

adiabatic instability

Shear bands
Adiabatic vs isothermal instabilities

adiabatic instabilities and strain localisation

- **shear bands seem to be the main instability that is observed in high velocity impact phenomena**
- **plugging is caused by a thermoplastic shear instability, (so is the fragmentation of an exploding cylinder)**

Adiabatic instabilities : Shear bands

- **Typical shear band widths are 10 to 100 microns**
- **High local values of shear strain : 5 to 100**
- **Ultra high local shear strain rates : 10000/s to 1000000/s**
- **Local temperature rises several hundred degrees**
- **High propagation speeds : typically 1000 m/s**
- **Not a crack**
- **Shear bands are precursors to rupture**

- **Cfr. Tzavaras**

Adiabatic instabilities : Localisation mechanism

- **Under isothermal conditions metals strain harden**
- **Under high strain rates conditions change from isothermal to adiabatic**
- **If heat diffusion is too slow to equalize temperatures in the timescale of the loading then shear bands may occur**
- **Non-uniform strains induce non-uniform heating**
- **Hot spots are softer, cold spots are harder, this amplifies the non-uniformity of the strain field**
- **Two effects oppose the instability : heat diffusion and momentum diffusion induced by strain rate dependency**

adiabatic instabilities and strain localisation

- **Assume an elasto-plastic material with strain hardening and linear thermal softening :**

$$\sigma_y = f(\varepsilon_p)h(T) = f(\varepsilon_p)\left(1 - \frac{T - T_R}{T_M - T_R}\right)$$

- **The maximum force criterion under plane stress conditions gives :**

$$\frac{d\sigma_y}{d\varepsilon_p} = \sigma_y \frac{(4 - 3a - 3a^2 + 4a^3)}{4(1 + a^2 - a)^{3/2}} \qquad a = \frac{\sigma_2}{\sigma_1}$$

- **With special cases for uniaxial tension and pure shear :**

$$\frac{d\sigma_y}{d\varepsilon_p} = \sigma_y \qquad a = 0$$

$$\frac{d\sigma_y}{d\varepsilon_p} = 0 \qquad a = -1$$

- **The previous formulas contain total derivatives : yield stress is considered a function of equivalent plastic strain AND temperature**

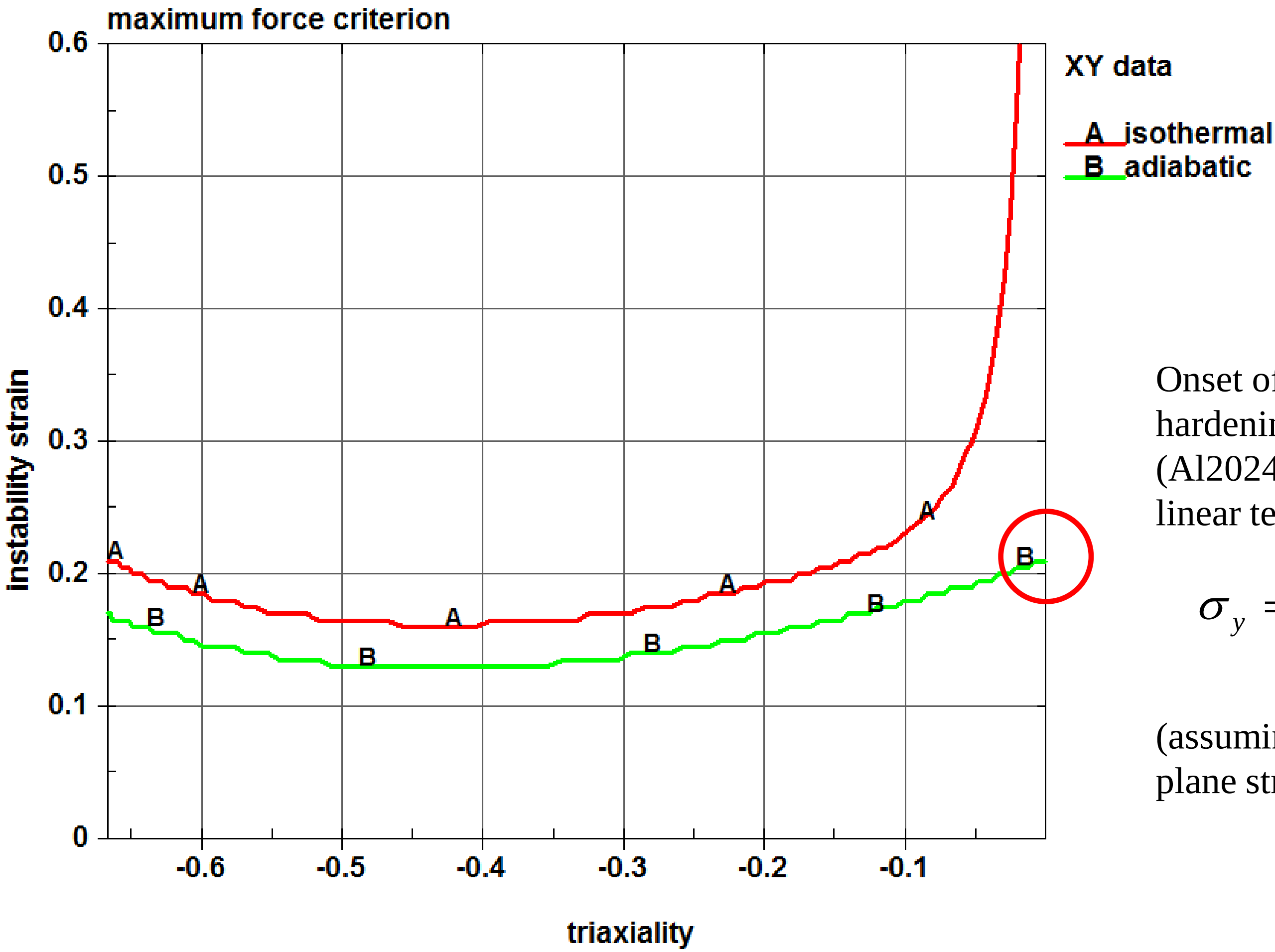
adiabatic instabilities and strain localisation

- **We can derive an adiabatic instability condition :**

$$\left.\begin{aligned} \frac{d\sigma_y}{d\varepsilon_p} &= \sigma_y \frac{\left(4-3a-3a^2+4a^3\right)}{4\left(1+a^2-a\right)^{3/2}} \\ \frac{d\sigma_y}{d\varepsilon_p} &= \frac{\partial\sigma_y}{\partial\varepsilon_p} + \frac{\partial\sigma_y}{\partial T}\frac{dT}{d\varepsilon_p} \end{aligned}\right\} \Rightarrow \frac{\partial\sigma_y}{\partial\varepsilon_p} = \sigma_y \frac{\left(4-3a-3a^2+4a^3\right)}{4\left(1+a^2-a\right)^{3/2}} - \frac{\partial\sigma_y}{\partial T}\frac{dT}{d\varepsilon_p}$$

$$\left.\begin{aligned} dT &= \frac{dW}{\rho C_p} = \frac{\sigma_y d\varepsilon_p}{\rho C_p} \Rightarrow \frac{dT}{d\varepsilon_p} = \frac{\sigma_y}{\rho C_p} \\ \frac{\partial\sigma_y}{\partial T} &= -\frac{f\left(\varepsilon_p\right)}{T_M - T_R} \\ \frac{\partial\sigma_y}{\partial\varepsilon_p} &= \frac{\partial f\left(\varepsilon_p\right)}{\partial\varepsilon_p}\frac{T-T_R}{T_M-T_R} \end{aligned}\right\} \Rightarrow \boxed{\frac{\partial f\left(\varepsilon_p\right)}{\partial\varepsilon_p} = f\left(\varepsilon_p\right)\frac{\left(4-3a-3a^2+4a^3\right)}{4\left(1+a^2-a\right)^{3/2}} + \frac{f^2\left(\varepsilon_p\right)}{\left(T_M-T_R\right)\rho C_p}}$$

adiabatic instabilities and strain localisation



Onset of instability for a strain hardening elasto-plastic material (Al2024) with linear temperature dependency :

$$\sigma_y = f\left(\varepsilon_p\right)\frac{T - T_R}{T_M - T_R}$$

(assuming small elastic strains and plane stress)

adiabatic instabilities and strain localisation

- **Analytical solution for the onset of shear banding in the case of a Johnosn-Cook law with linear temperature dependency :**

$$\left.\begin{aligned} &\frac{d\sigma_y}{d\varepsilon_p} = 0 \\ &\frac{d\sigma_y}{d\varepsilon_p} = \frac{\partial\sigma_y}{\partial\varepsilon_p} + \frac{\partial\sigma_y}{\partial T}\frac{dT}{d\varepsilon_p} \end{aligned}\right\} \Rightarrow \frac{\partial\sigma_y}{\partial\varepsilon_p} = -\frac{\partial\sigma_y}{\partial T}\frac{dT}{d\varepsilon_p}$$

$$dT = \frac{dW}{\rho C_p} = \frac{\sigma_y d\varepsilon_p}{\rho C_p} \Rightarrow \frac{dT}{d\varepsilon_p} = \frac{a + b\varepsilon_p^n}{\rho C_p}$$

$$\frac{\partial\sigma_y}{\partial T} = -\frac{a + b\varepsilon_p^n}{T_M - T_R} \left(\varepsilon_p = cte\right)$$

$$\Rightarrow \frac{\partial\sigma_y}{\partial\varepsilon_p} = -\frac{\partial\sigma_y}{\partial T}\frac{dT}{d\varepsilon_p} \Rightarrow bn\varepsilon_p^{n-1} = \frac{\left(a + b\varepsilon_p^n\right)^2}{\left(T_M - T_R\right)\rho C}$$

adiabatic instabilities and strain localisation

- **Analytical solution for the onset of adiabatic diffuse necking in the case of a Johnosn-Cook law with linear temperature dependency :**

$$\left.\begin{aligned} \frac{d\sigma_y}{d\varepsilon_p} &= \sigma_y \\ \frac{d\sigma_y}{d\varepsilon_p} &= \frac{\partial\sigma_y}{\partial\varepsilon_p} + \frac{\partial\sigma_y}{\partial T}\frac{dT}{d\varepsilon_p} \end{aligned}\right\} \Rightarrow \frac{\partial\sigma_y}{\partial\varepsilon_p} = \sigma_y - \frac{\partial\sigma_y}{\partial T}\frac{dT}{d\varepsilon_p}$$

$$dT = \frac{dW}{\rho C_p} = \frac{\sigma_y d\varepsilon_p}{\rho C_p} \Rightarrow \frac{dT}{d\varepsilon_p} = \frac{a + b\varepsilon_p^n}{\rho C_p}$$

$$\frac{\partial\sigma_y}{\partial T} = -\frac{a + b\varepsilon_p^n}{T_M - T_R}\left(\varepsilon_p = cte\right)$$

$$\Rightarrow \frac{\partial\sigma_y}{\partial\varepsilon_p} = \sigma_y - \frac{\partial\sigma_y}{\partial T}\frac{dT}{d\varepsilon_p} \Rightarrow bn\varepsilon_p^{n-1} = \left(a + b\varepsilon_p^n\right) + \frac{\left(a + b\varepsilon_p^n\right)^2}{\left(T_M - T_R\right)\rho C}$$

Material instabilities and strain localisation

- **example for quasistatic localisation plastic strain values :**

$$\left.\begin{aligned} a &= 0.2GPa \\ b &= 0.6GPa \\ n &= 0.4 \\ T_M - T_R &= 775 - 293 \\ \rho &= 7.8E-6kg/mm^3 \\ C_p &= 445kNmm/kg^\circ K \end{aligned}\right\} \Rightarrow \begin{cases} \varepsilon_p = 0.254 & \text{isothermal tension} \\ \varepsilon_p = 0.186 & \text{adiabatic tension} \\ \varepsilon_p = 0.299 & \text{adiabatic shear} \end{cases}$$

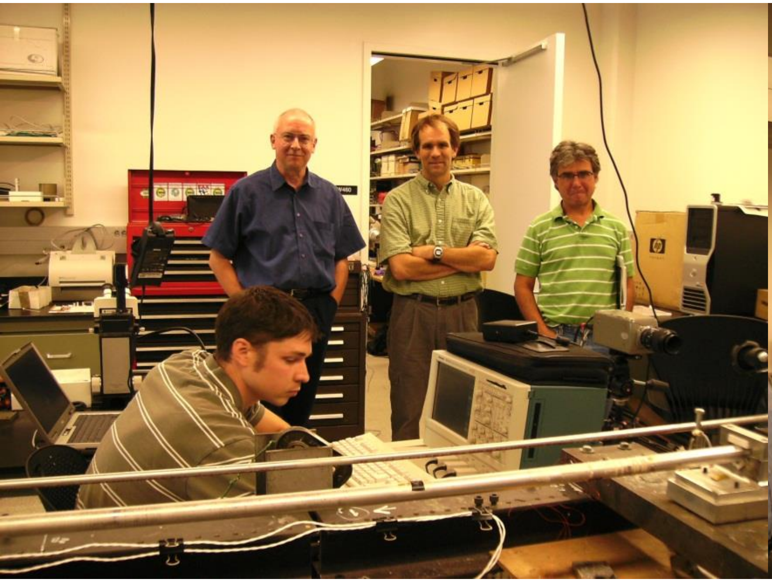
conclusion

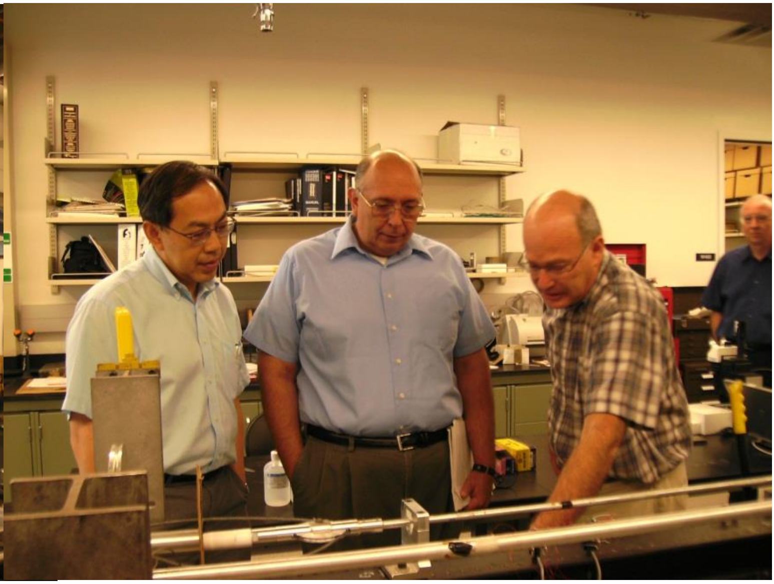
- Triaxiality dependent regularisation needs to be adapted to the conditions of the impact (temperature, rate…)
- Every material needs an individual assessment with respect to occurrence of plastic instability
- For a predictive simulation with respect to failure, the mesh size must take the width of the shear band into account
- The width of the shear band depends a.o. on the hardness and strength of the material (see reference)
- Depending on the width of the shear band (10 to 50 micron) the number of elements over the thickness of the target plate needed for a failure simulation can be 100 or more (see reference)

references

- **Are numerical simulations of ballistic impact predictive ? Borvik, Hopperstad, Langseth, Berstad, 2011**

Development of a material and failure model for Ti-6-4

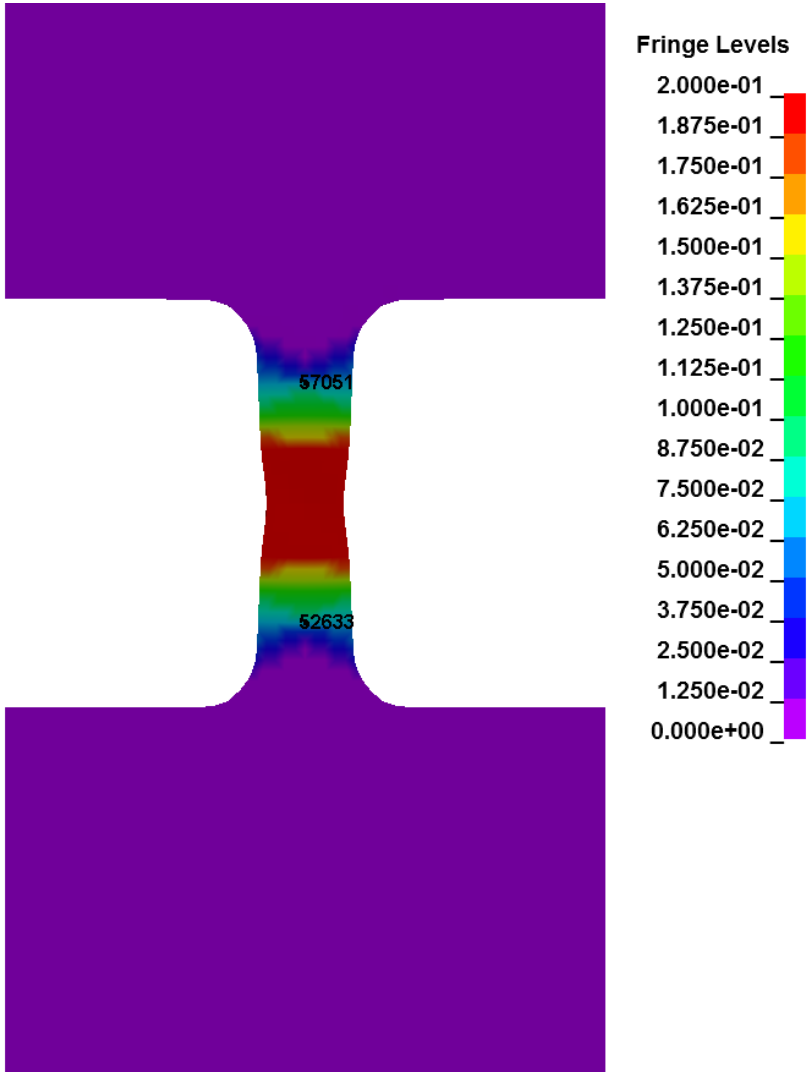


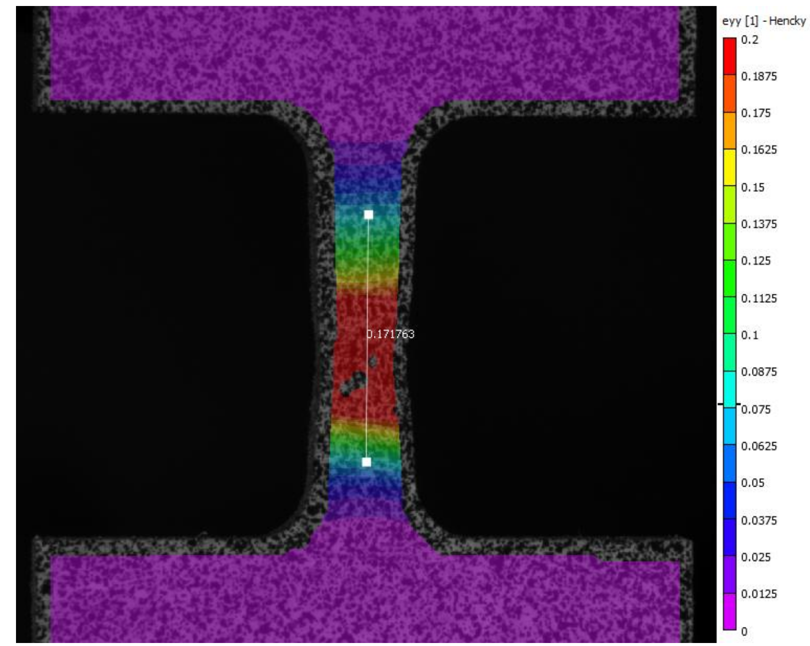


FAA-OSU-GWU-NASA Columbus 2007

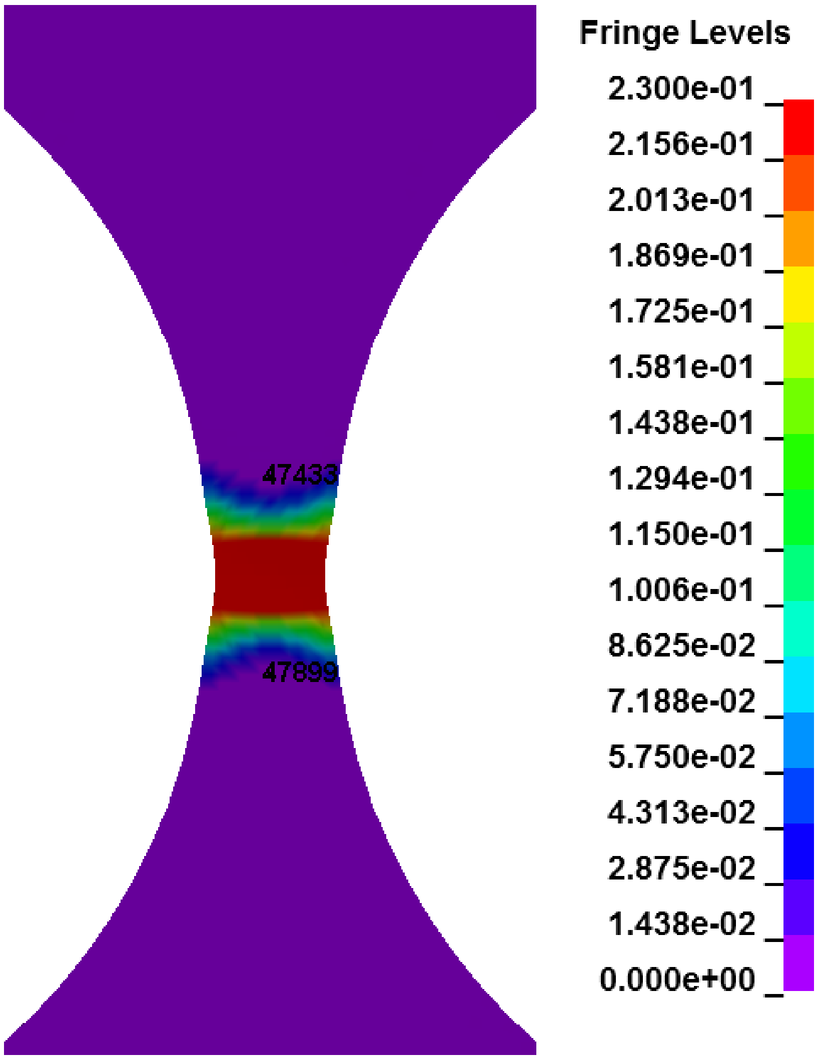
Part 2 : failure model

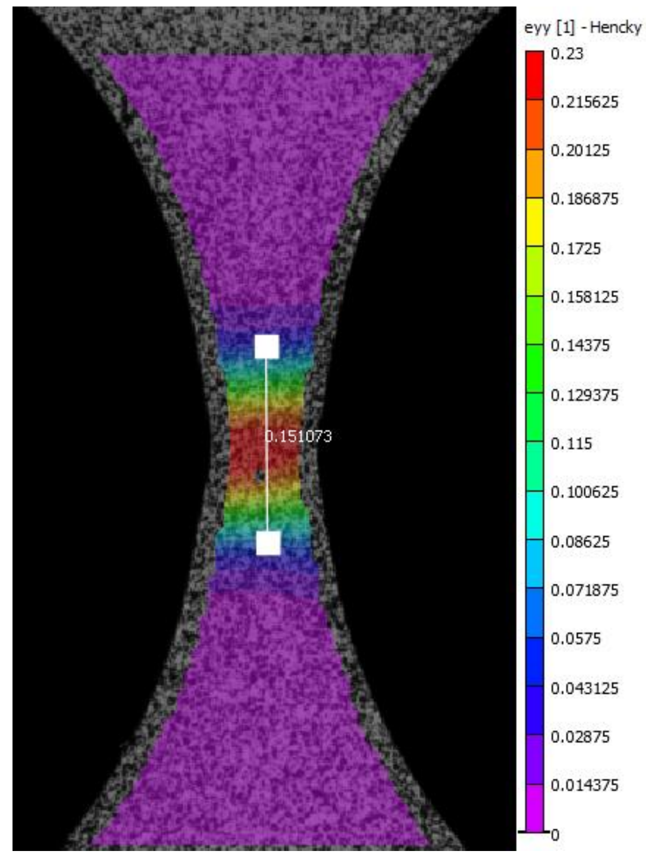
DIC Comparison – Plane Stress 1



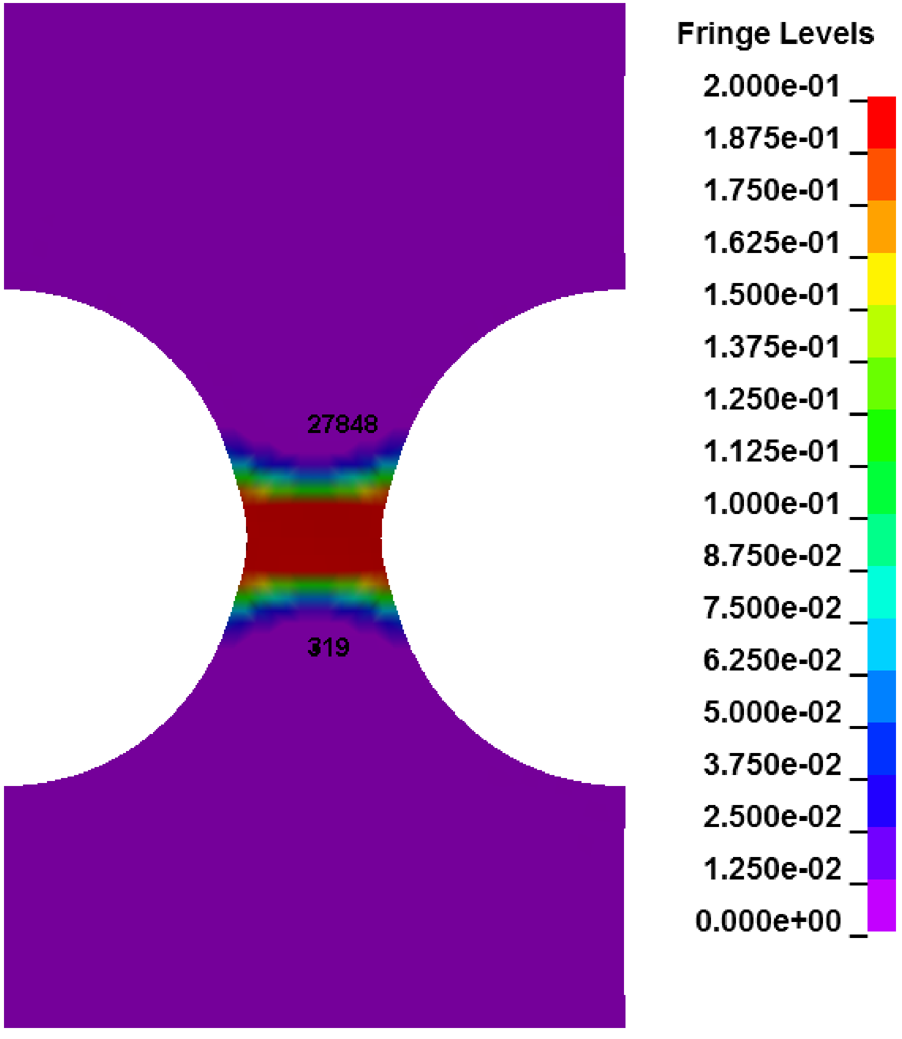


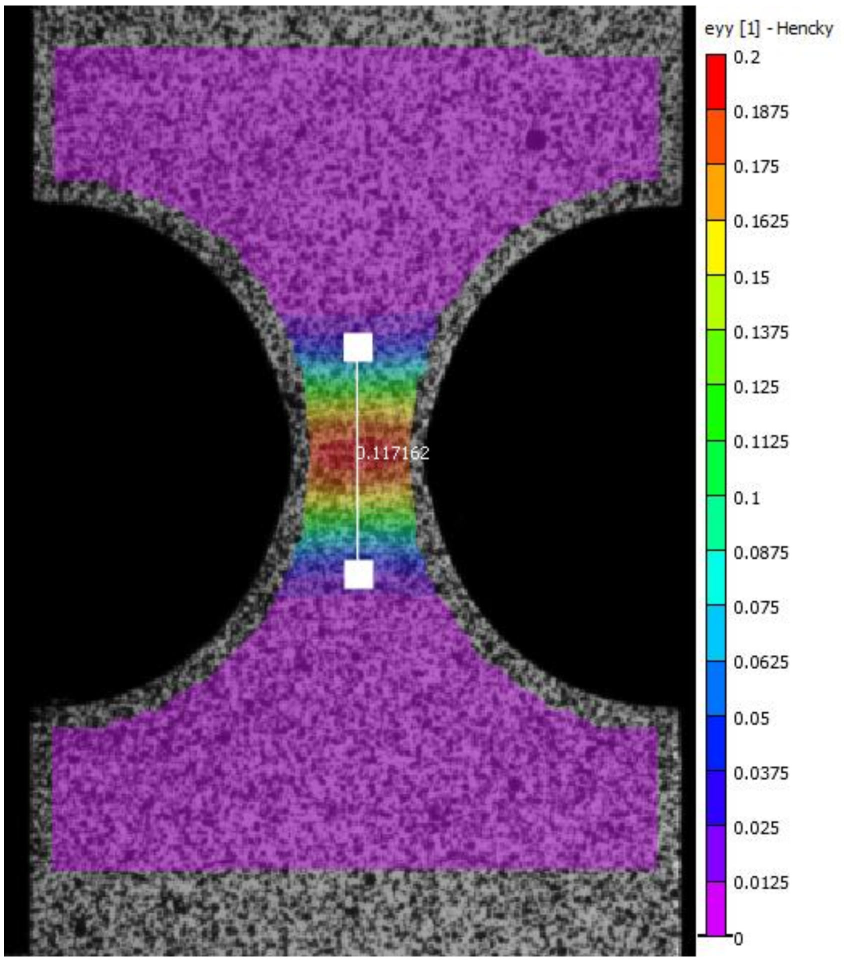
DIC Comparison – Plane Stress 2



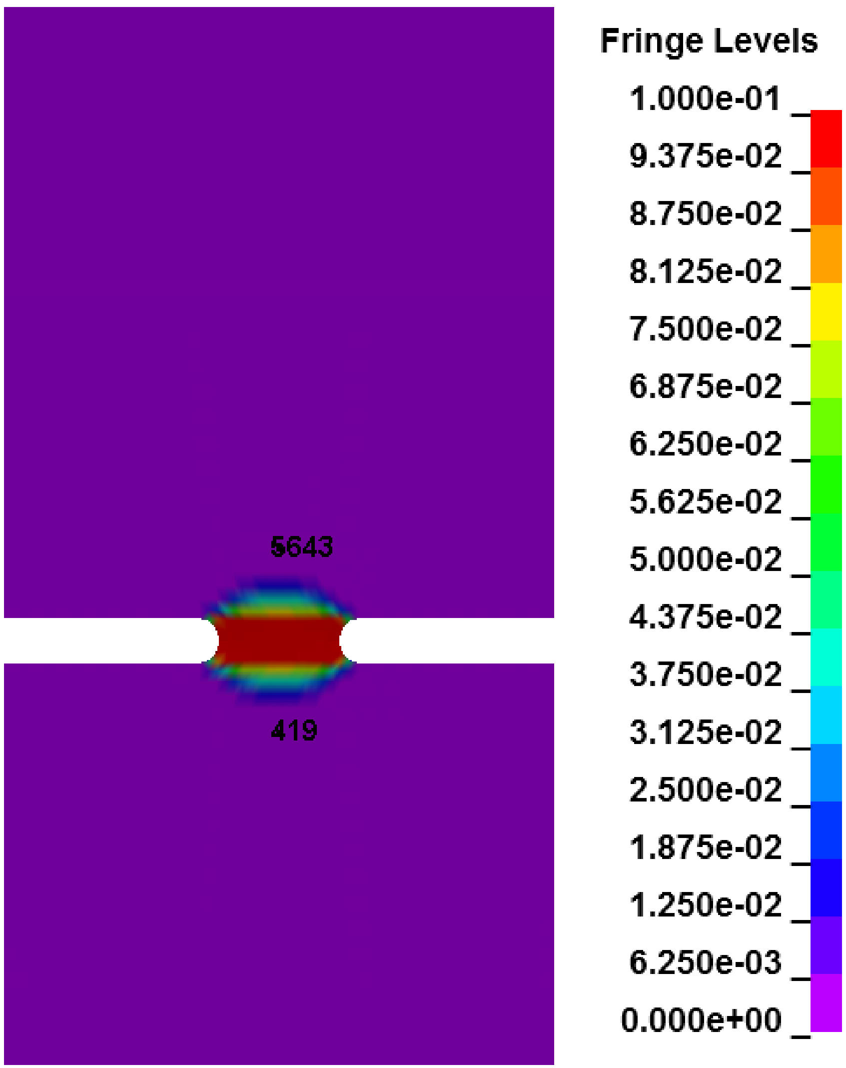


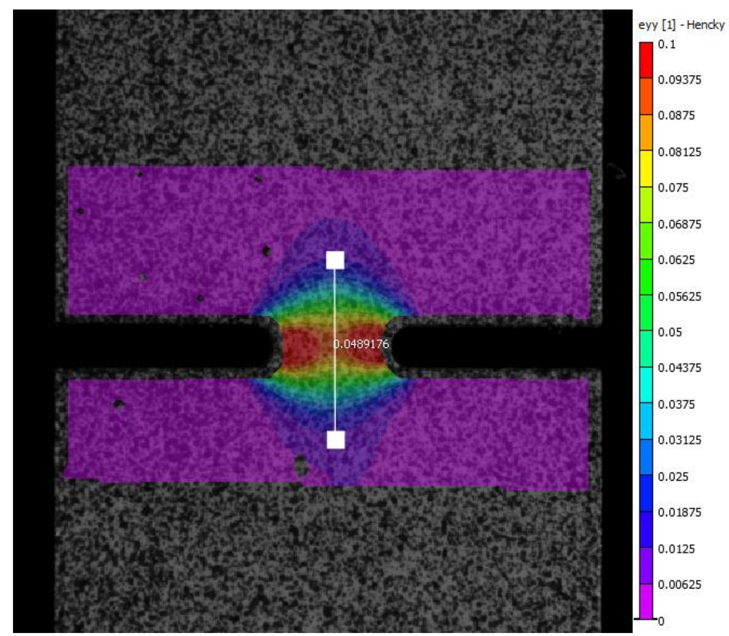
DIC Comparison – Plane Stress 3



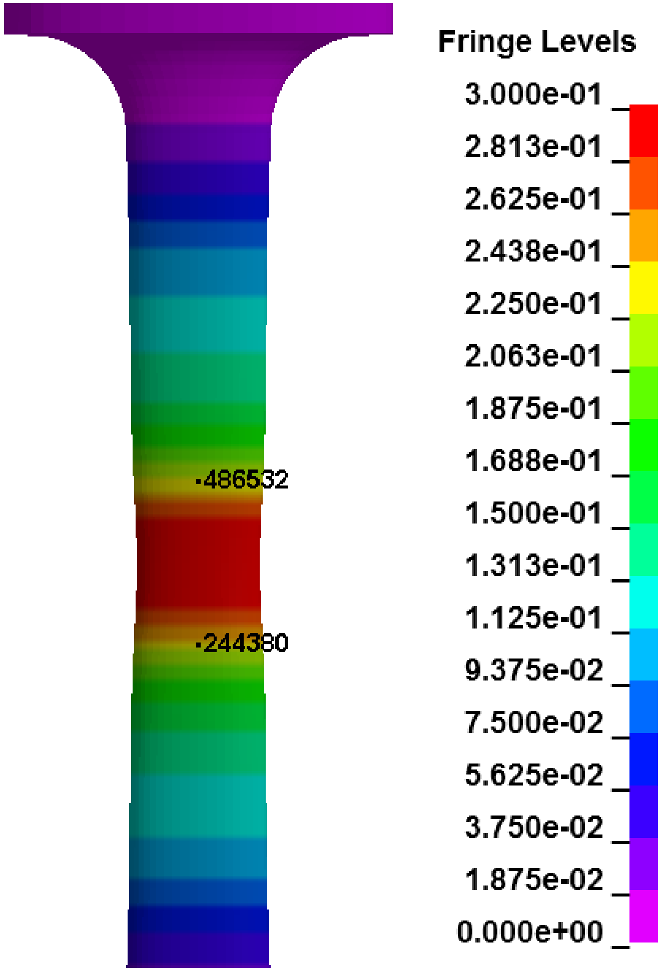


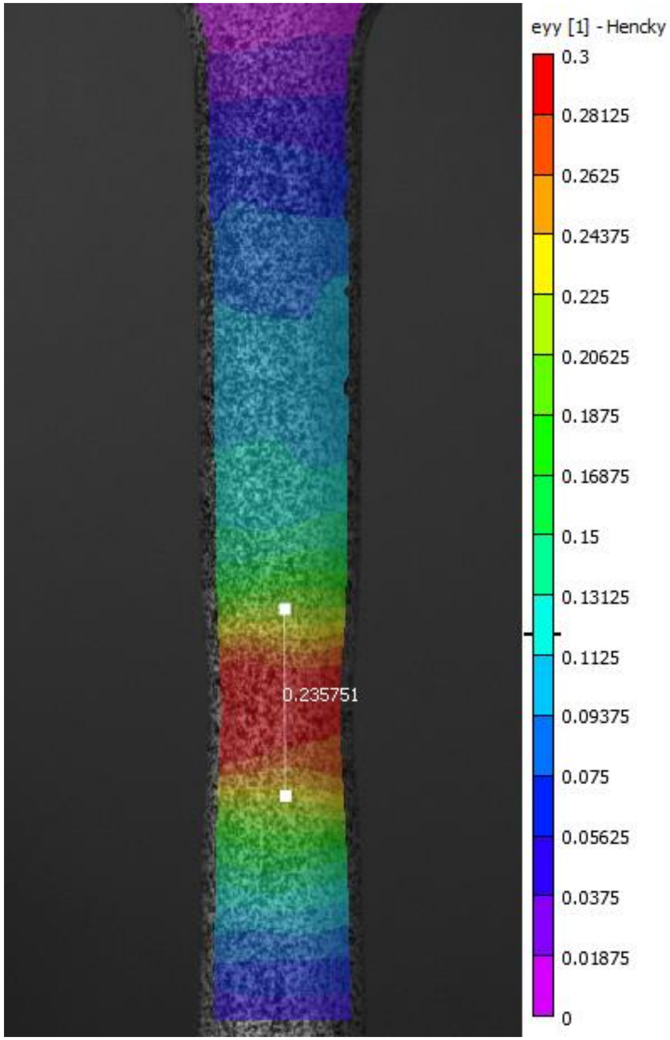
DIC Comparison – Plane Stress 4



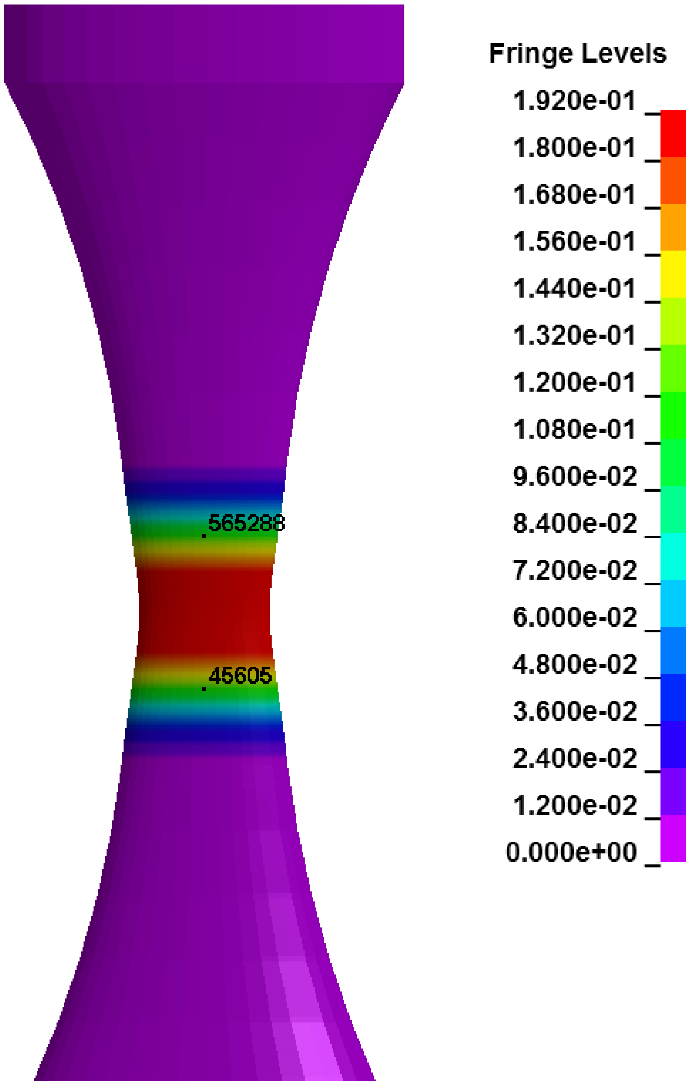


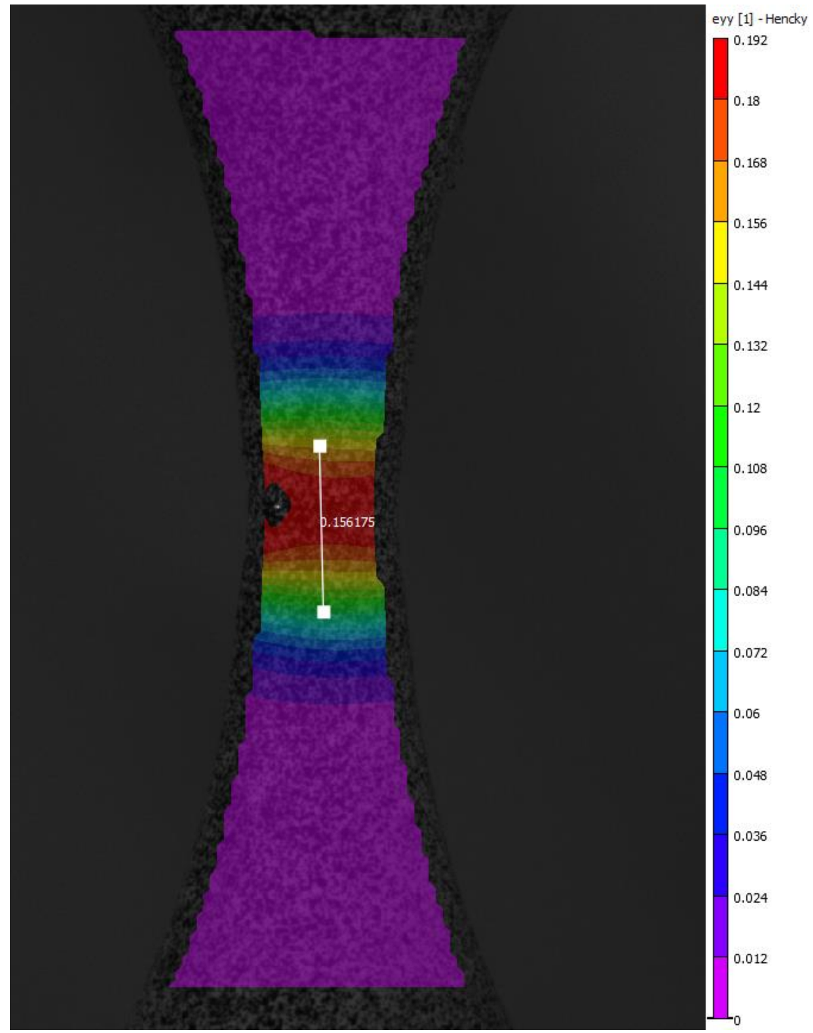
DIC Comparison – Axisymmetric 1



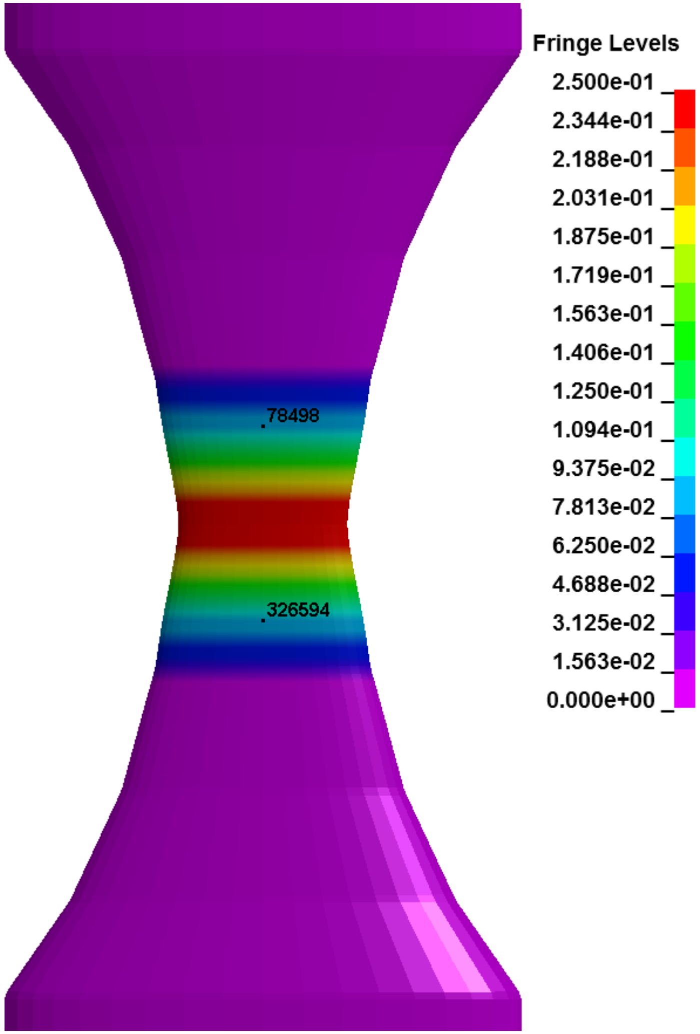


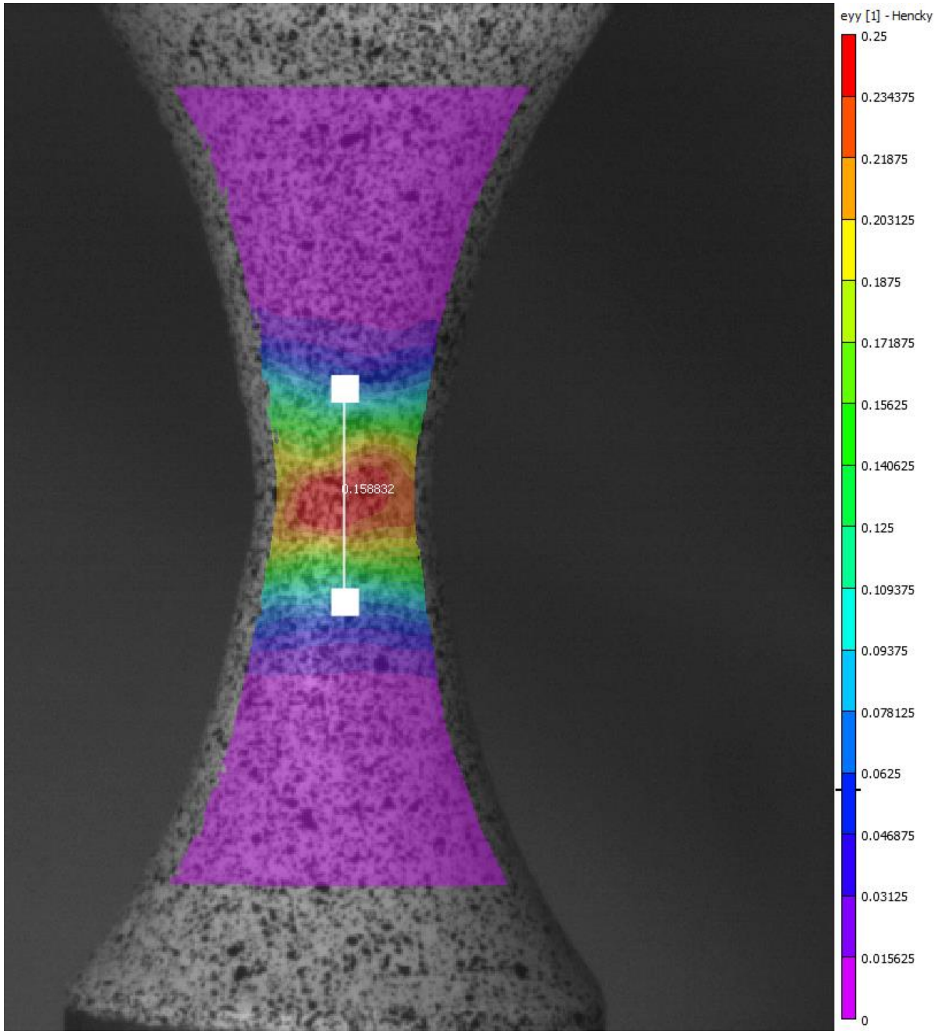
DIC Comparison – Axisymmetric 2



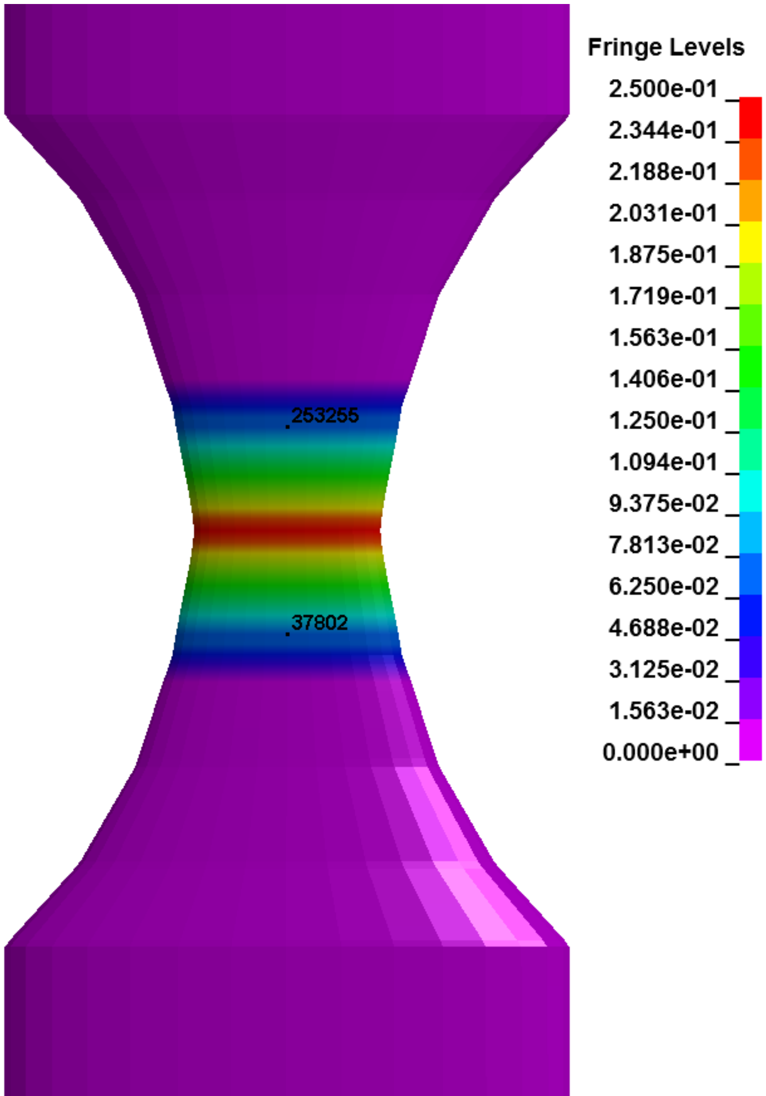


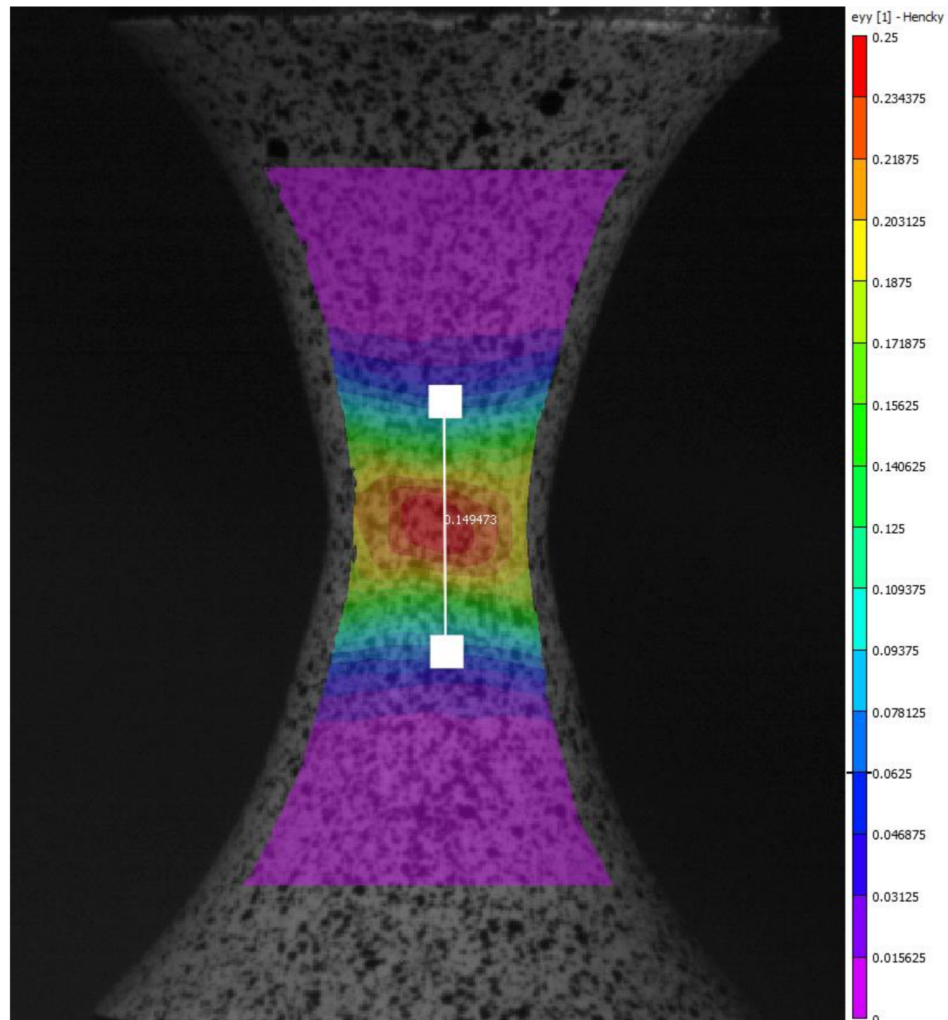
DIC Comparison – Axisymmetric 3



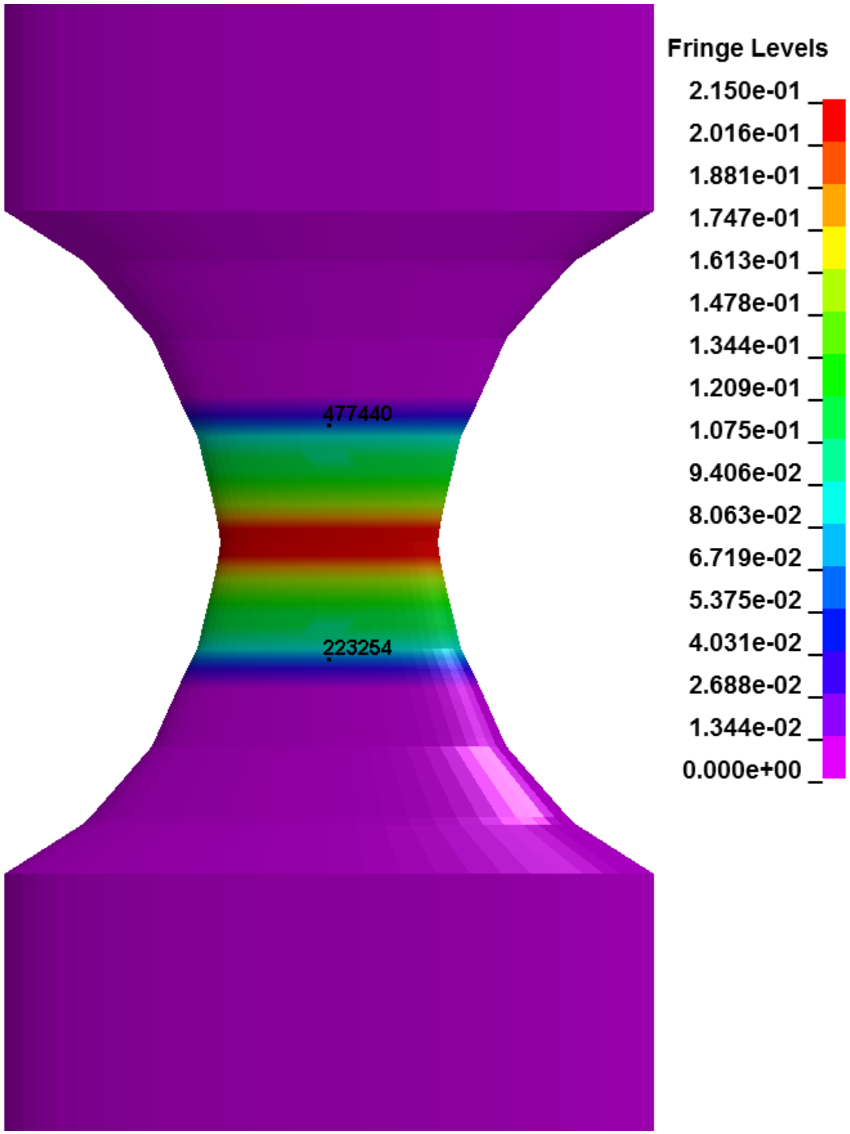


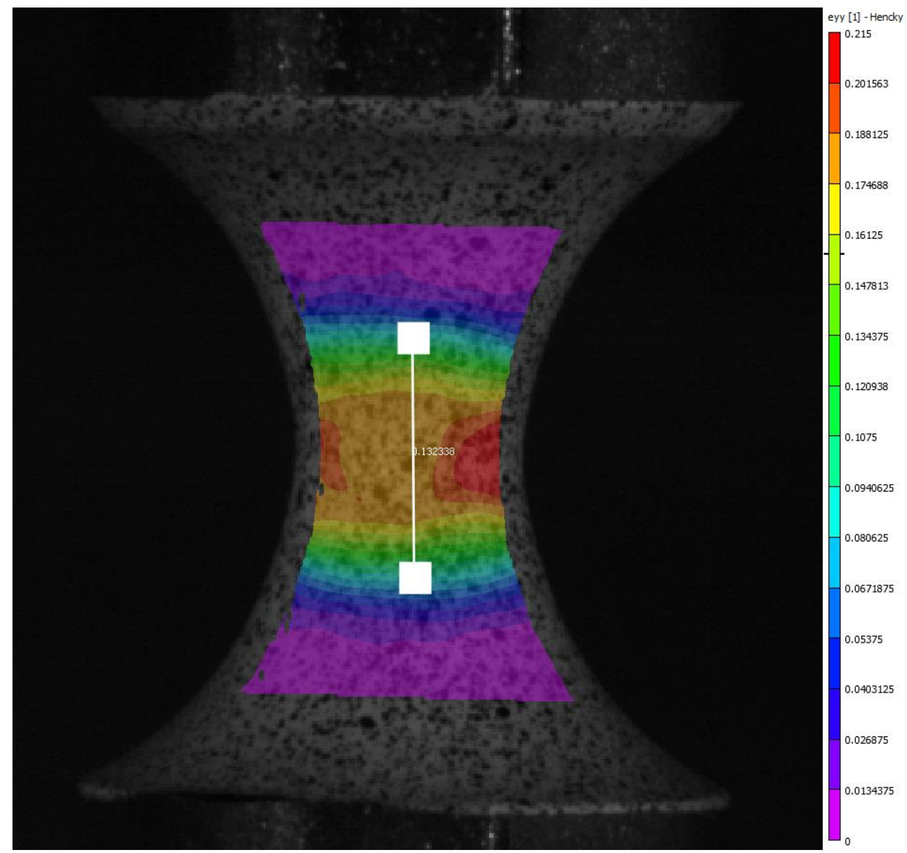
DIC Comparison – Axisymmetric 4



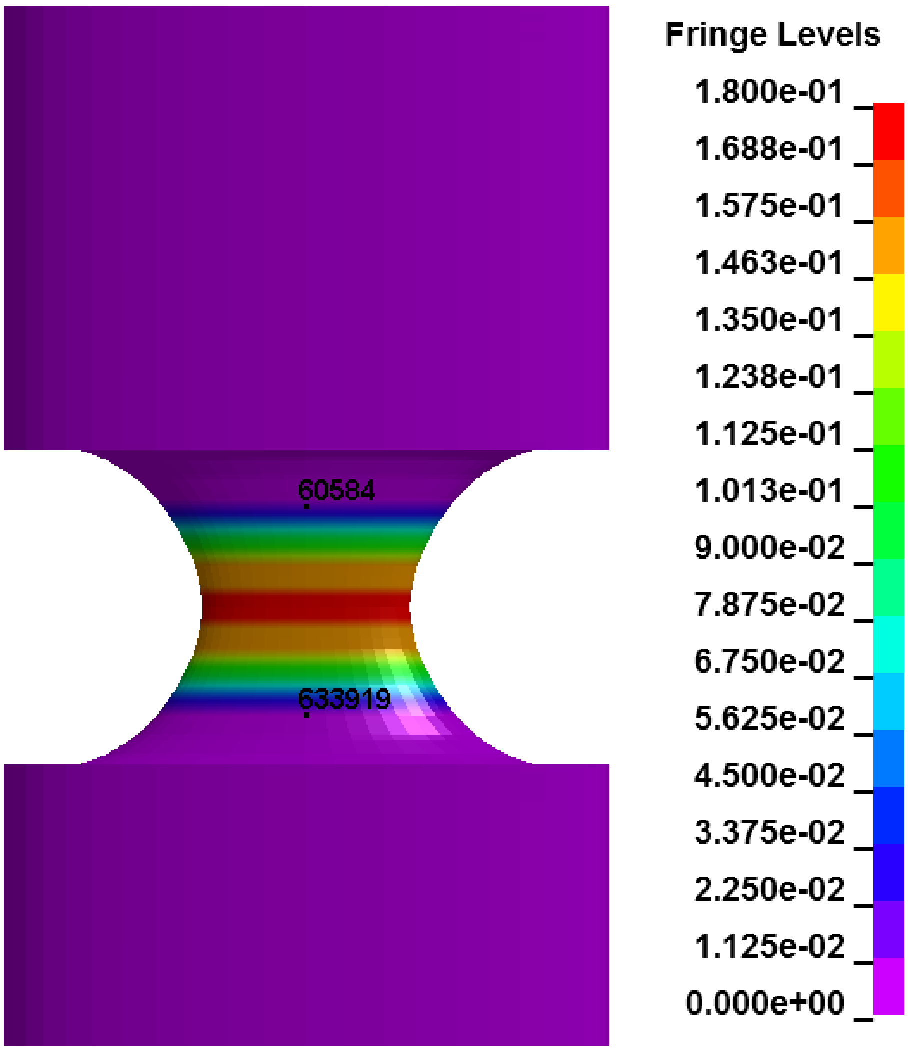


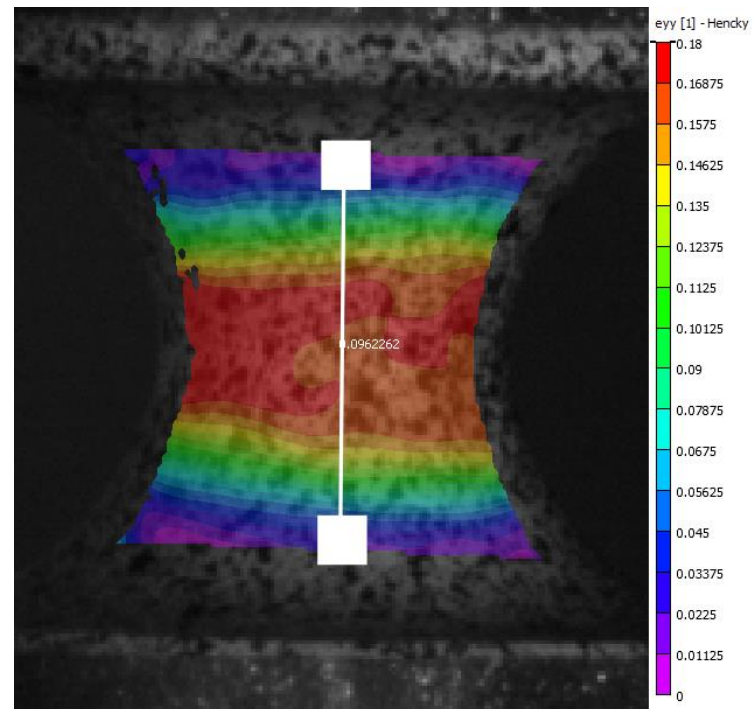
DIC Comparison – Axisymmetric 5



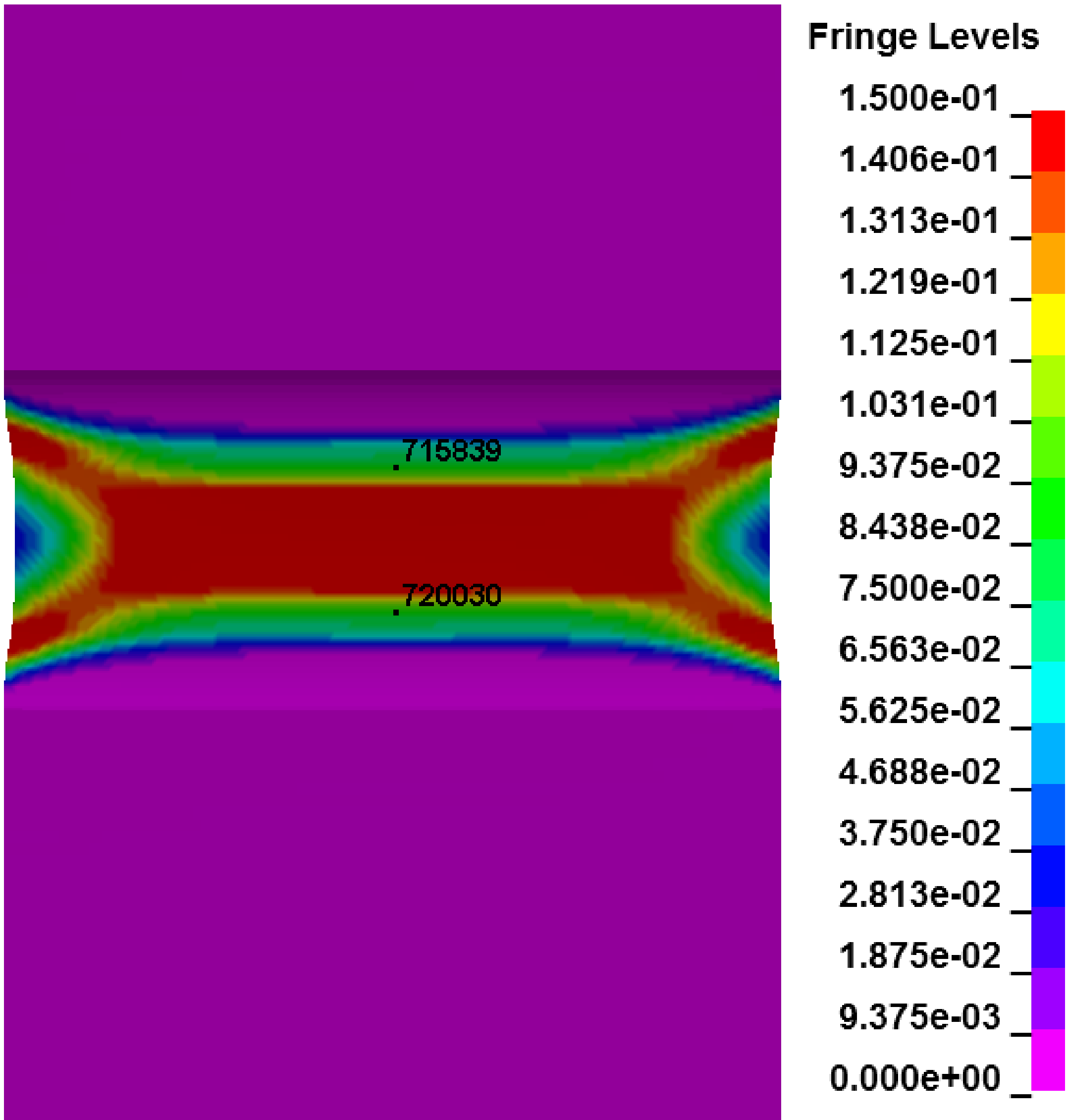


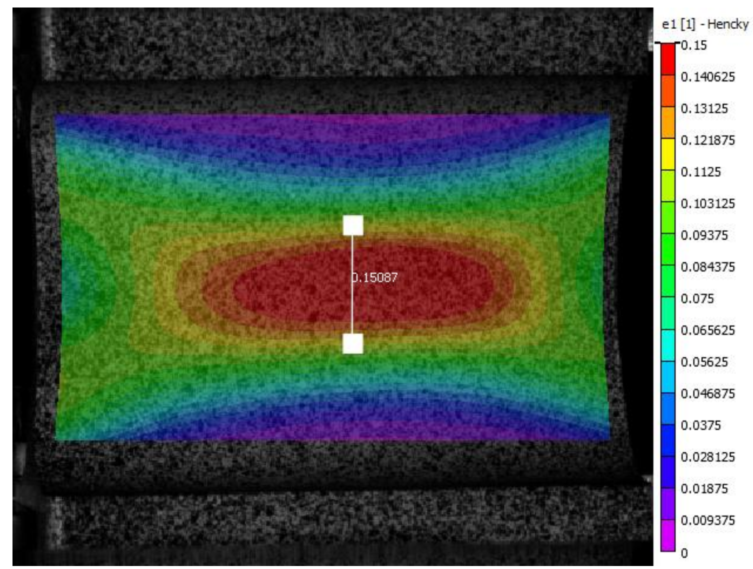
DIC Comparison – Axisymmetric 6



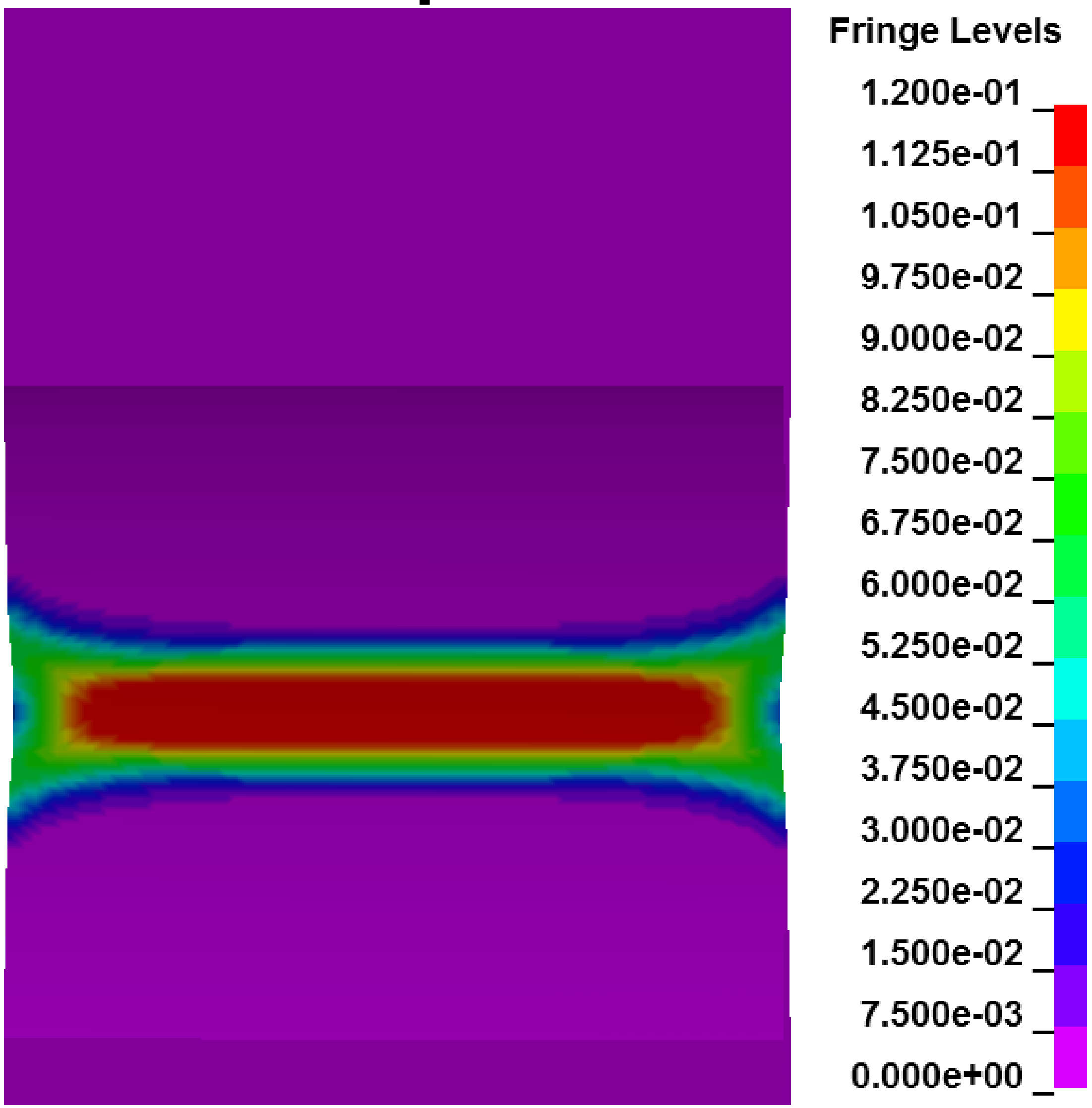


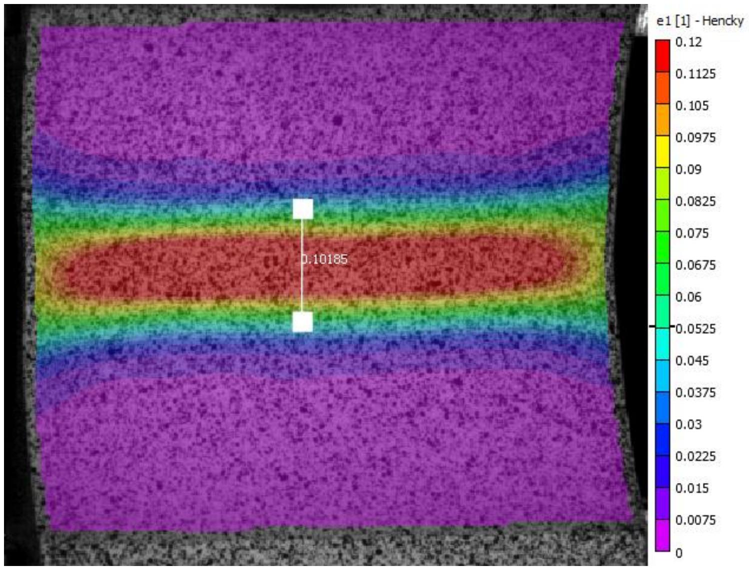
DIC Comparison – Plane Strain 1



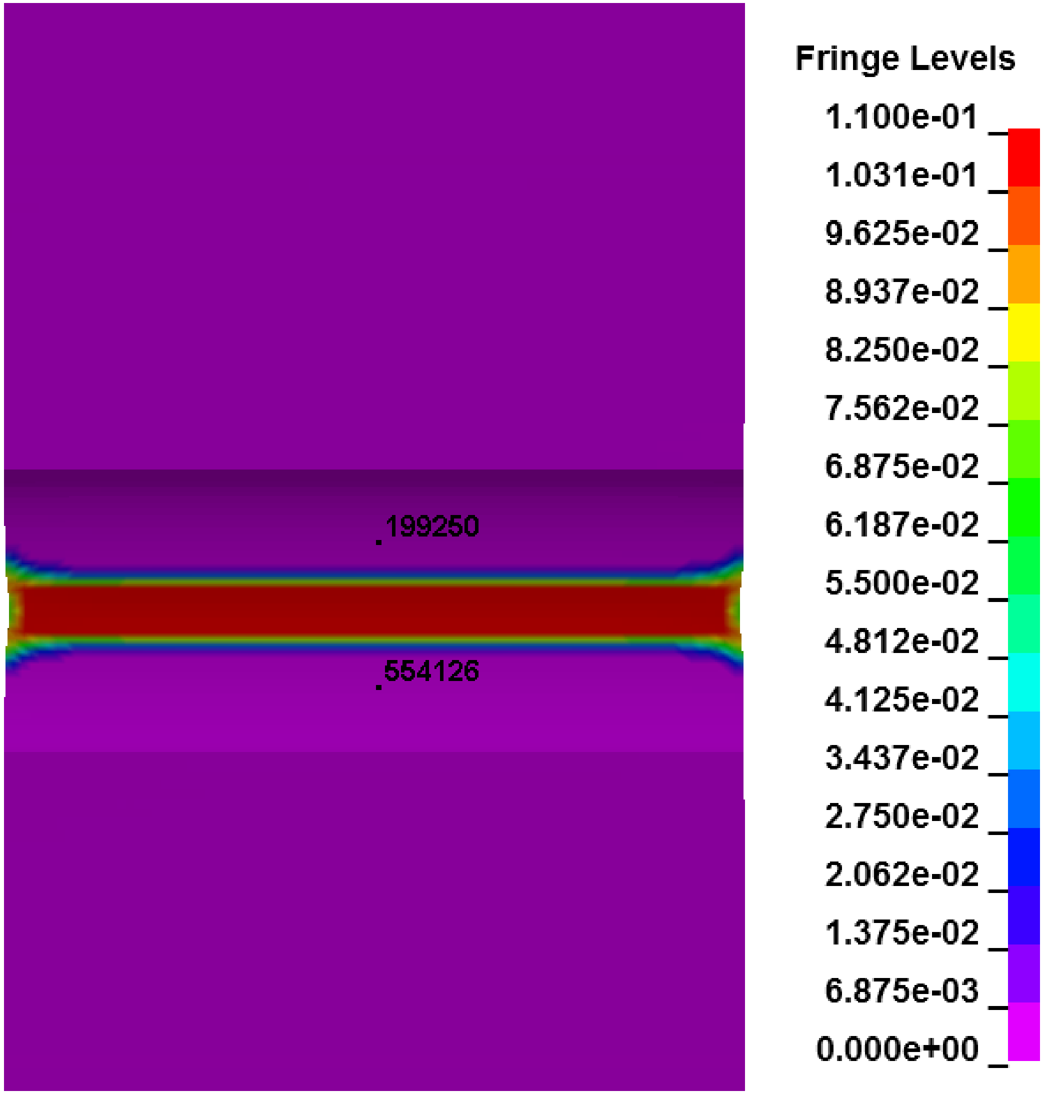


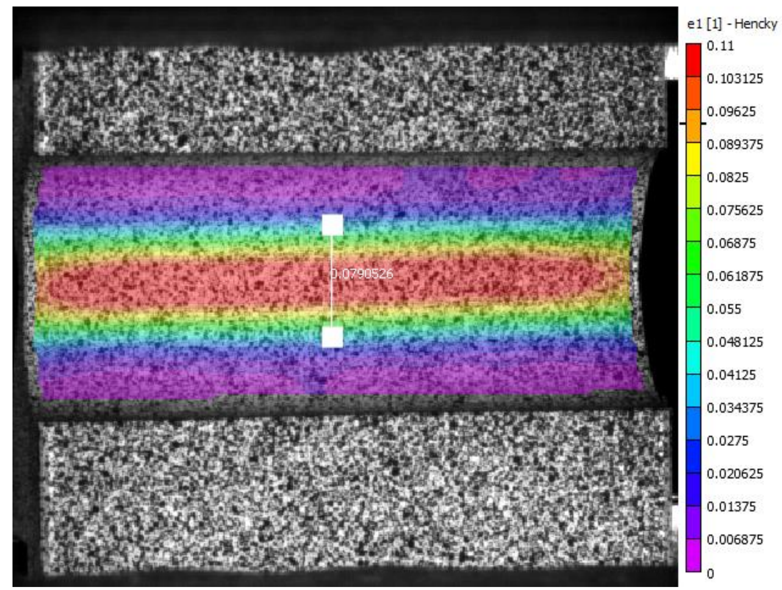
DIC Comparison – Plane Strain 2



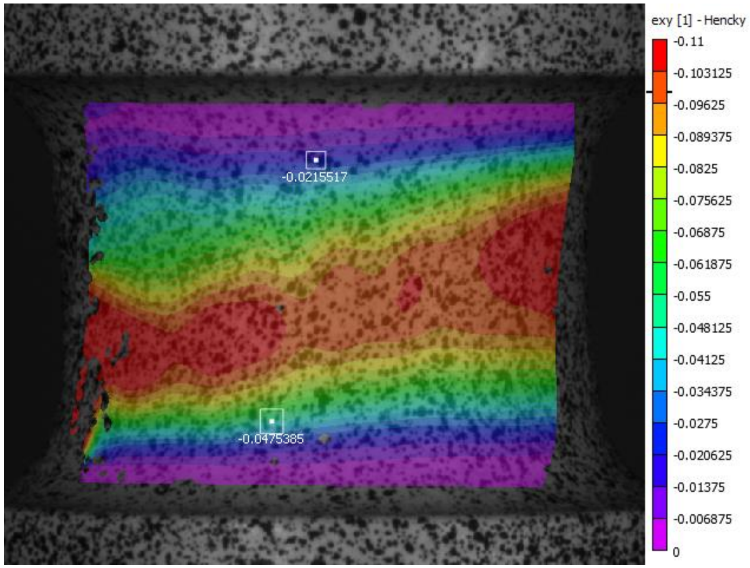


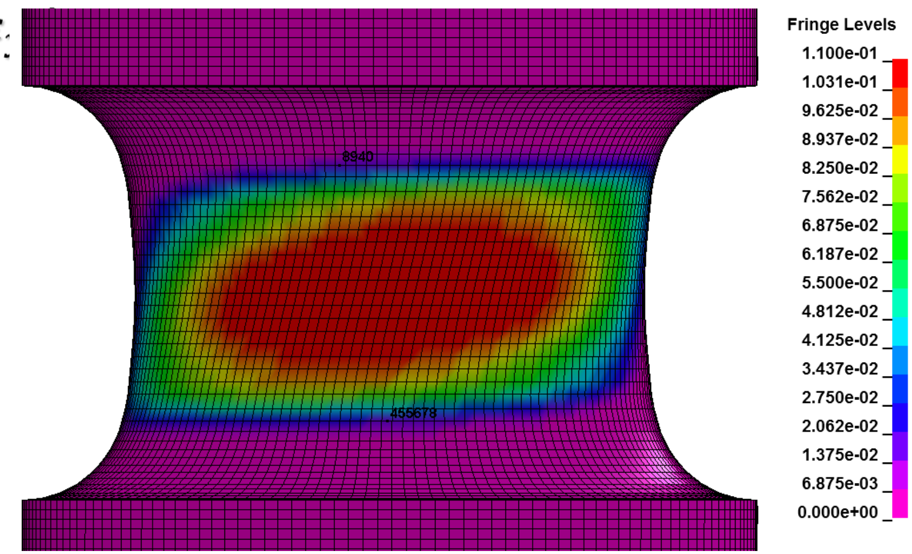
DIC Comparison – Plane Strain 3

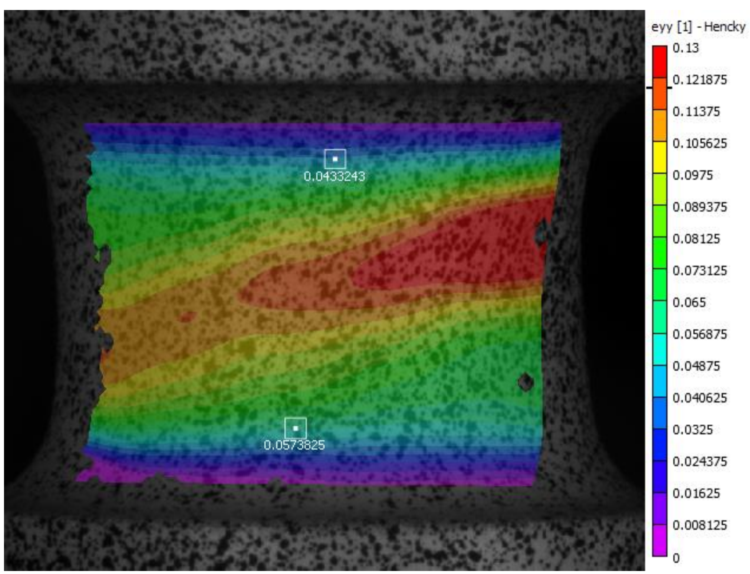


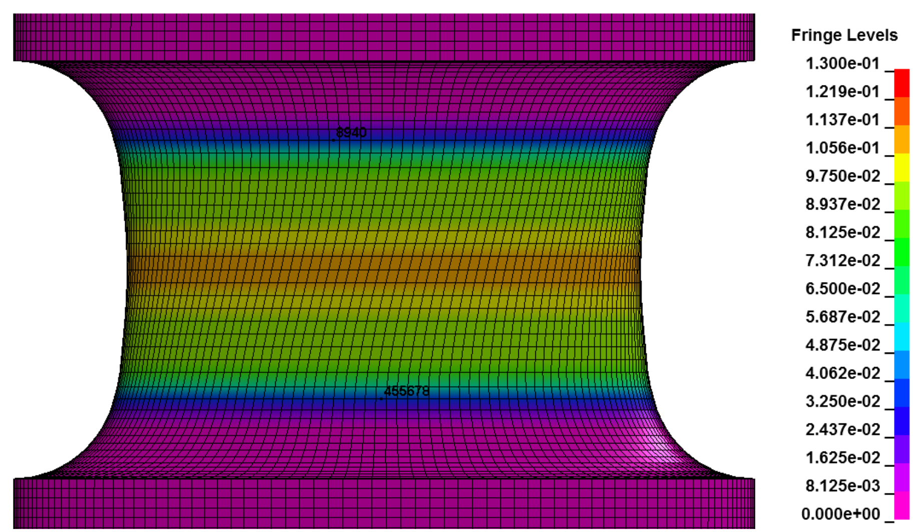


Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

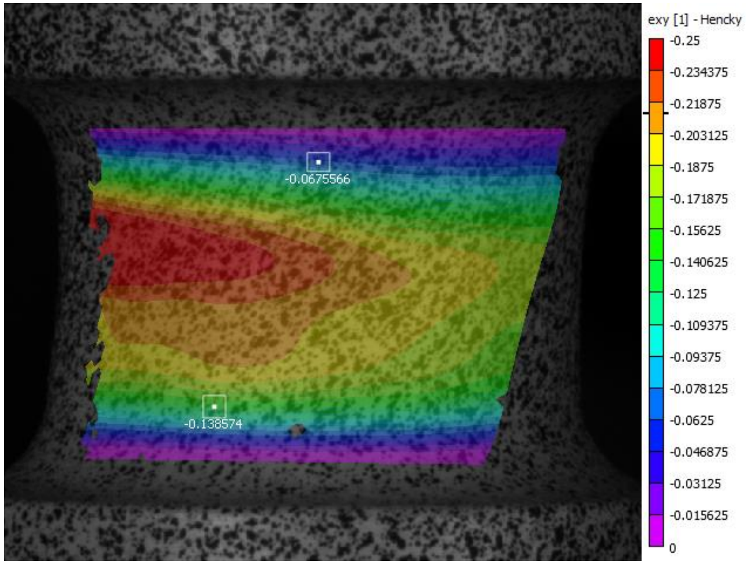




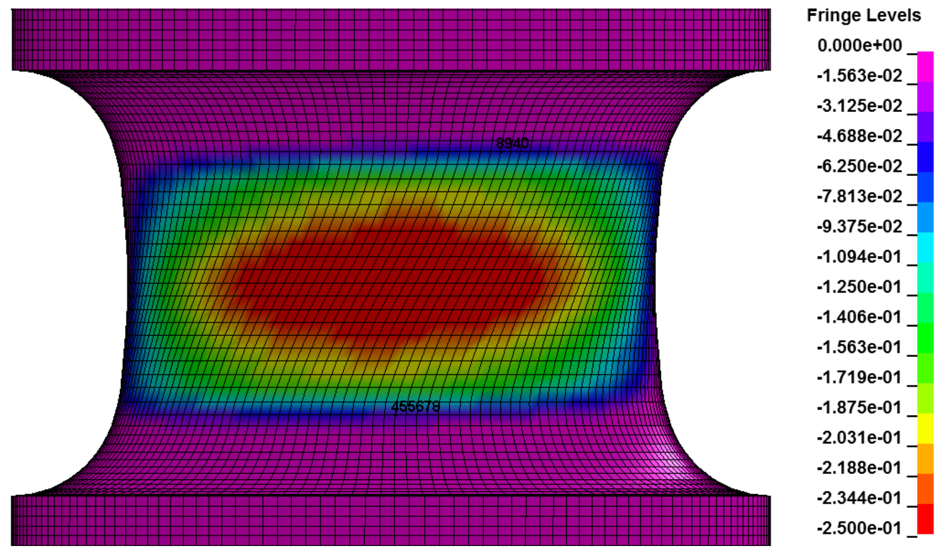


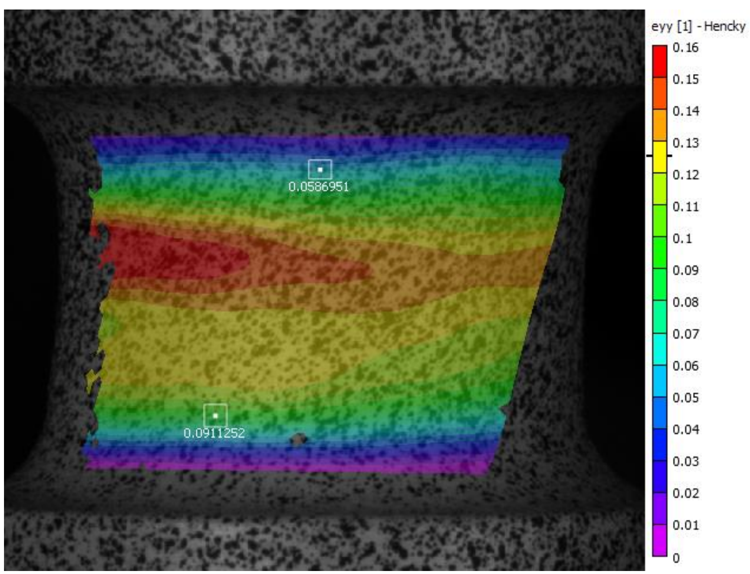


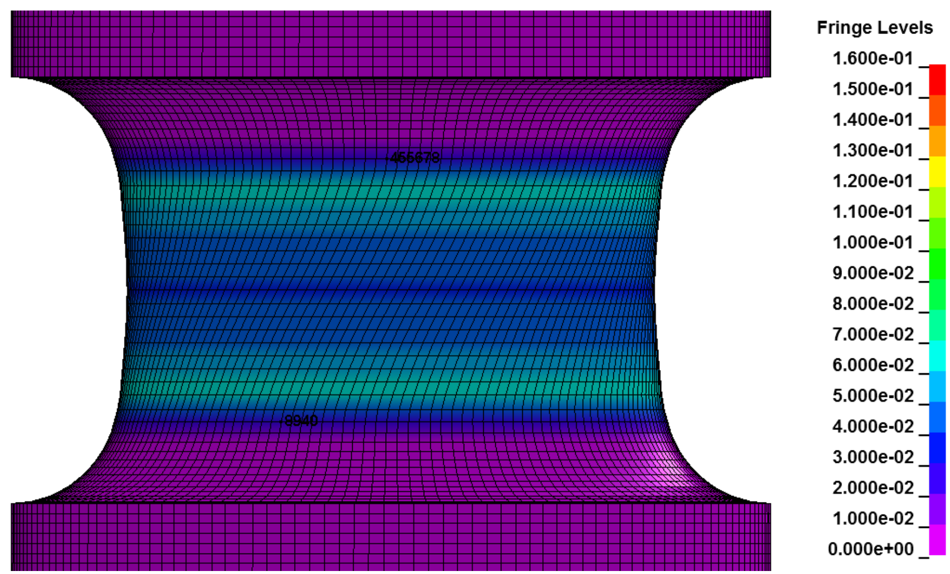
Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V



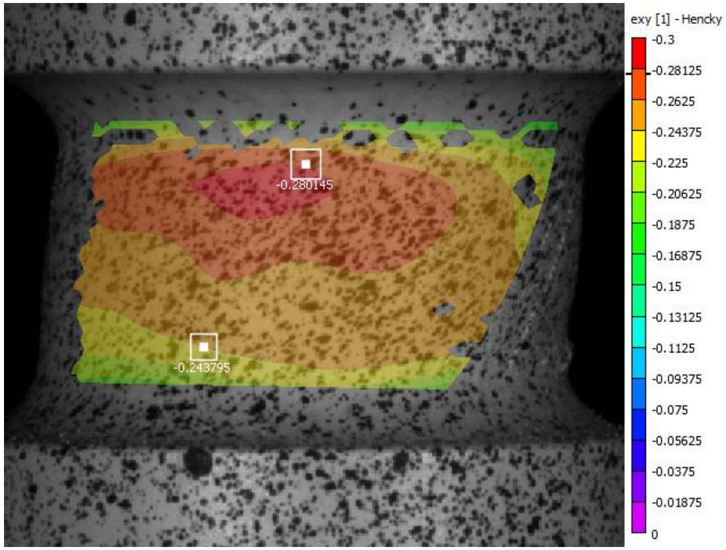
$\varepsilon_{xy}, \varepsilon$

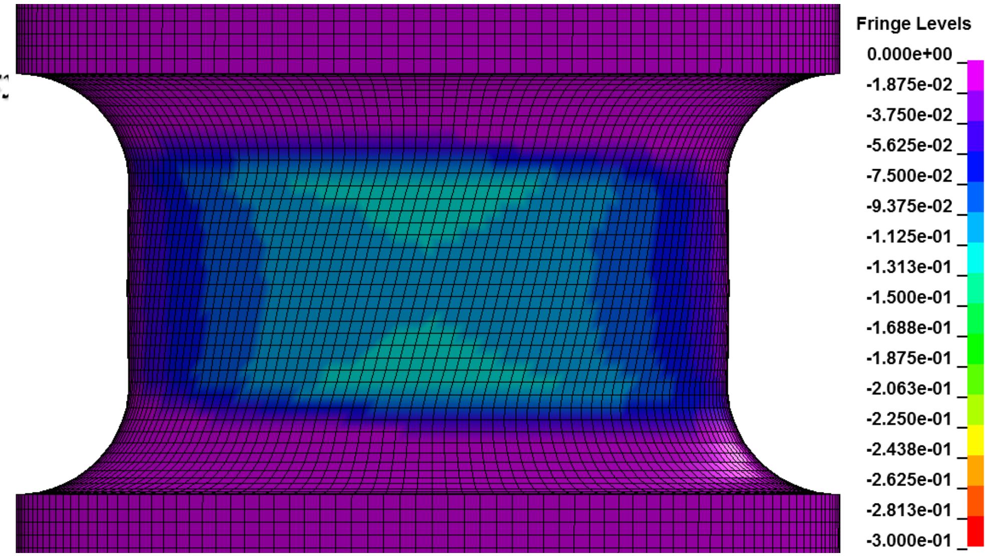


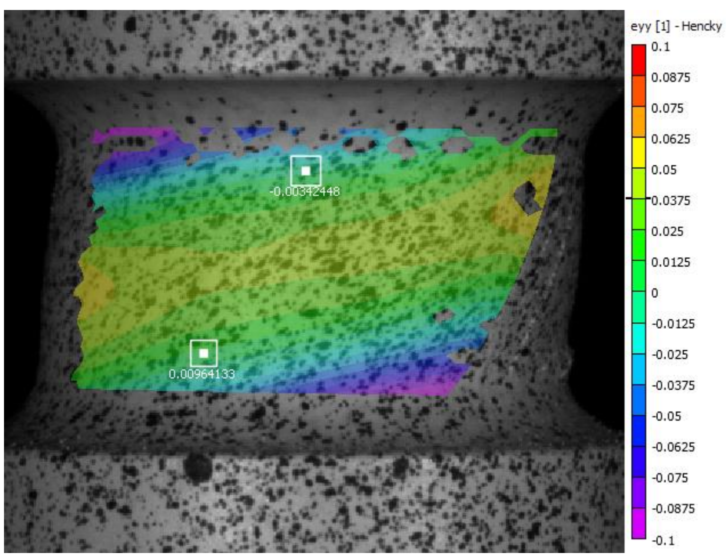


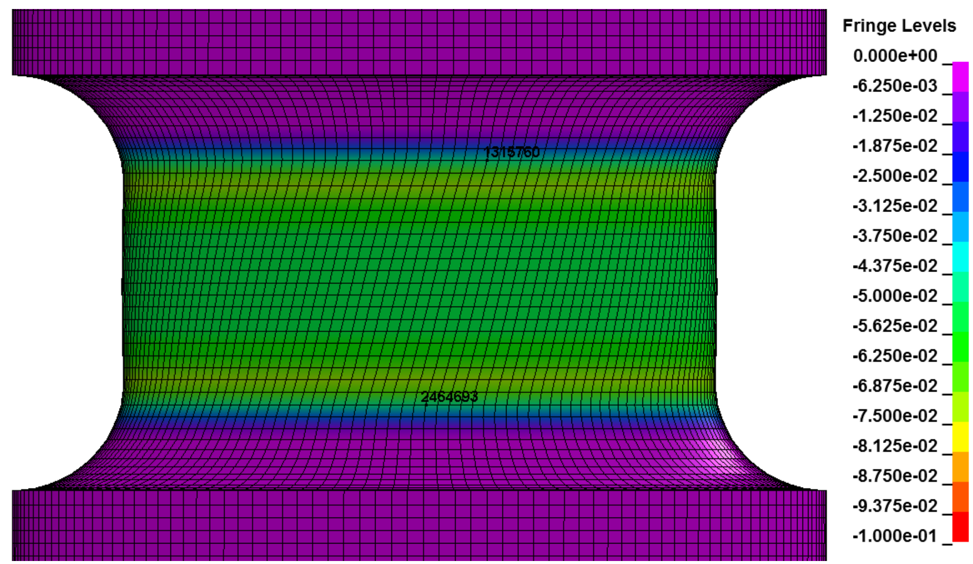


Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V



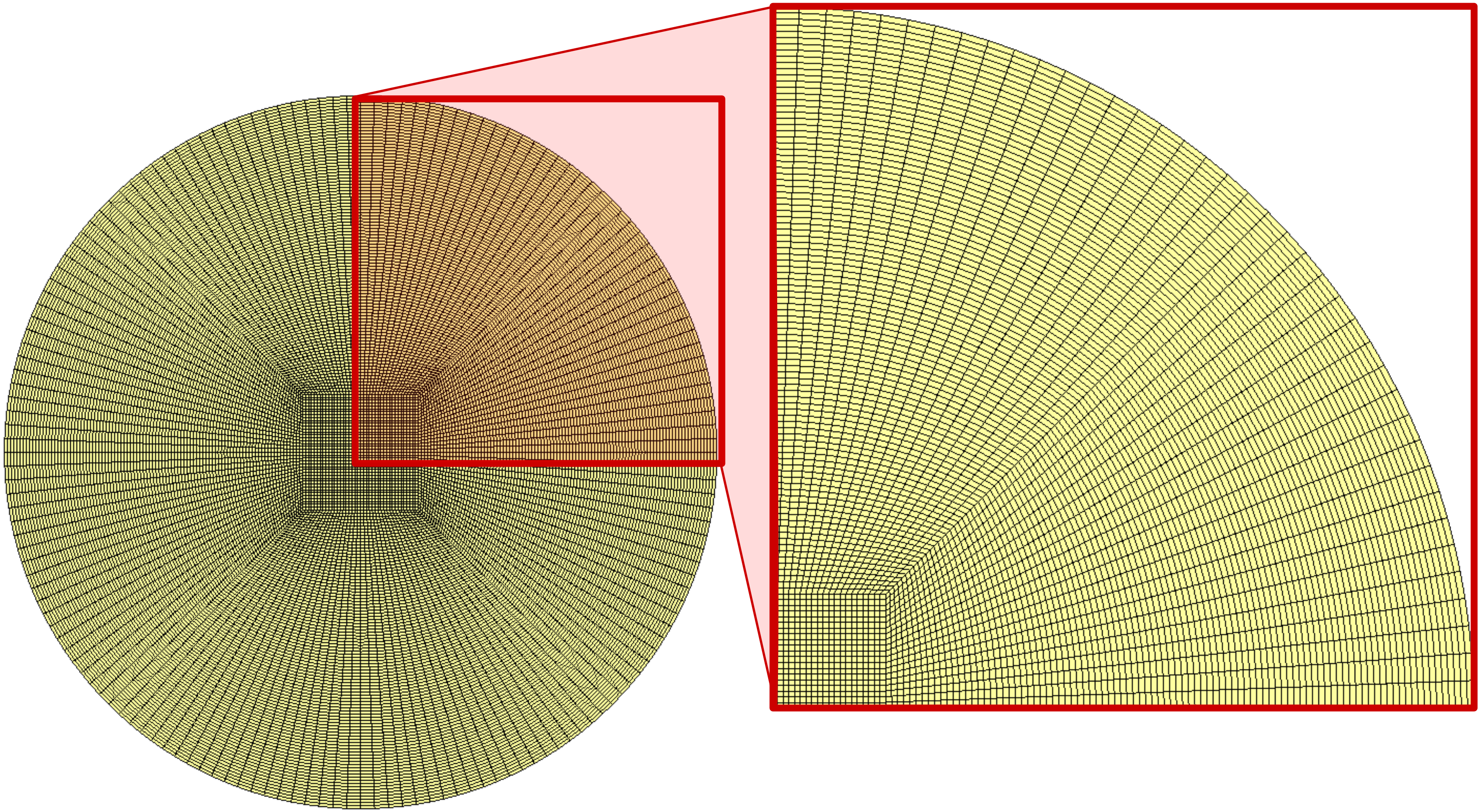




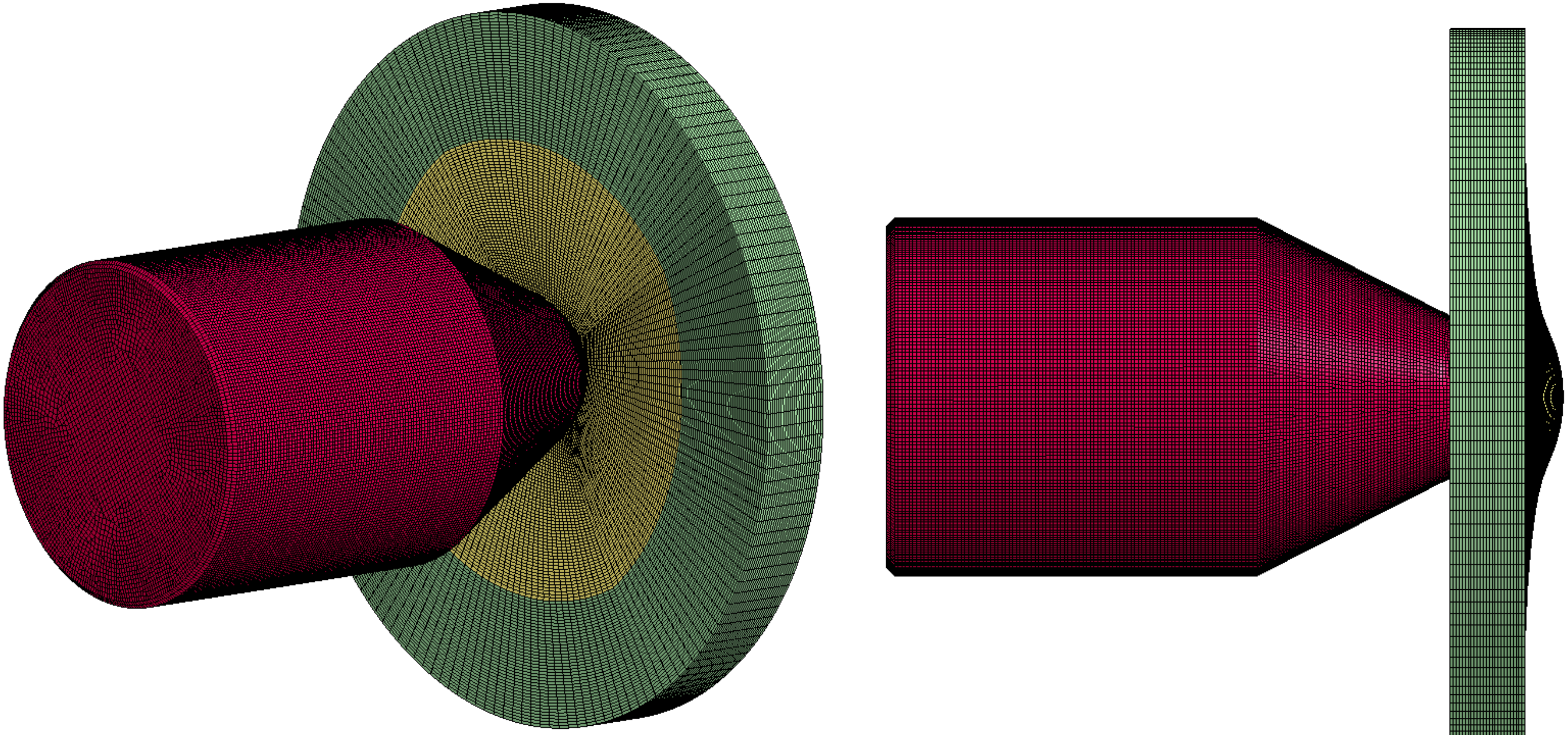


Large diameter punch tests :Specimen Geometry

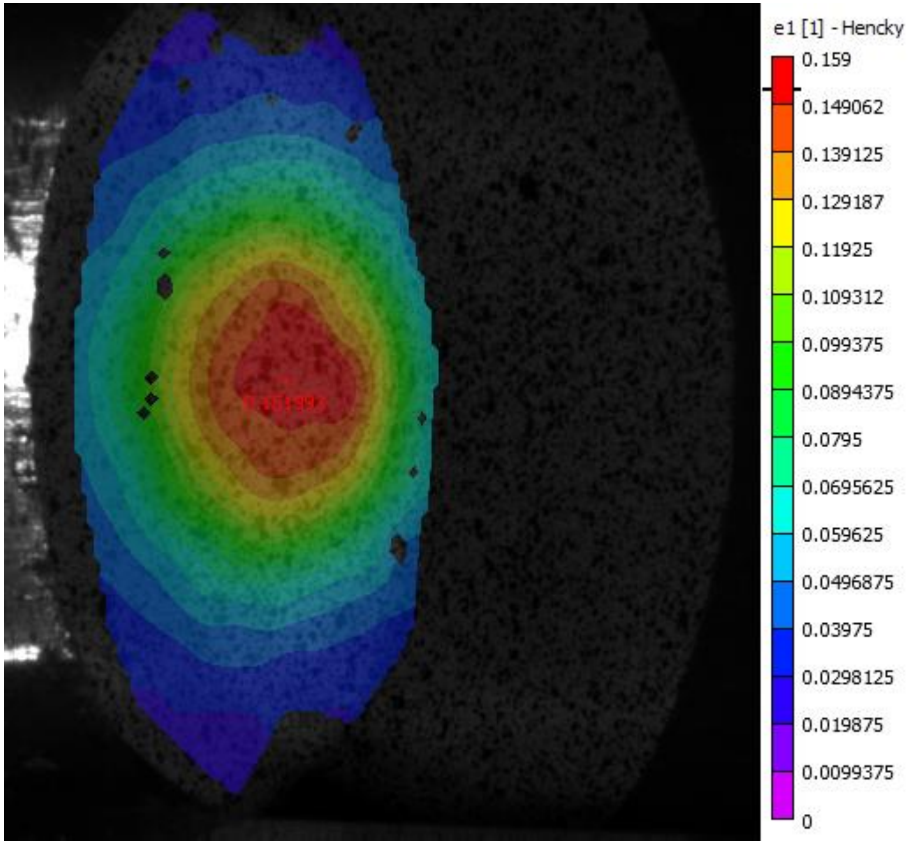
- **420,000 elements (0.2 mm element size)**

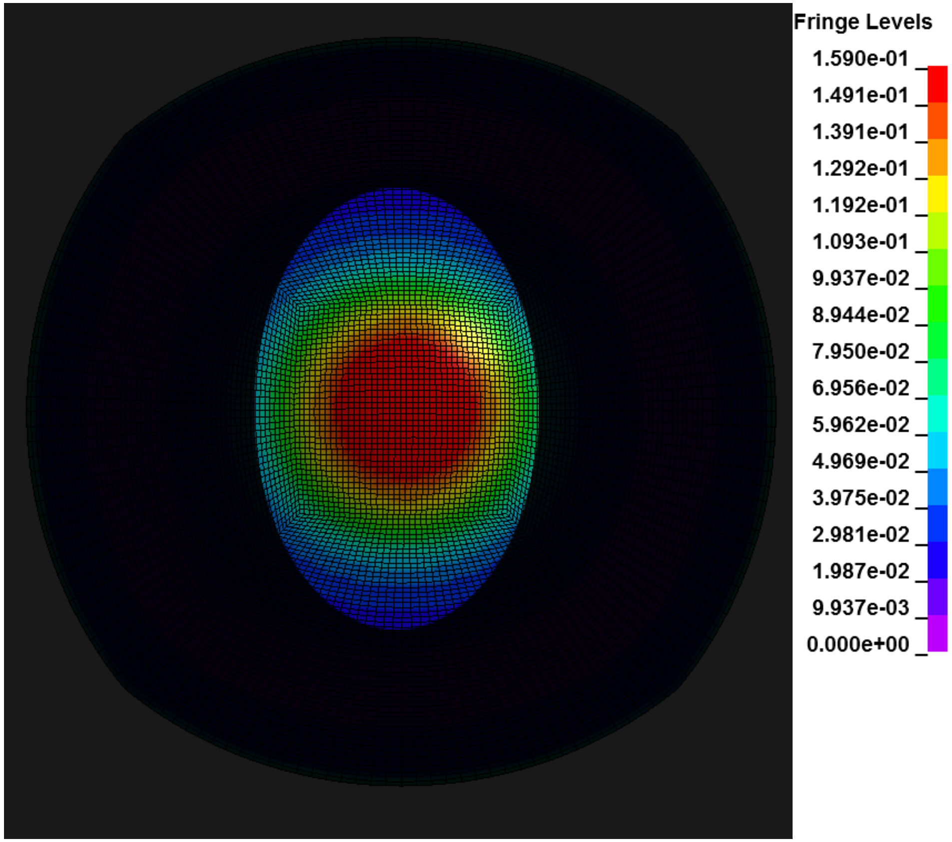


Punch Test Results – Punch 1

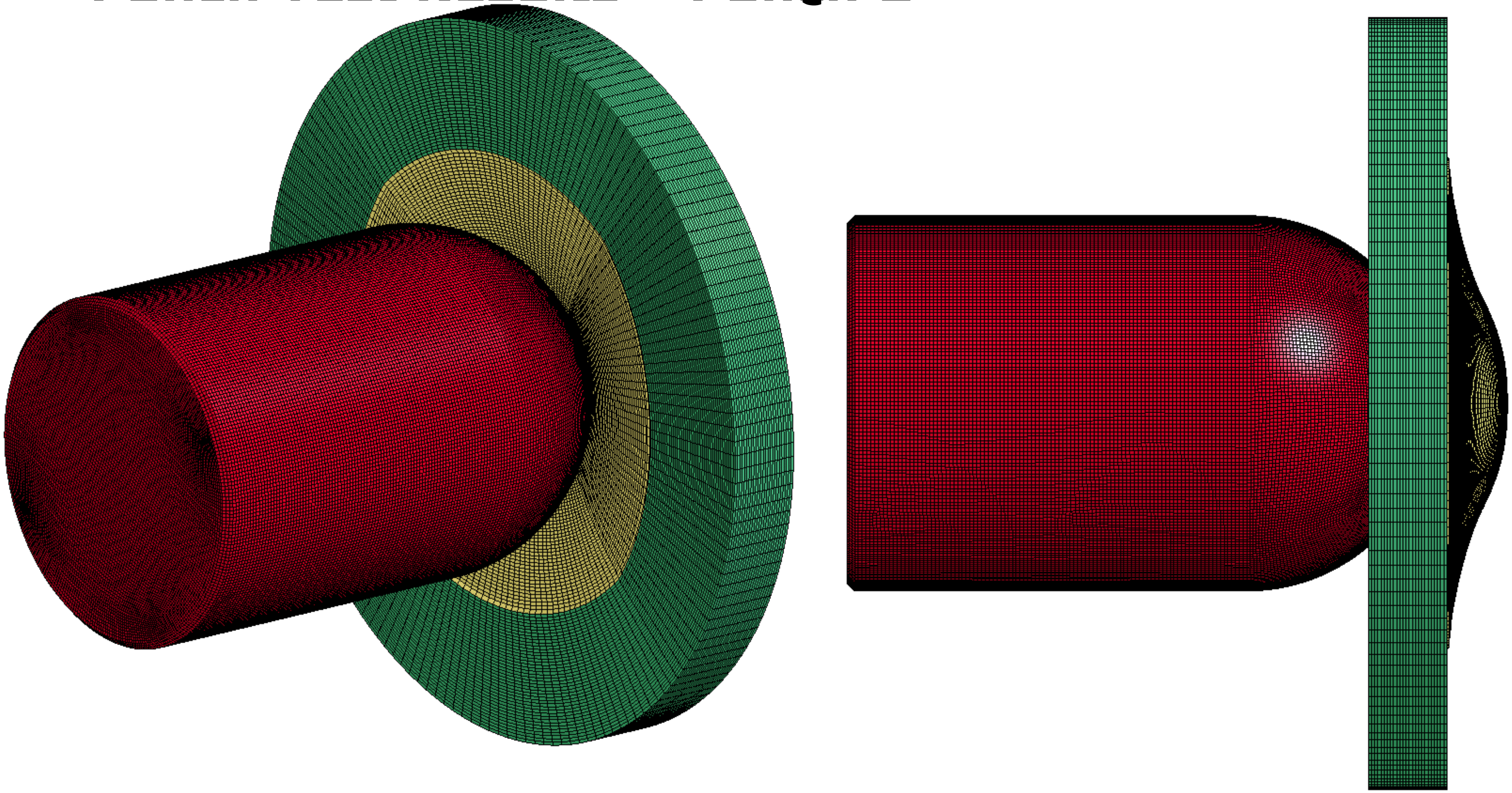


Punch Test Results – Punch 1

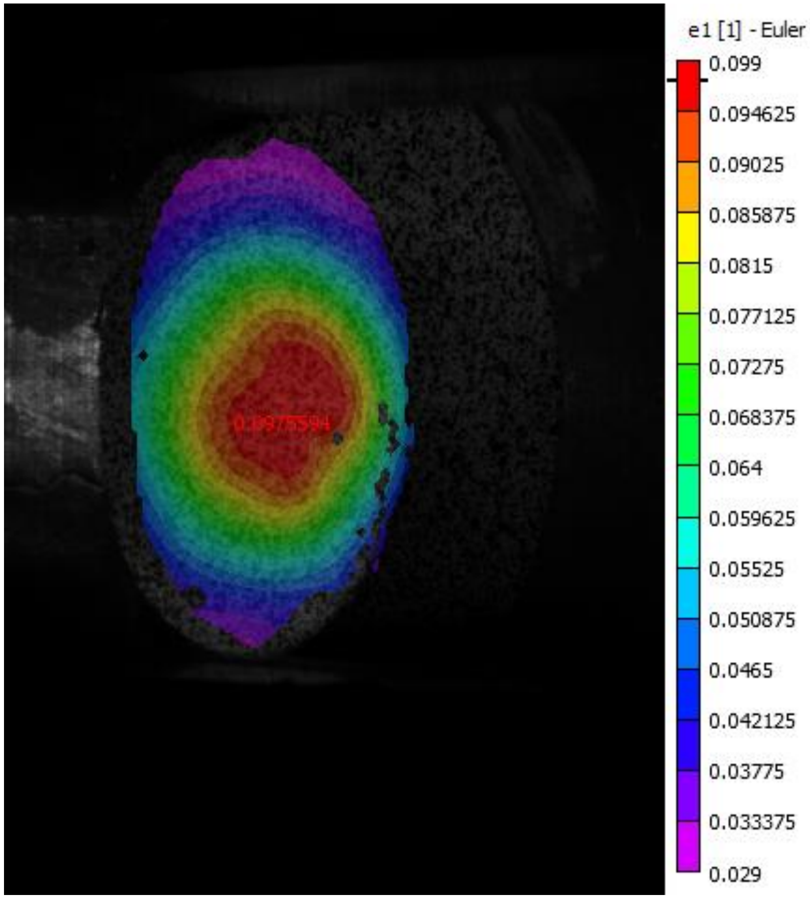


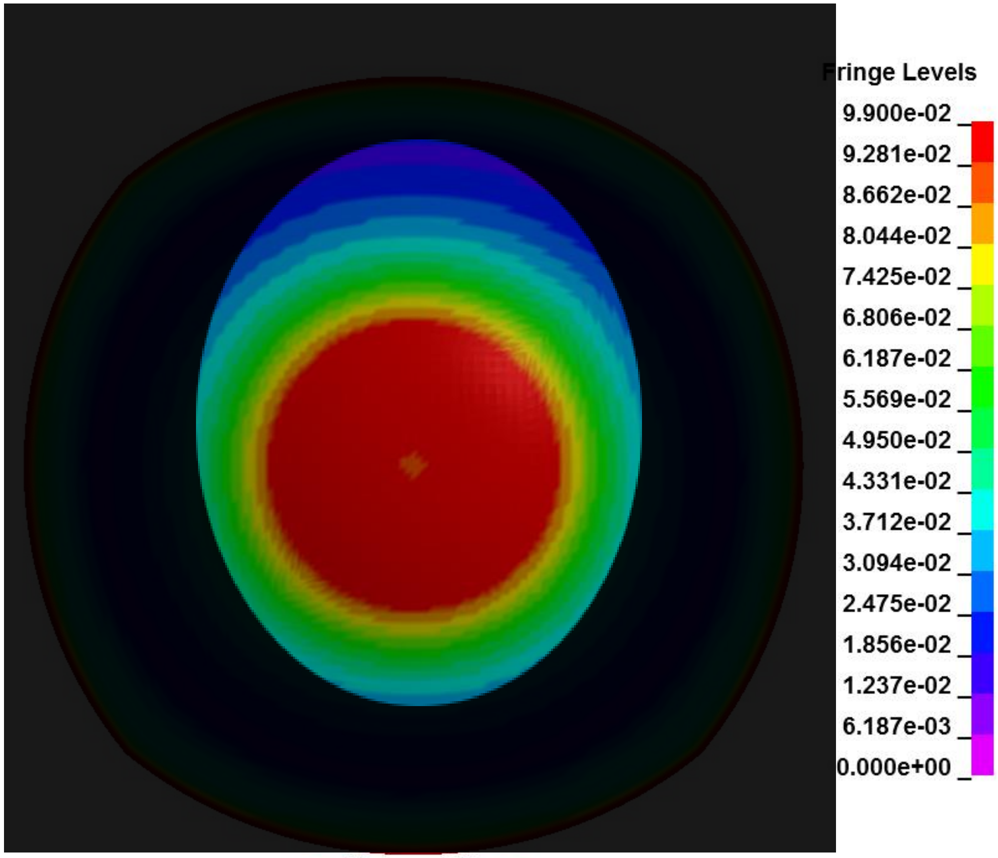


Punch Test Results – Punch 2

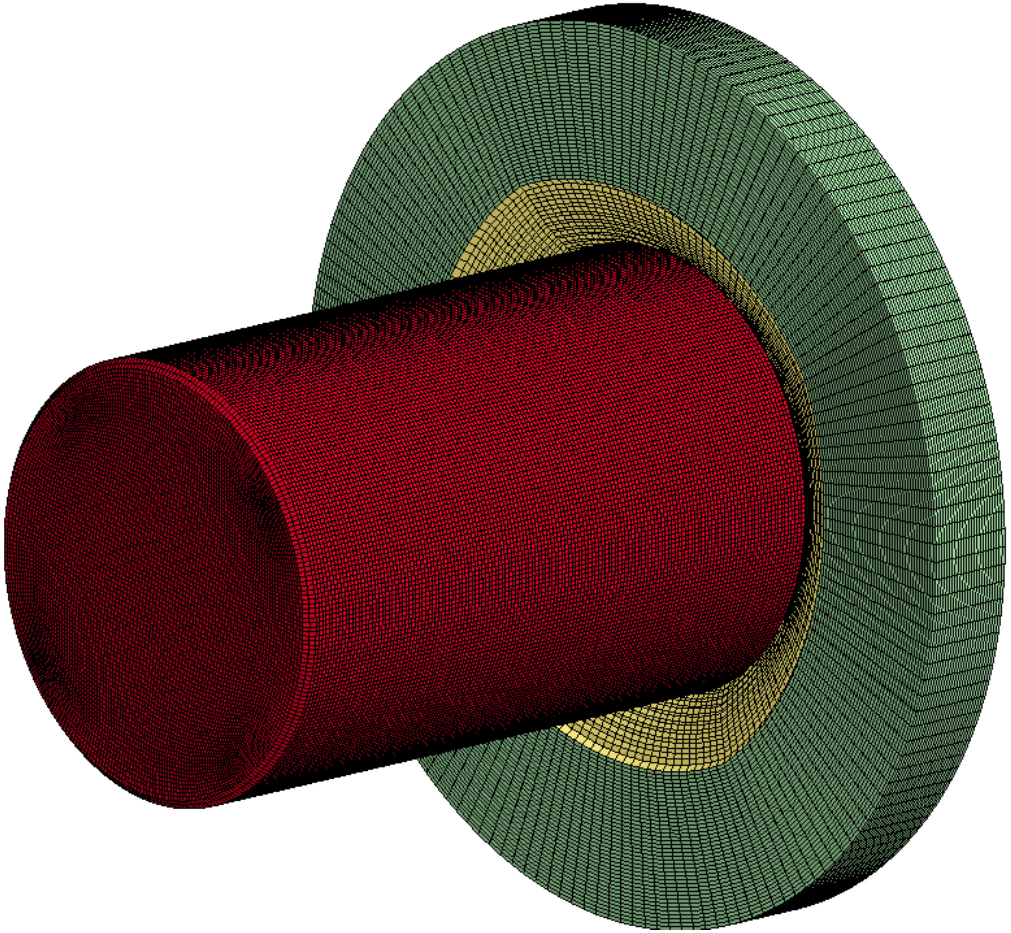


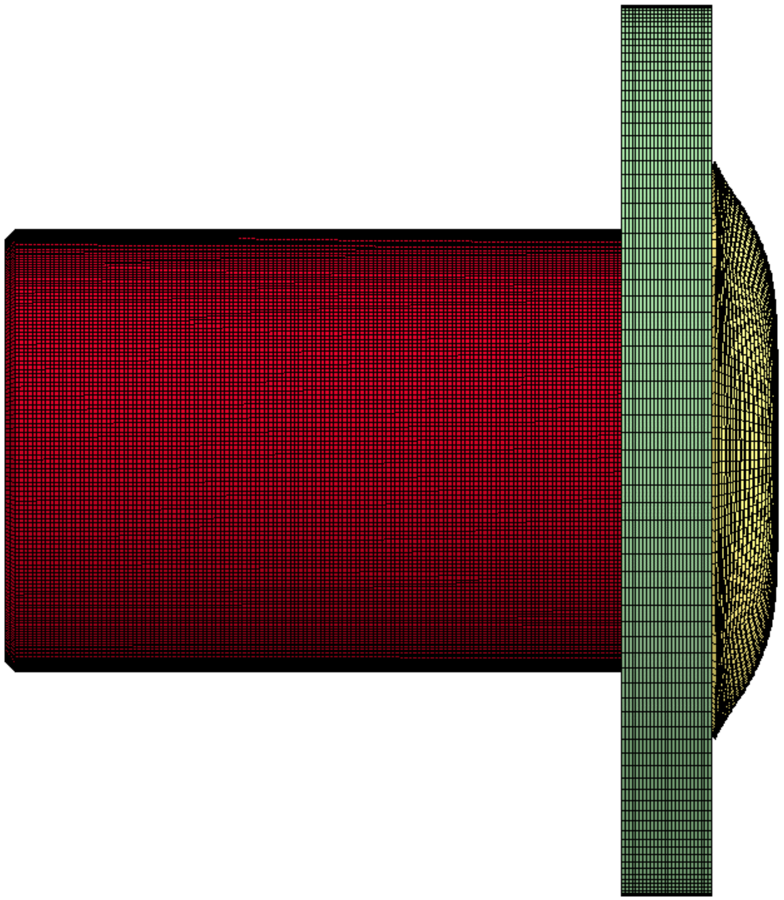
Punch Test Results – Punch 2



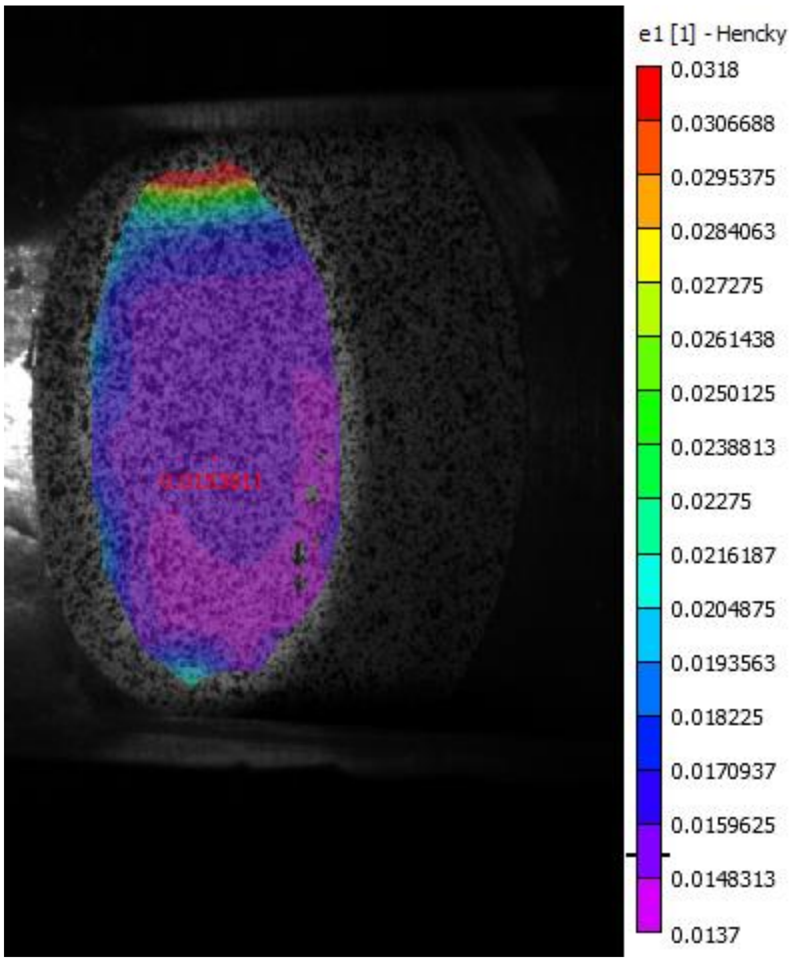


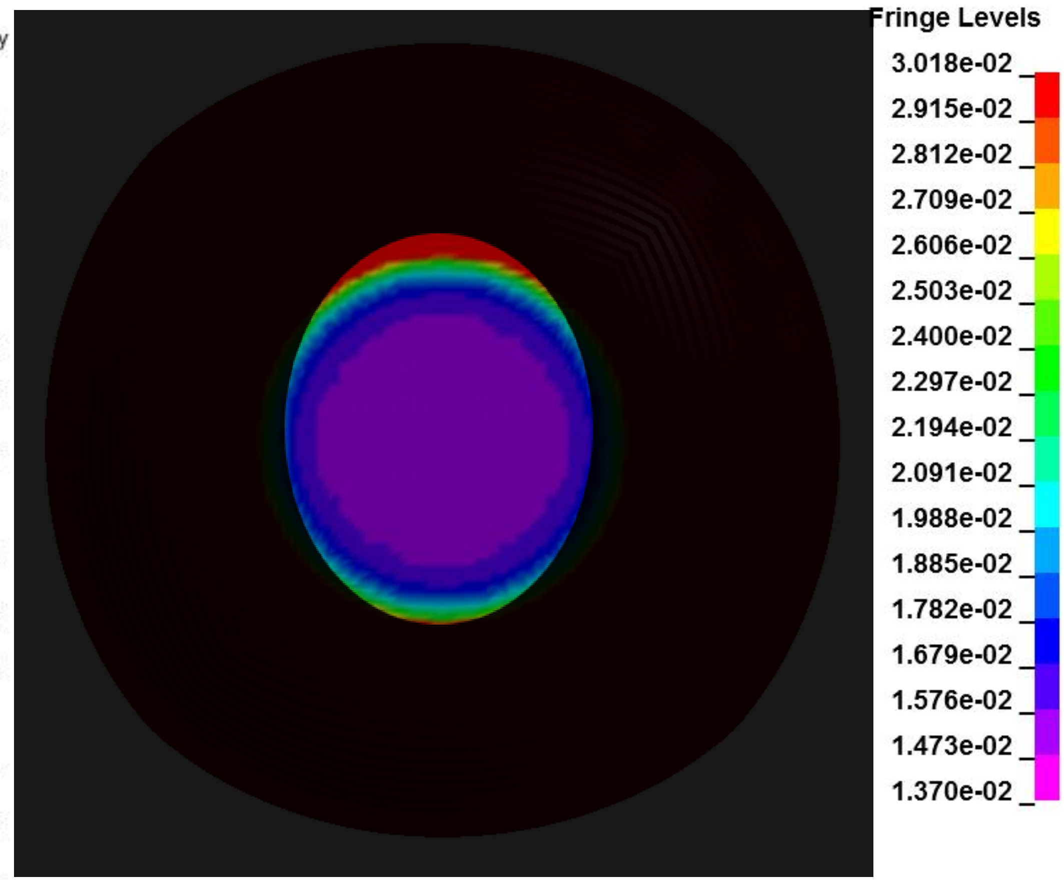
Punch Test Results – Punch 3





Punch Test Results – Punch 3



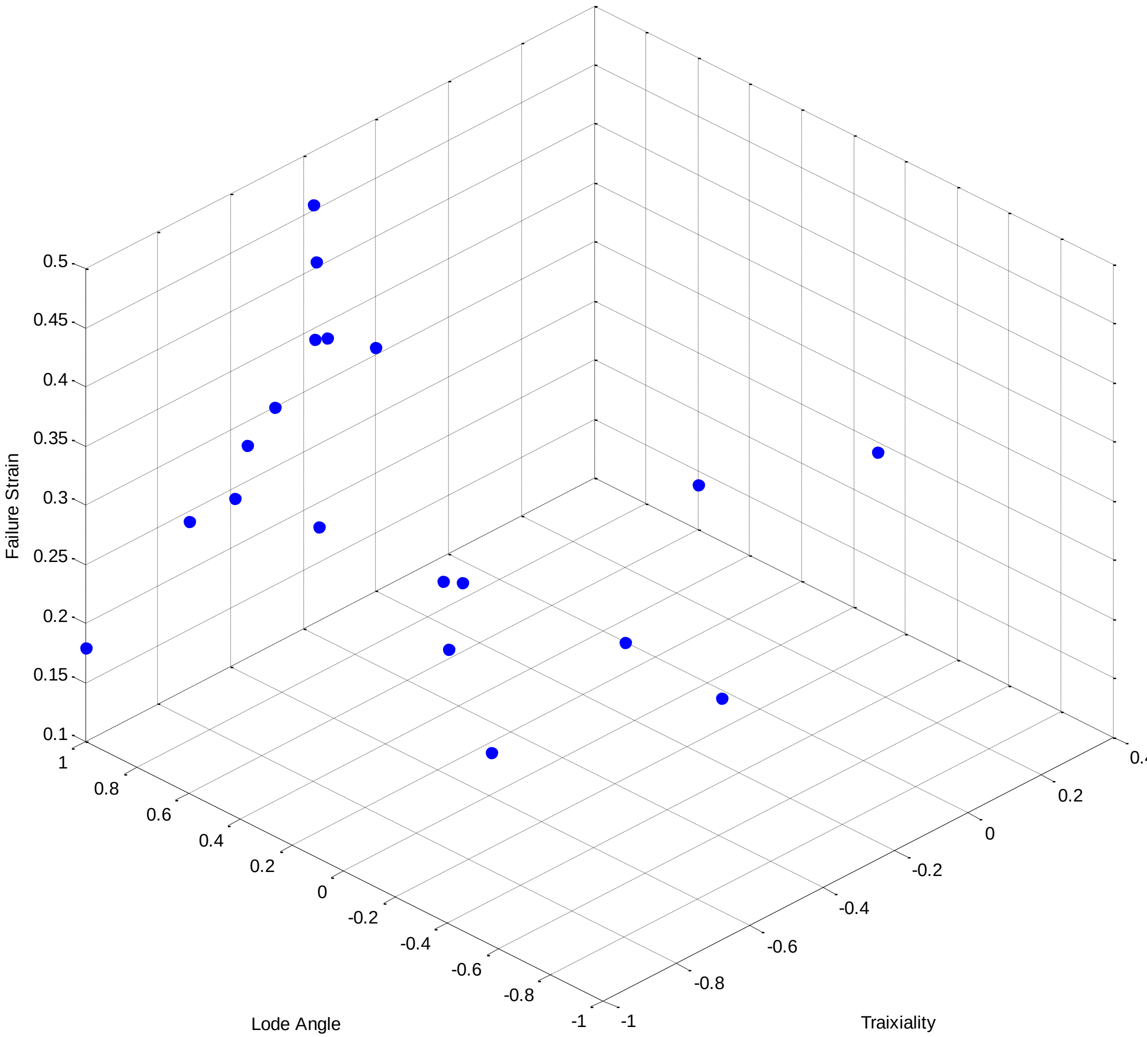


Completed Failure Table

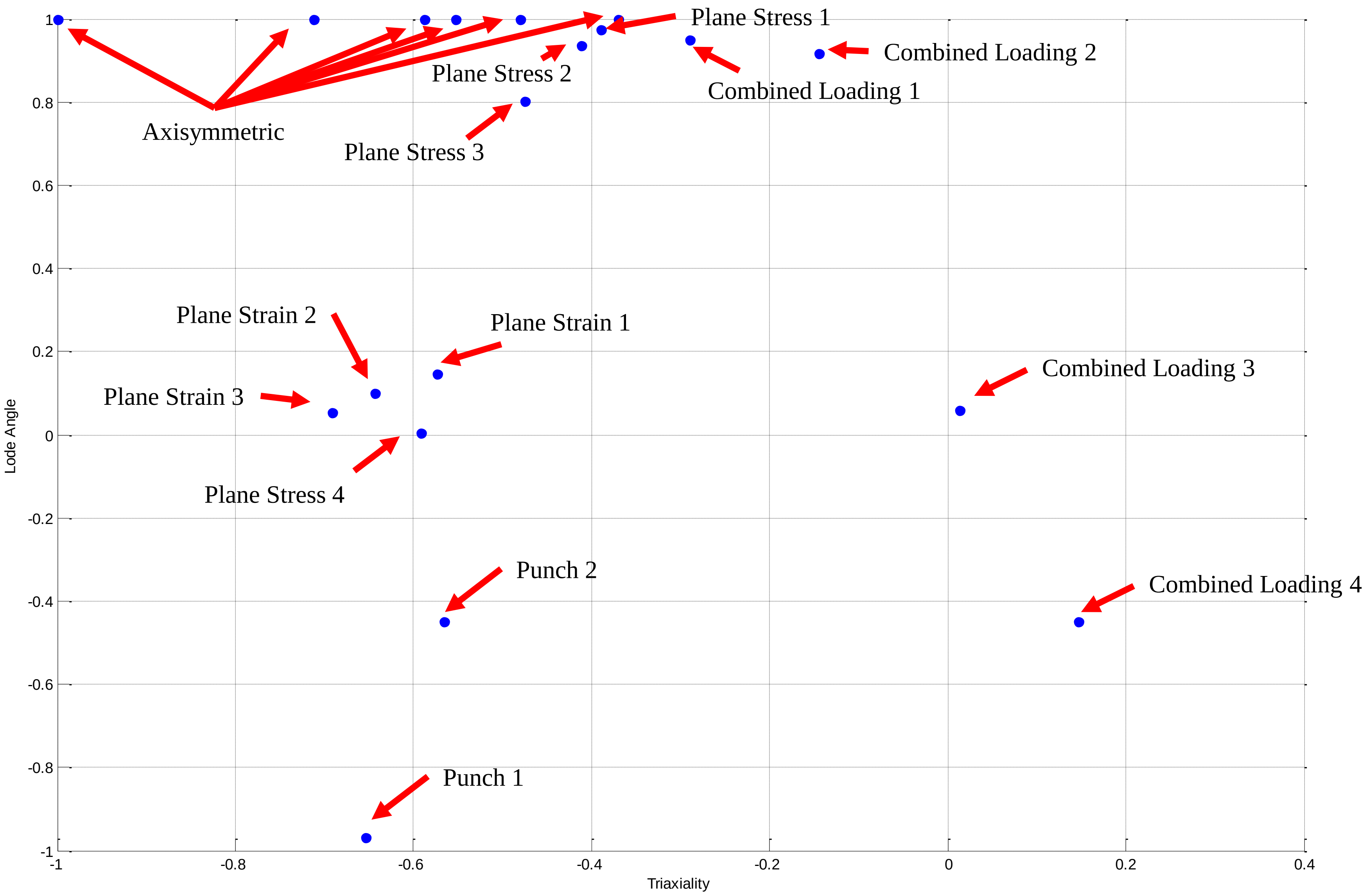
Test Number	Geometry	OSU			GMU		
		Triaxiality	Lode Parameter	Failure Strain	Triaxiality	Lode Parameter	Failure Strain
SG1	Plane Stress	0.400	0.850	0.590	0.390	0.975	0.460
SG2		0.431	0.719	0.440	0.412	0.935	0.420
SG3		0.489	0.528	0.430	0.475	0.803	0.380
SG4		0.583	0.014	0.140	0.592	0.005	0.135
SG5	Axisymmetric	0.369	1.000	0.310	0.370	1.000	0.340
SG6		0.492	1.000	0.310	0.480	1.000	0.300
SG7		0.564	1.000	0.320	0.553	1.000	0.280
SG8		0.618	1.000	0.270	0.588	1.000	0.240
SG9		0.751	1.000	0.270	0.712	1.000	0.240
SG10		0.956	1.000	0.220	1.000	1.000	0.180
SG11	Plane Strain	0.470	0.506	0.210	0.573	0.146	0.260
SG12		0.660	0.040	0.220	0.643	0.099	0.220
SG13		0.768	0.025	0.210	0.691	0.054	0.290
LR1	Combined Loading	0.252	0.706	0.290	0.289	0.949	0.191
LR2		0.150	0.400	0.510	0.145	0.917	0.325
LR3		0.000	0.000	0.430	0.014	0.059	0.259
LR4		-0.148	-0.394	0.420	-0.147	-0.450	0.321
Punch1	Punch Tests				0.653	-0.969	0.297
Punch2					0.565	-0.475	0.276
Punch3					-0.077	-0.073	0.766

Data points

Test Number	GMU		
	Triaxiality	Lode Parameter	Failure Strain
SG1	0.390	0.975	0.460
SG2	0.412	0.935	0.420
SG3	0.475	0.803	0.380
SG4	0.592	0.005	0.135
SG5	0.370	1.000	0.340
SG6	0.480	1.000	0.300
SG7	0.553	1.000	0.280
SG8	0.588	1.000	0.240
SG9	0.712	1.000	0.240
SG10	1.000	1.000	0.180
SG11	0.573	0.146	0.260
SG12	0.643	0.099	0.220
SG13	0.691	0.054	0.290
LR1	0.289	0.949	0.191
LR2	0.145	0.917	0.325
LR3	0.014	0.059	0.259
LR4	-0.147	-0.450	0.321
Punch1	0.653	-0.969	0.297
Punch2	0.565	-0.475	0.276
Punch3	-0.077	-0.073	0.766

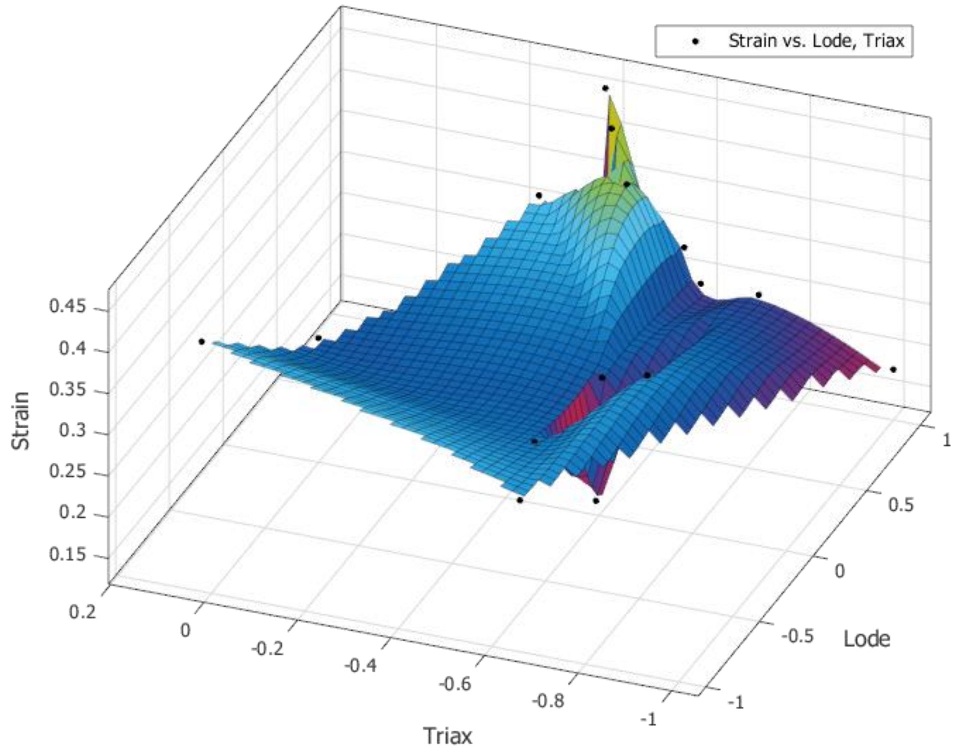


Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

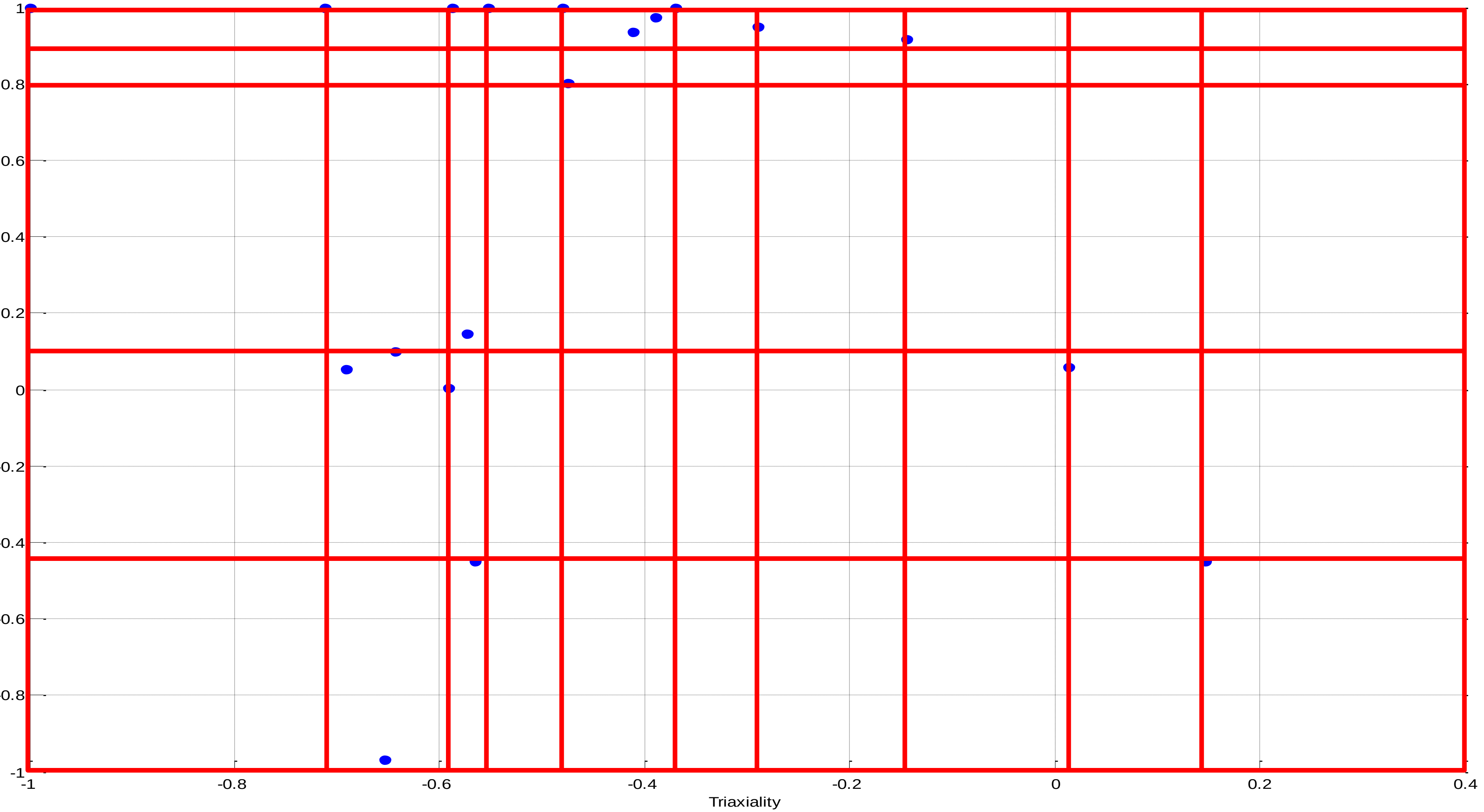


Failure Surface Plan

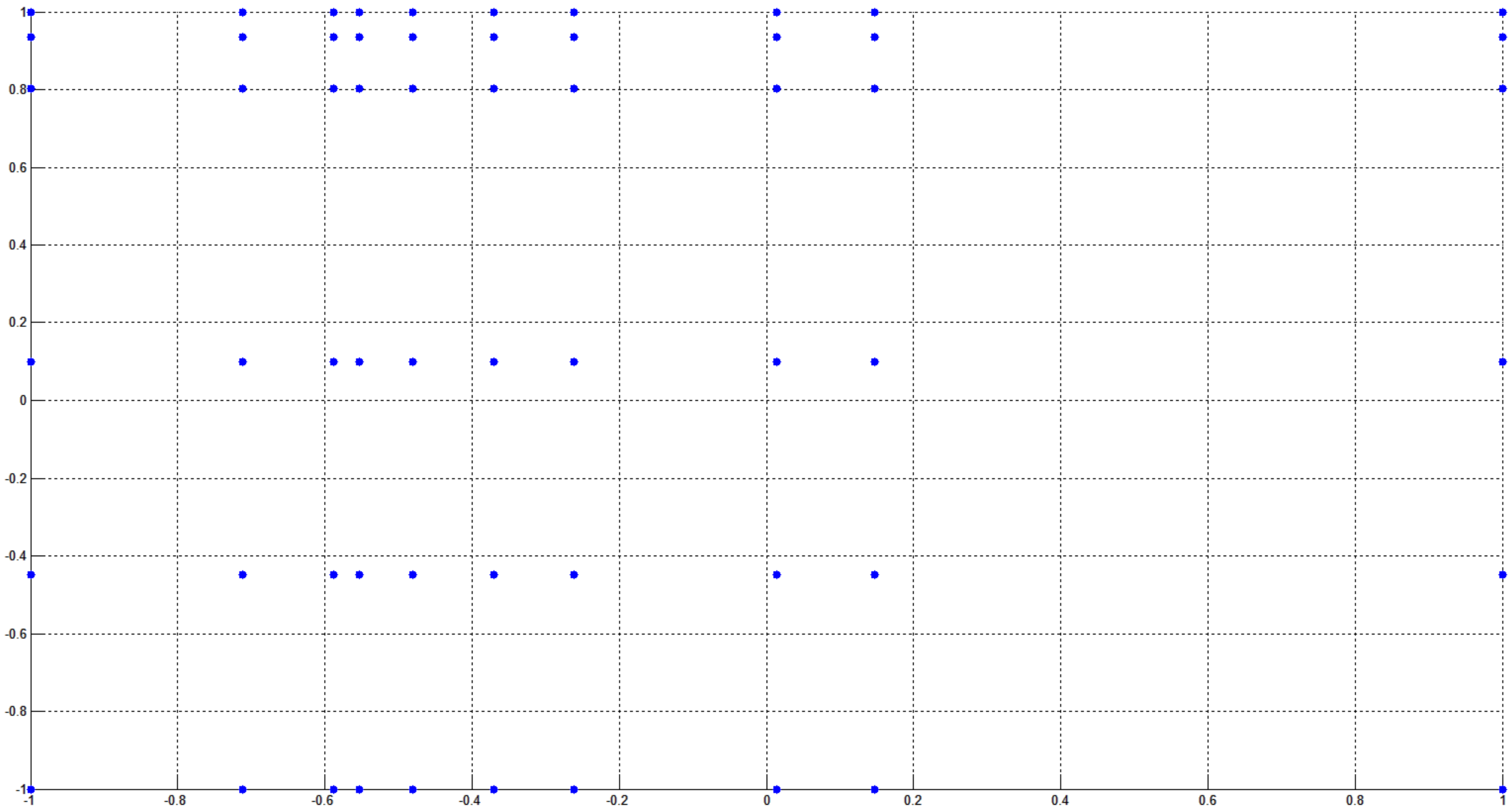
- Automatic surface interpolation methods do not work as well for data sets with large voids and clusters
- Also very difficult because the boundaries are not defined with discrete points
- New plan:
  - Cluster
  - Grid
  - Interpolate



Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V



Cluster and Grid Plan



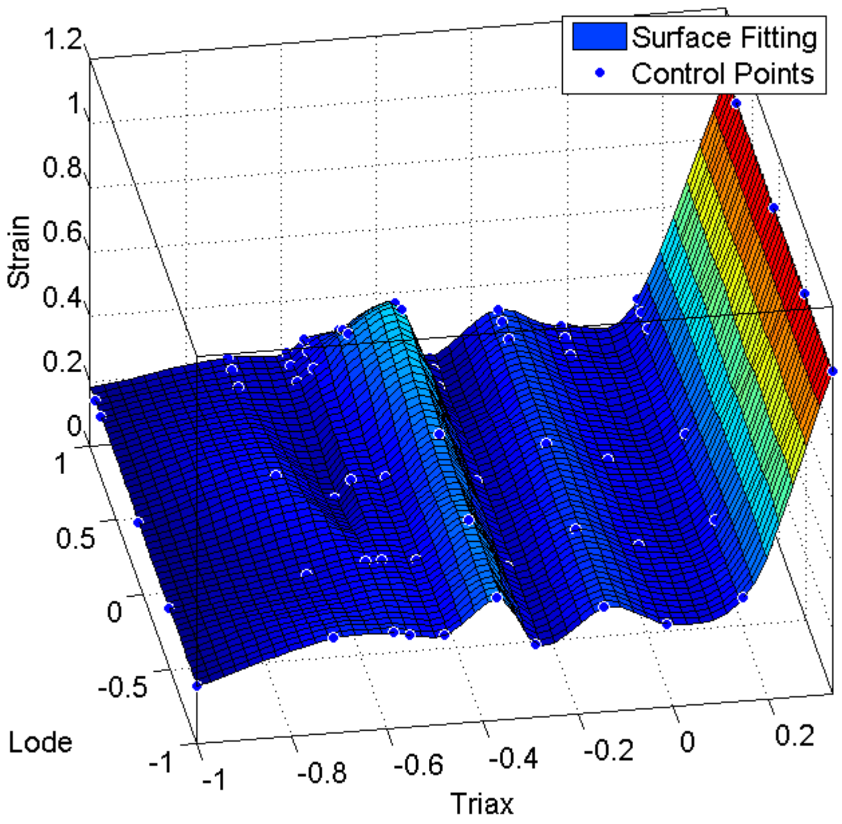
Grid Points

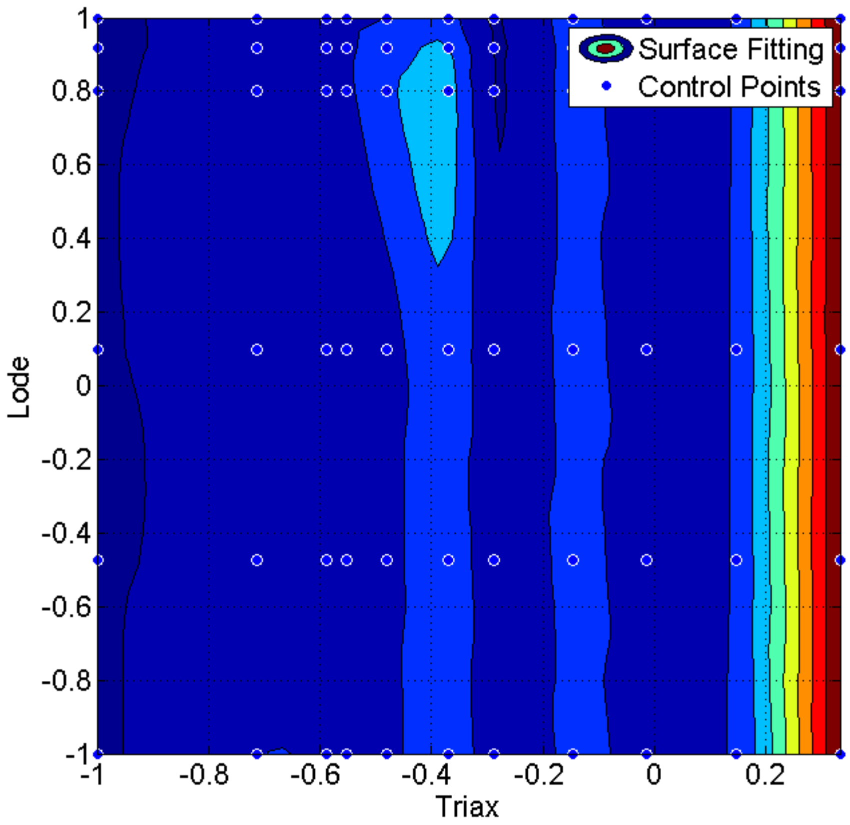
Failure Surface Fitting

- **MATLAB code was written to implement "control point matrix strategy"**
- **Code implementation:**

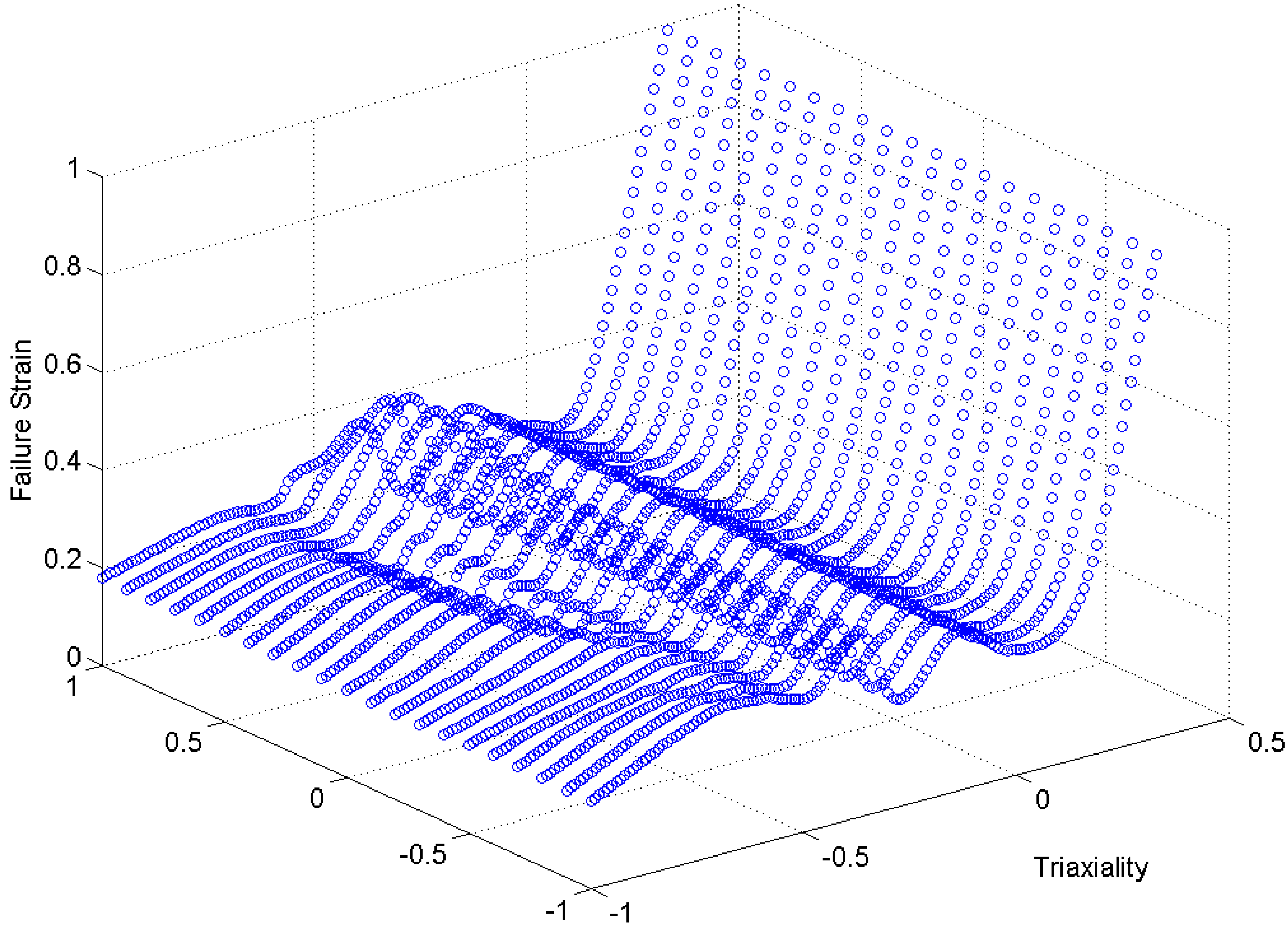
1. **Initializing matrices for Triaxiality, Lode angle, and failure strain**
2. **Populating Triaxiality and Lode angle matrices with grid points**
3. **Populating failure strain by selecting nearest test data point**
   - This sometimes included averaging two or three nearest test data points
4. **Implement Curve Fitting Toolbox generated code for fitting a surface**
   - From Triaxiality of -1 to 0.33
   - From Lode angle of -1 to 1
5. **Create evaluation points using generated fit and store into matrix**
   - Triaxiality: [-1:.01:.33] (every 0.1 units / 134 total points)
   - Lode angle=[-1:.1:1] (every 0.1 units / 21 points)
   - 2814 total points (21 ls-dyna curves)
6. **Generate keyword file automatically using evaluation matrices in previous step**

Surface Fitting Result

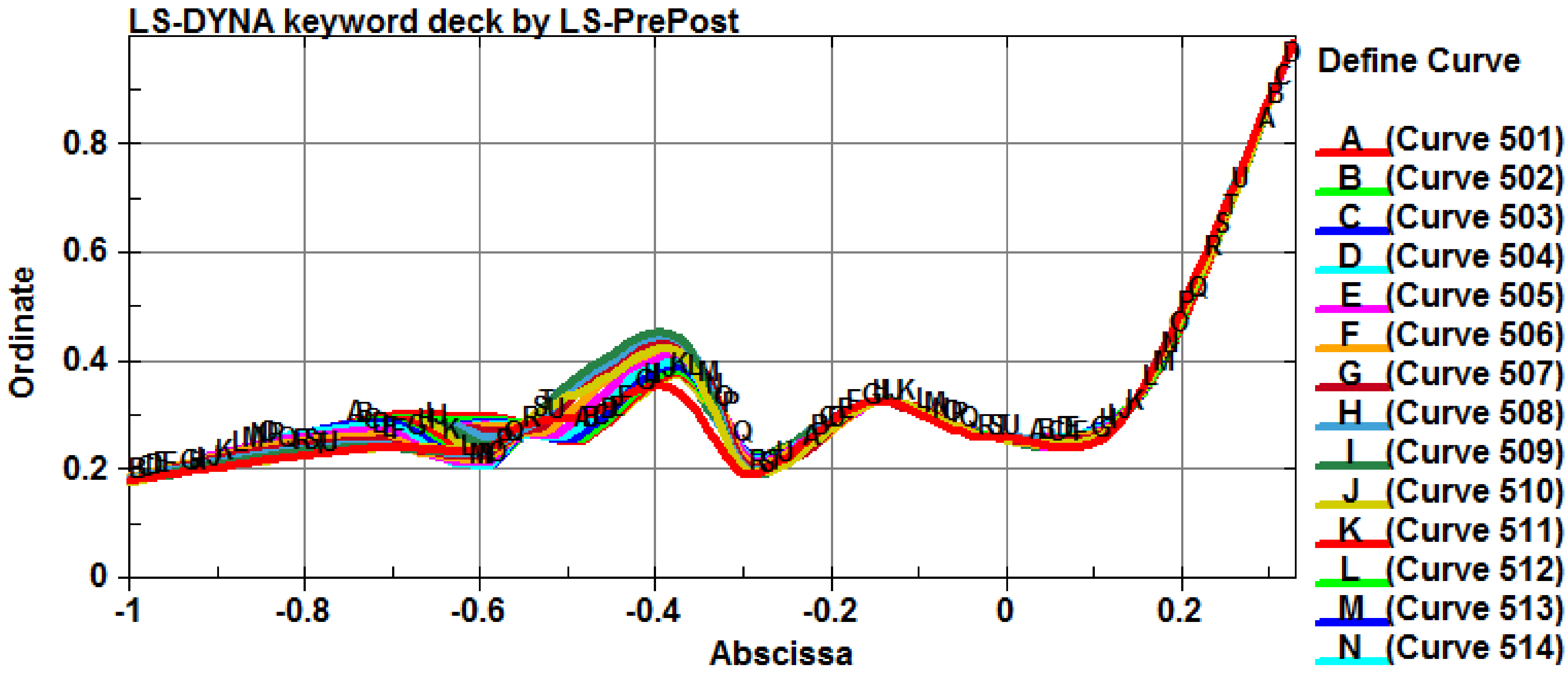




Evaluation Points Result



Keyword File



Test #	GMU		
	Triaxiality	Lode Parameter	Failure Strain
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SG2	-0.412	0.935	0.420
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SG4	-0.592	0.005	0.135
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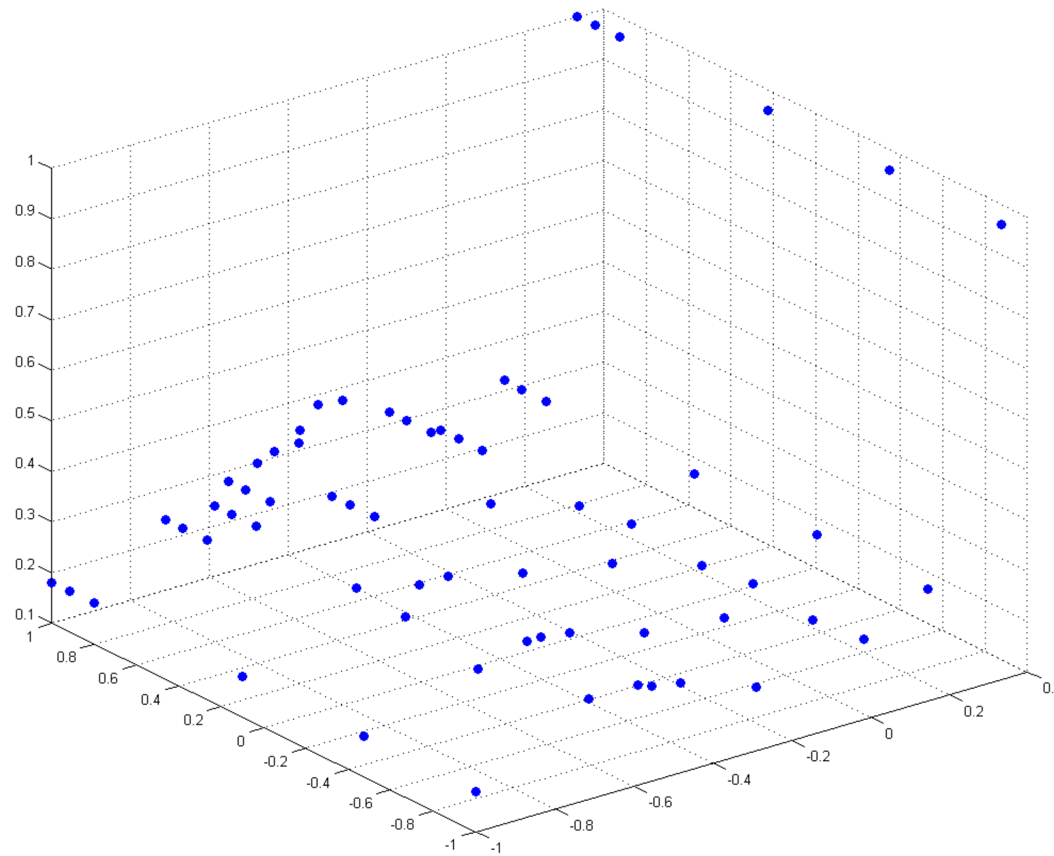
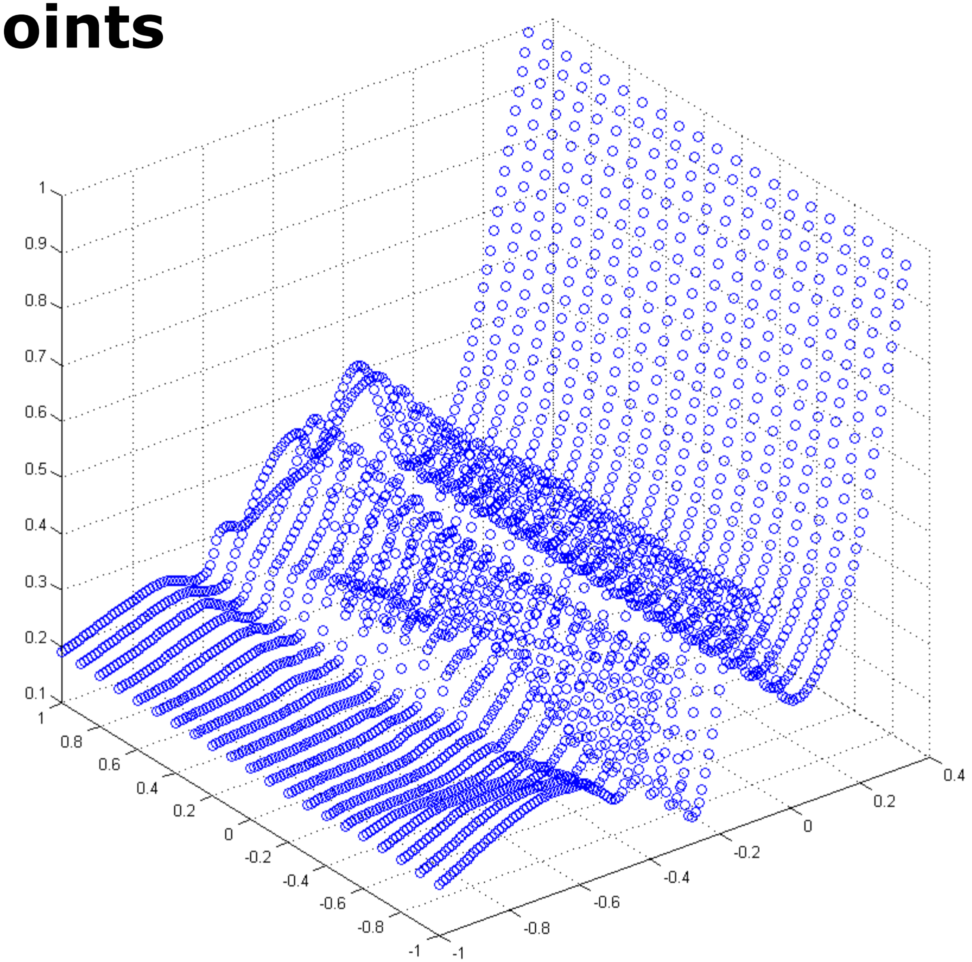
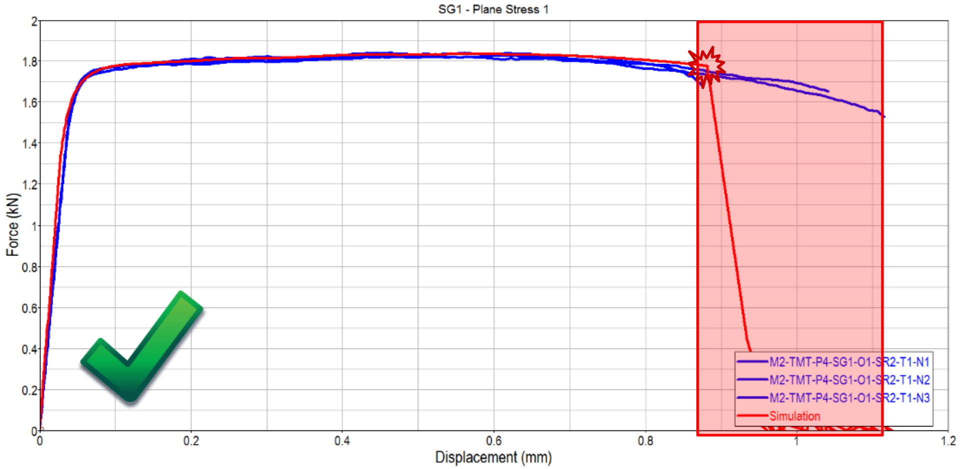
LR4	0.147	-0.450	0.321
Punch 1	-0.653	-0.969	0.297
Punch 2	-0.565	-0.475	0.276

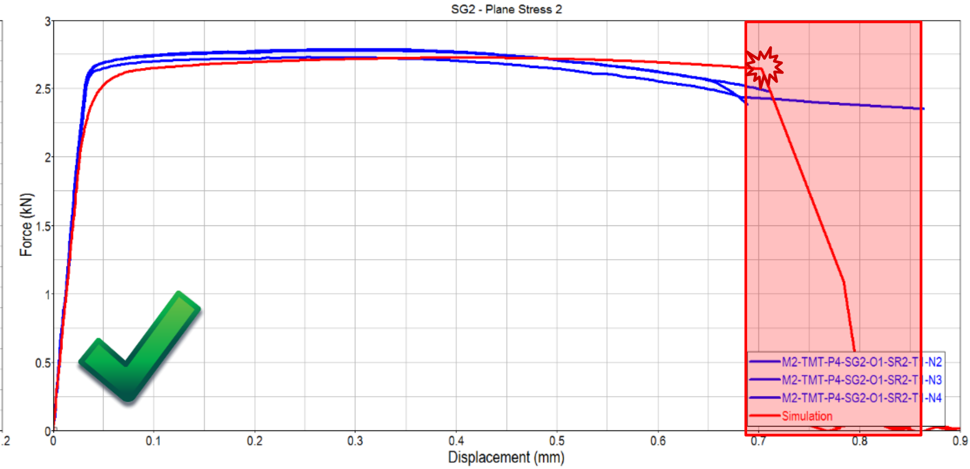


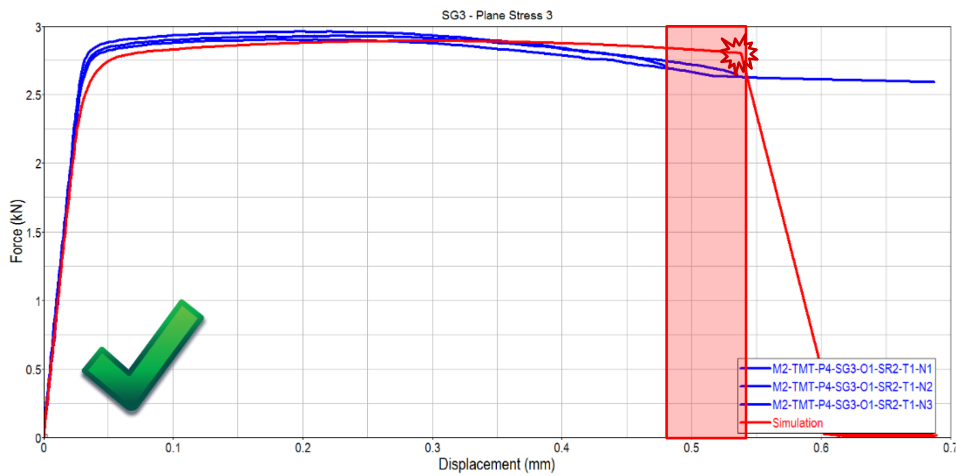
Surface Points

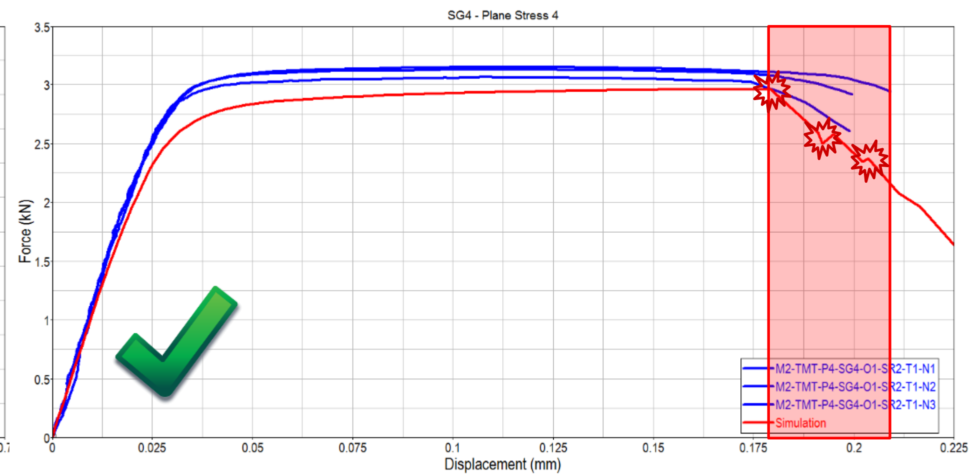


Plane Stress





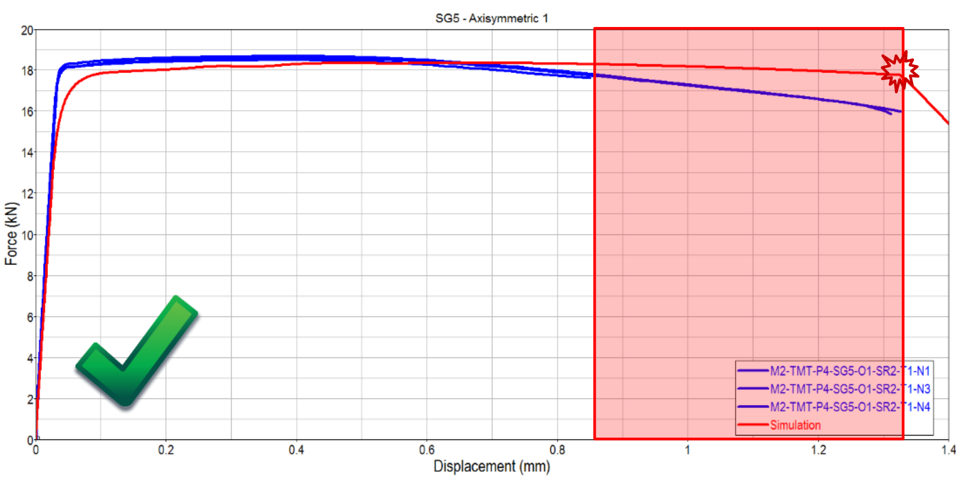


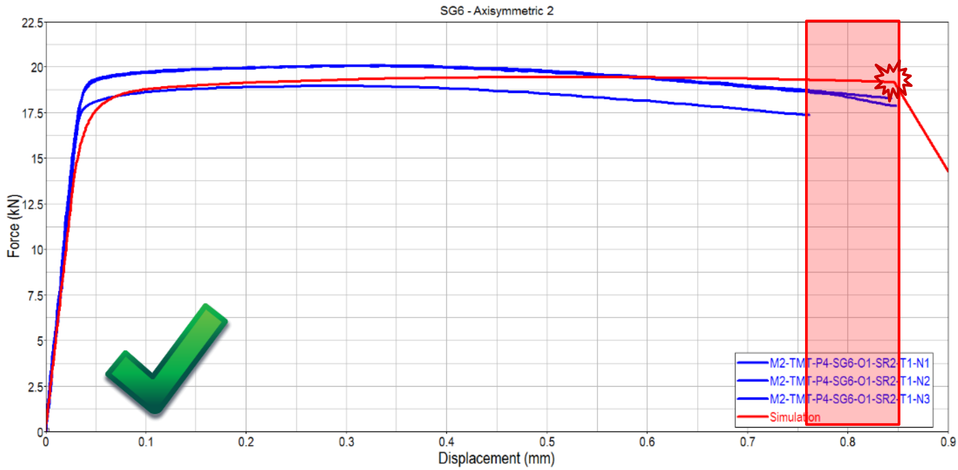


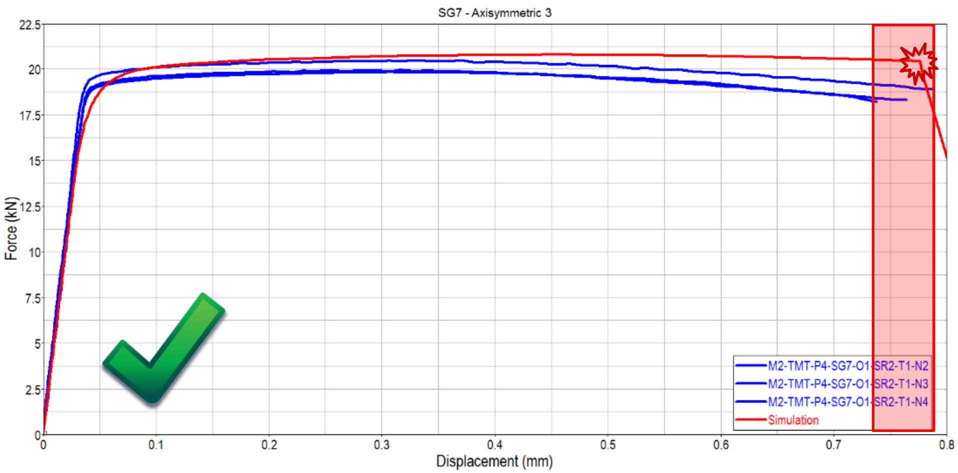
Correct Failure   Incorrect Failure   No Failure

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

Axisymmetric







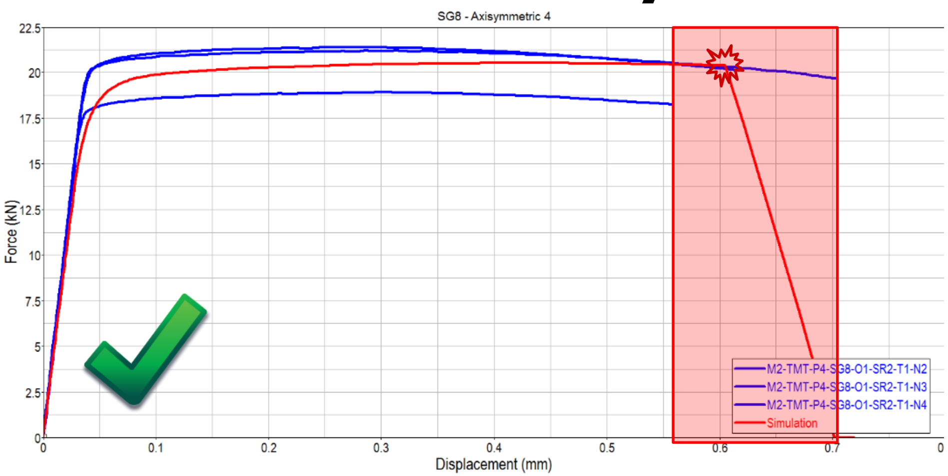
Correct Failure

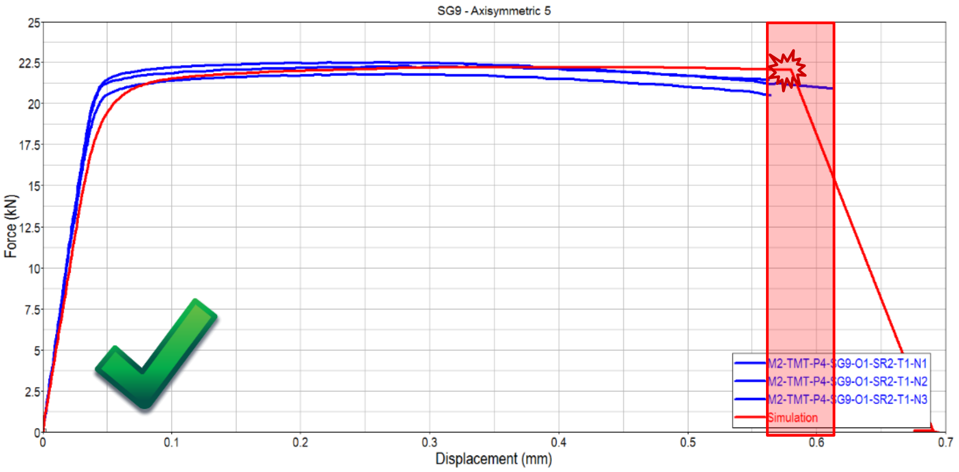
Incorrect Failure

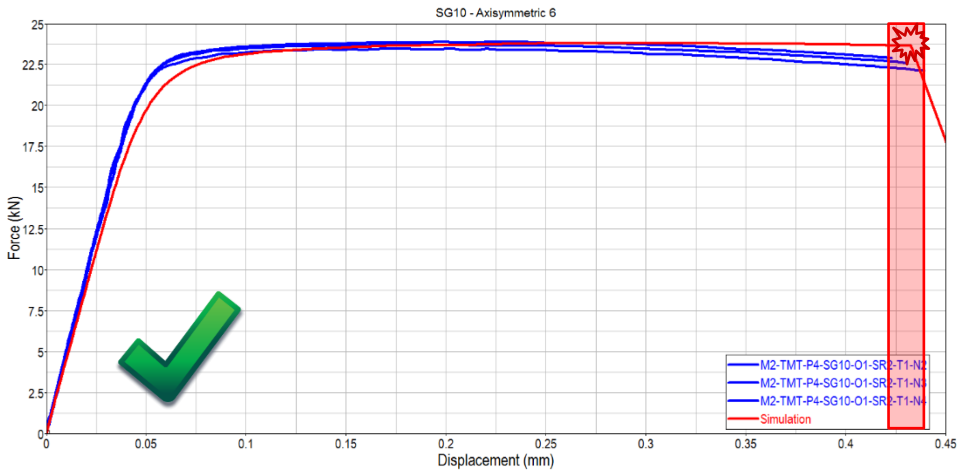
No Failure

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

Axisymmetric



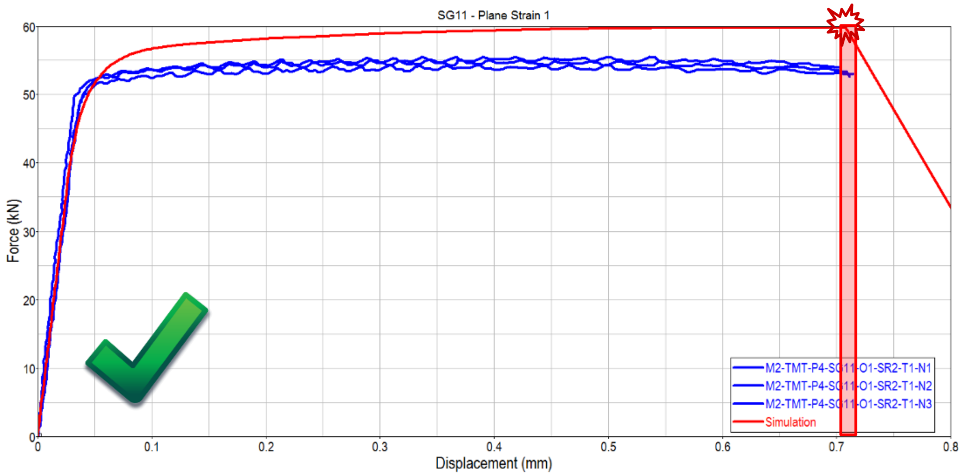


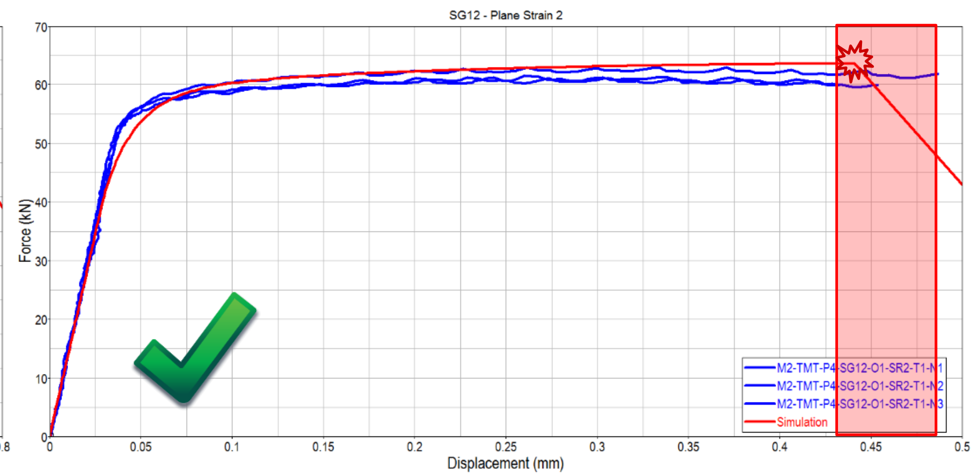


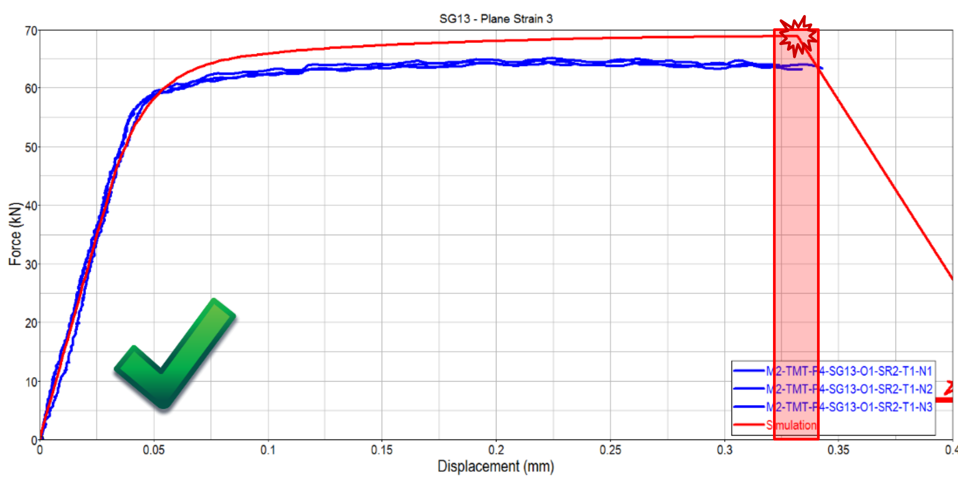
Correct Failure Incorrect Failure No Failure

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

Plane Strain

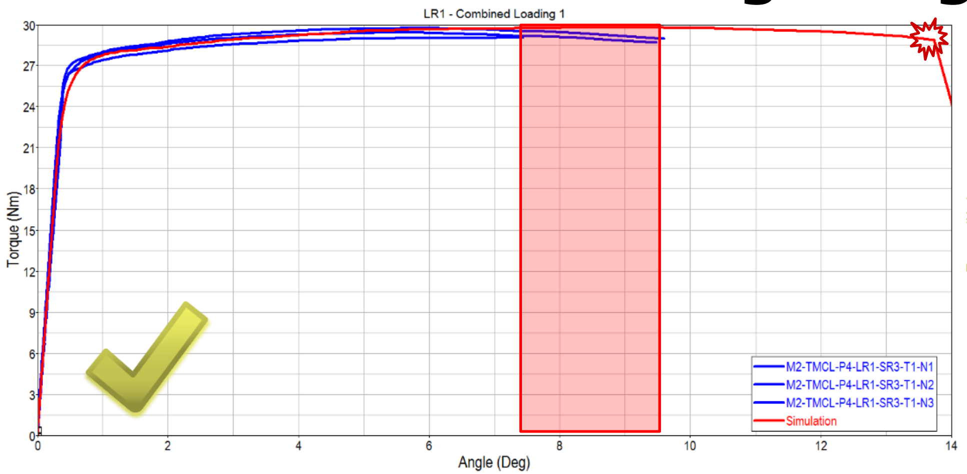


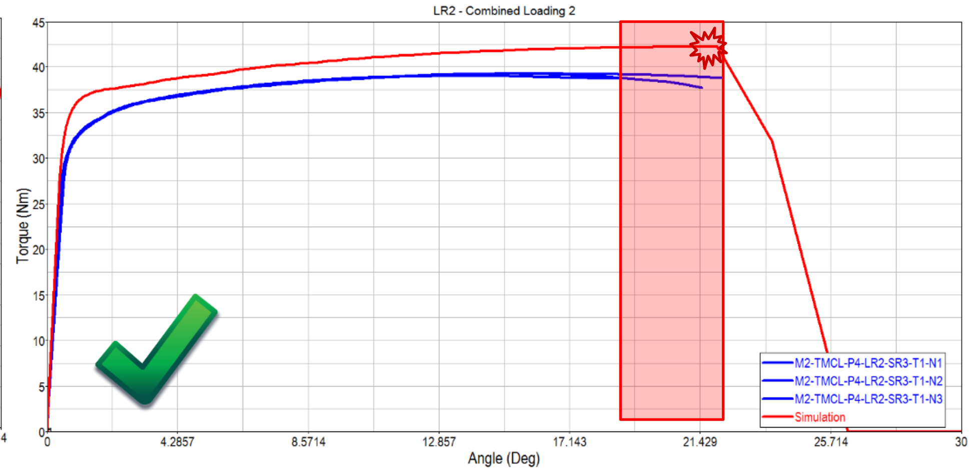


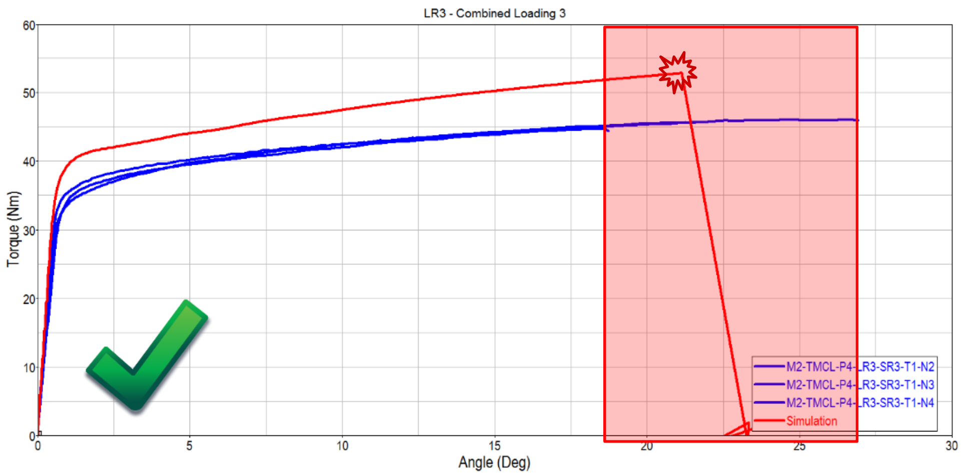


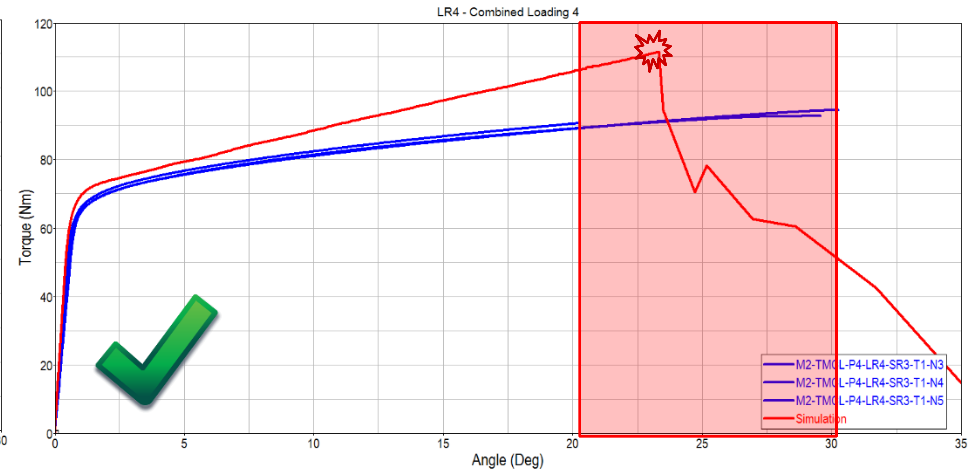
Correct Failure Incorrect Failure No Failure

Combined Loading - Angle



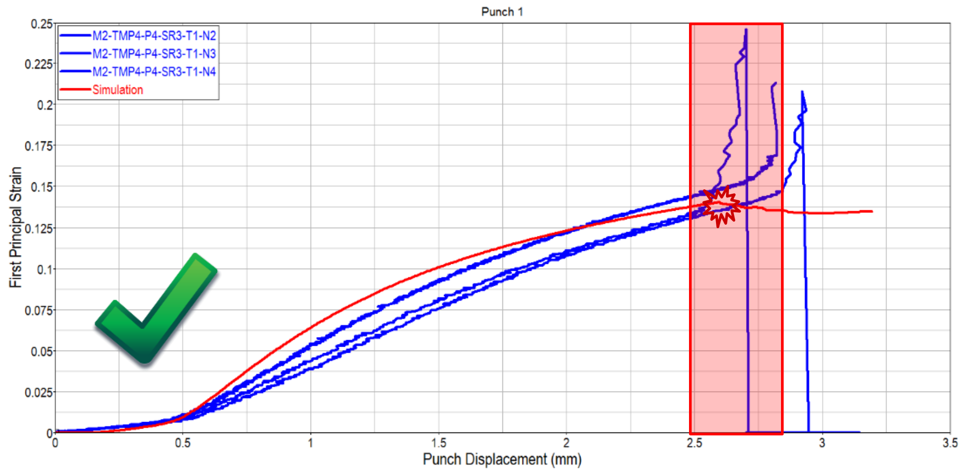


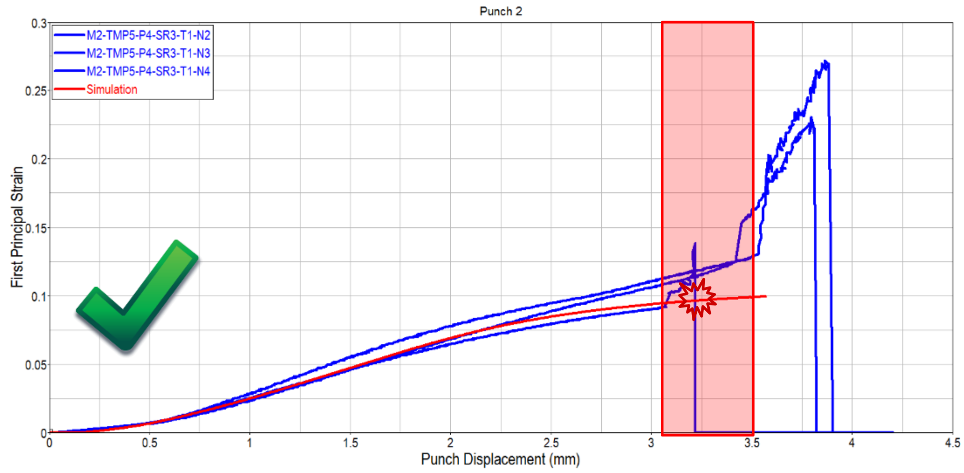




Correct Failure Incorrect Failure No Failure

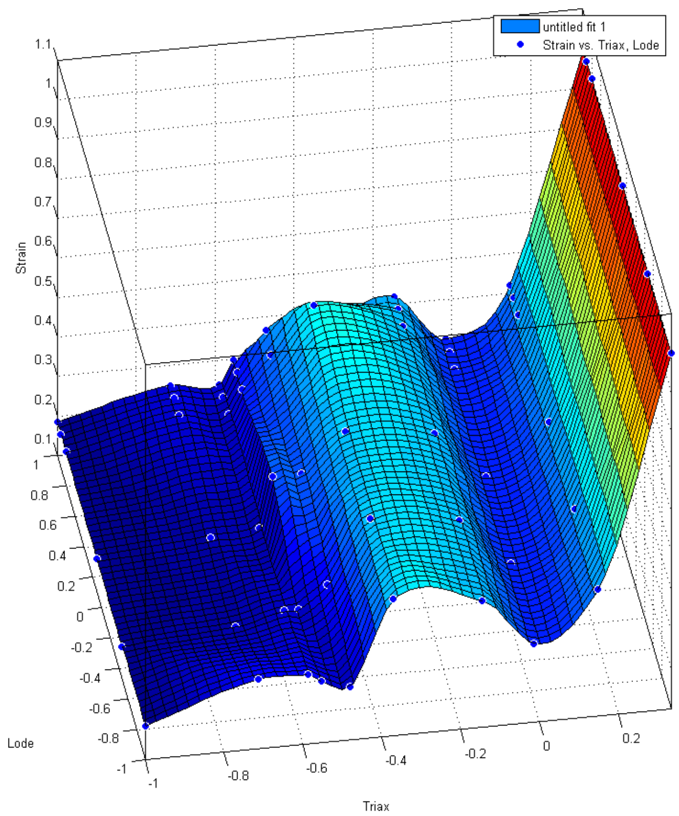
Punch Tests

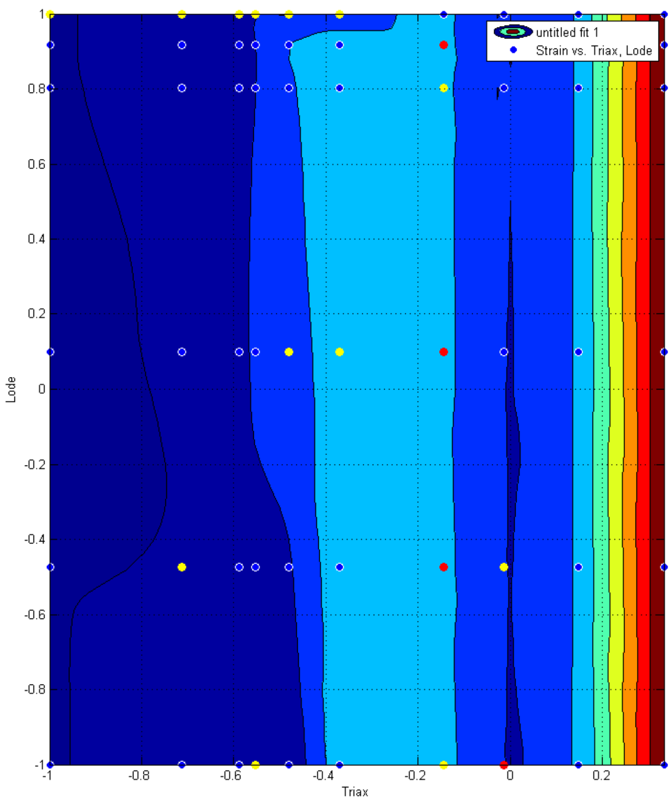




Correct Failure Incorrect Failure No Failure

Final Failure Surface

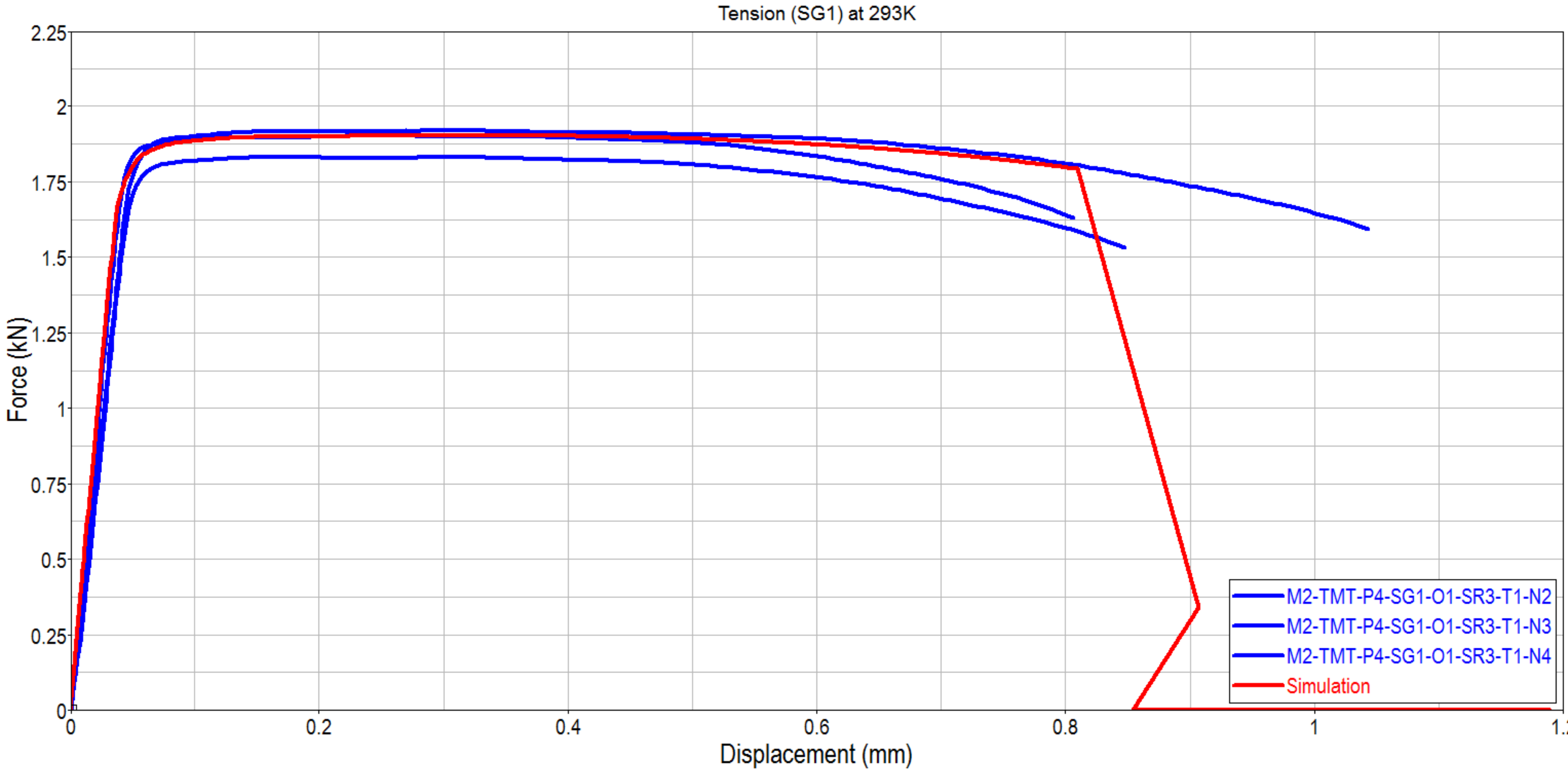




Temperature dependency

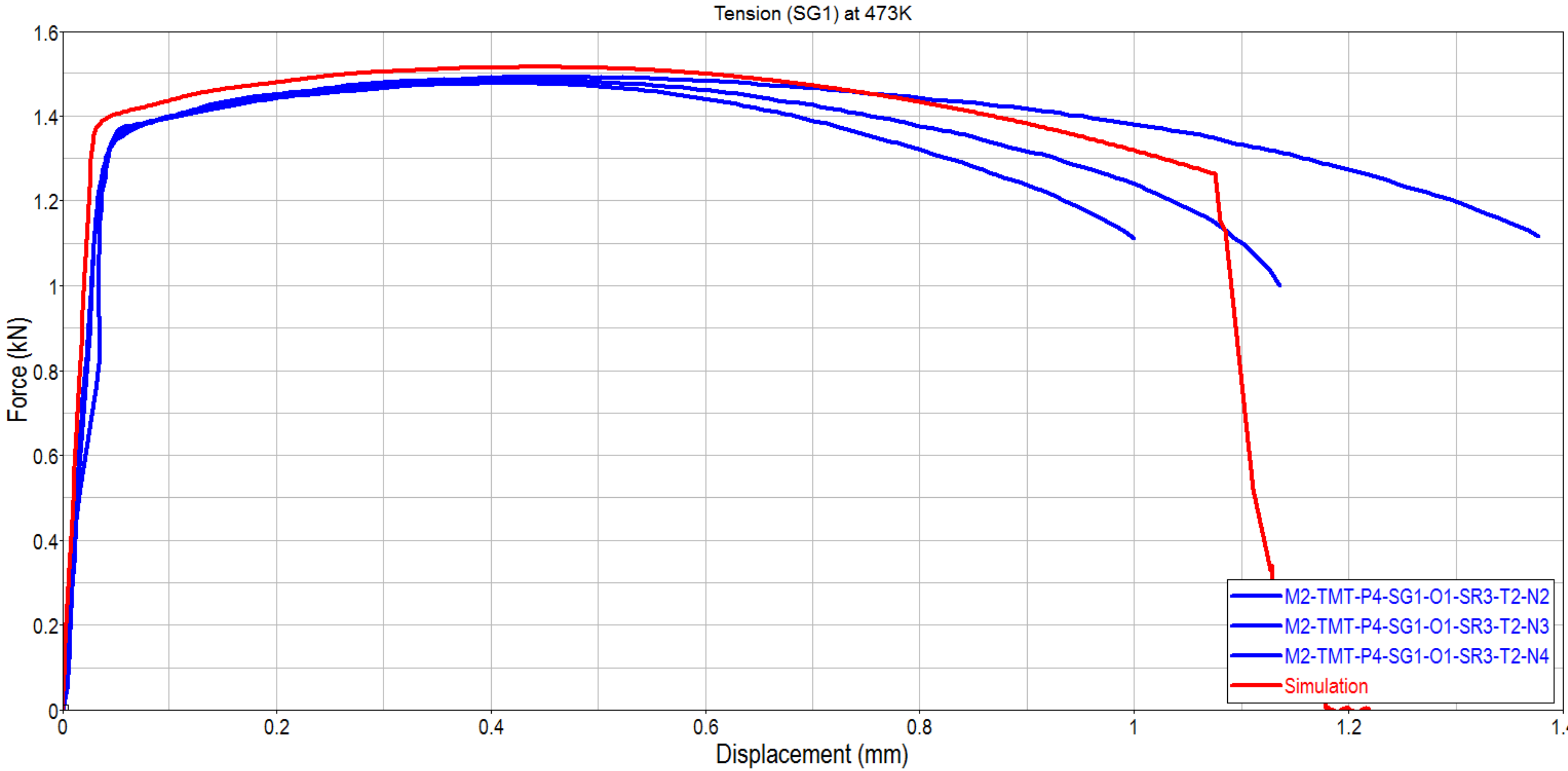
- Generate scaling factor for failure surface based on temperature simulation results
- Temperature tests were quasi-static, so we assume no rate effects, they were also isothermal, so we assume no adiabatic (heat) effects
- Therefore every temperature test is simulated at an arbitrary speed (1000 times higher then reality) using a SINGLE hardening curve specified as the rate dependent 'table'
- This allows to determine a failure strain for every temperature in the usual way by matching the displacement at failure
- From the failure strain for every temperature we derive a scaling function for the failure surface, thus we assume that the temperature effects on the failure surface are independent of the state of stress
- This is 'optimistic' but compatible with the multiplicative split approach used in the Johnson-Cook type laws

293K – With Failure



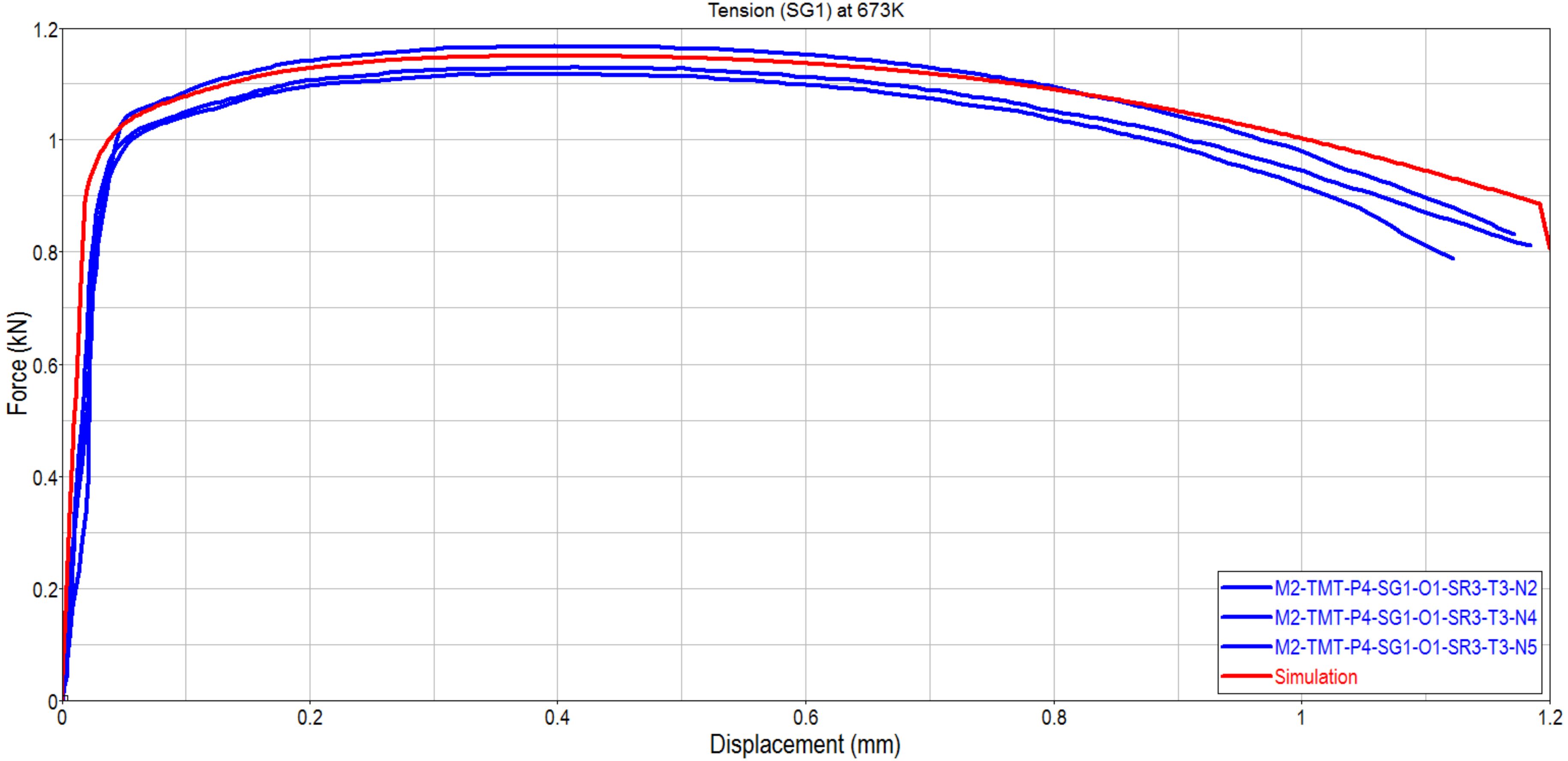

```
*MAT_TABULATED_JOHNSON_COOK_TITLE
MAT_224_Ti64
$       mid        ro         e        pr        cp        tr      beta    numint
          2 4.4300E-6 110.00000  0.342000     526.3       293  0.800000  1.000000
$      lck1      lckt       lcf       lcg       lch       lci
       8003      8003      3000                5000
```

473K – With Failure



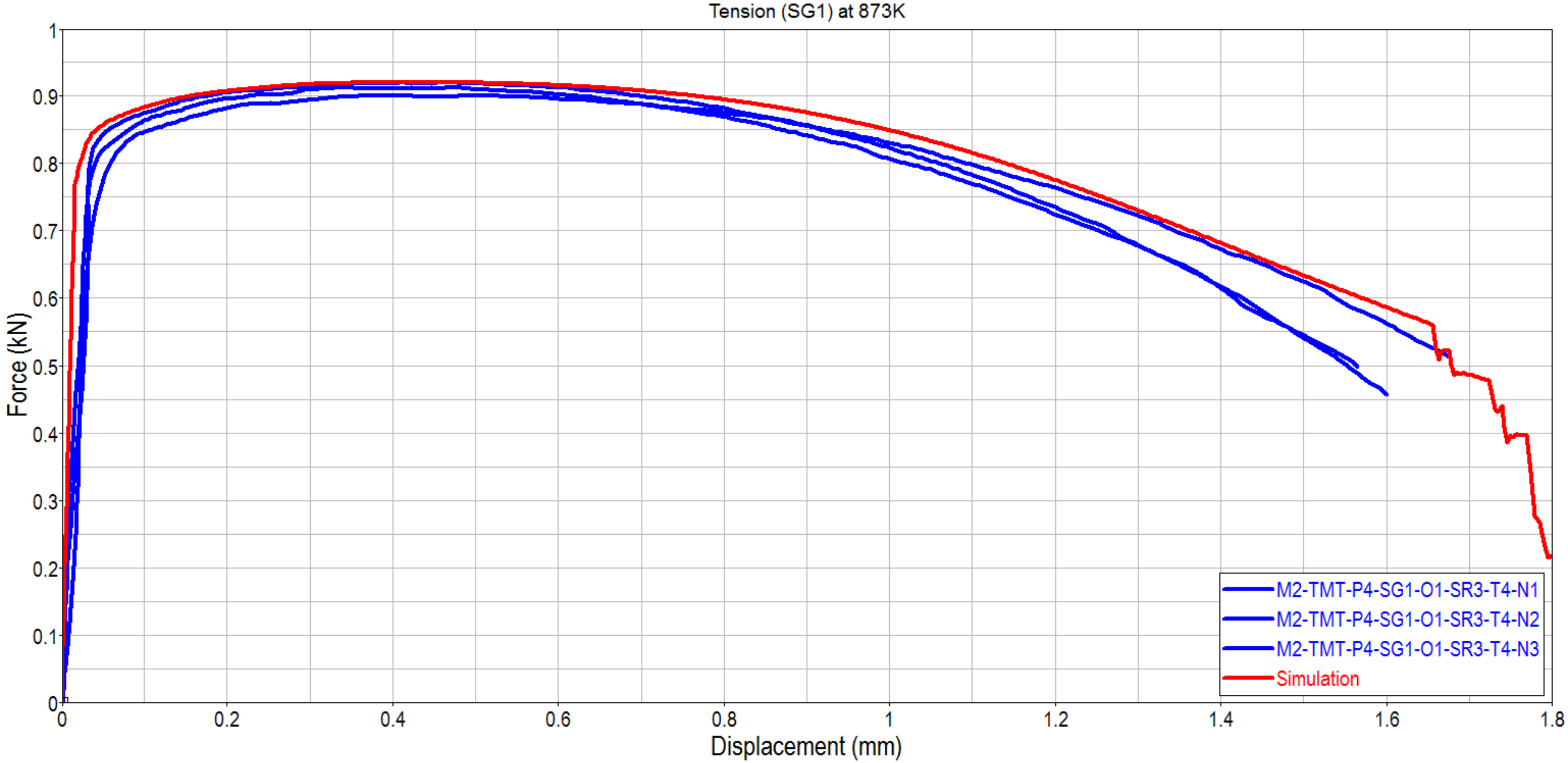

```
*MAT_TABULATED_JOHNSON_COOK_TITLE
MAT_224_Ti64
$      mid        ro         e        pr        cp        tr      beta    numint
         2 4.4300E-6 110.00000  0.342000     526.3       293  0.800000  1.000000
$     lck1      lckt       lcf       lcg       lch       lci
      8004      8004      3000                5000
```

673K – With Failure




```
*MAT_TABULATED_JOHNSON_COOK_TITLE
MAT_224_Ti64
$      mid        ro         e        pr        cp        tr      beta    numint
         2 4.4300E-6 110.00000  0.342000     526.3       293  0.800000  1.000000
$     lck1      lckt       lcf       lcg       lch       lci
      8005      8005      3000                5000
```

873K – With Failure




```
*MAT_TABULATED_JOHNSON_COOK_TITLE
MAT_224_Ti64
$      mid        ro         e        pr        cp        tr      beta    numint
         2 4.4300E-6 110.00000  0.342000     526.3       293  0.800000  1.000000
$     lck1      lckt       lcf       lcg       lch       lci
      8006      8006      3000                5000
```

Temperature dependency of failure

- **Created a temperature scaling curve for the failure surface**

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$              Failure - Temperature Curve                 $
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*DEFINE_CURVE
$     LCID       SIDR        SFA        SFO       OFFA       OFFO     DATYP
      5000
$                  A1                    O1
              293.00                  1.000
              473.15                  1.950
              673.15                  1.950
              873.15                  2.950
             1877.00                  2.950
```

- **Capped at 873 K**

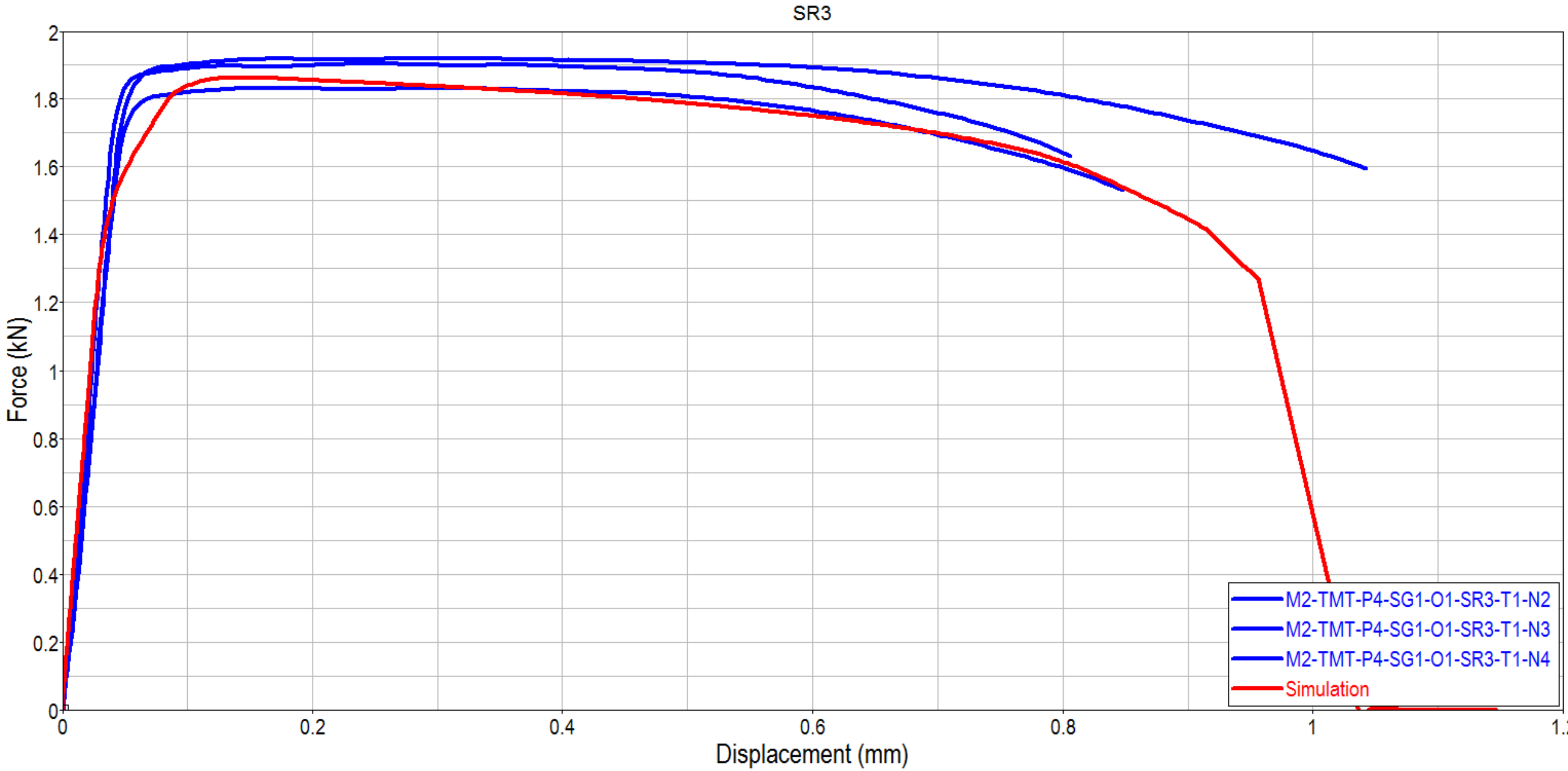
Strain Rate dependency

- We now simulate the rate dependent tests SR3, SR4 and SR5 at real life velocities using the full input: rate dependent table, temperature dependent table, failure surface, temperature scaling function and strain rate scaling function

- SR3 is 1/s, SR4 is 600/s and SR5 is 1500/s, in dynamic experiments we have temperature as well as strain rate effects

- Some tuning of the strain rate scaling function is necessary to obtain good failure response in all 3 cases

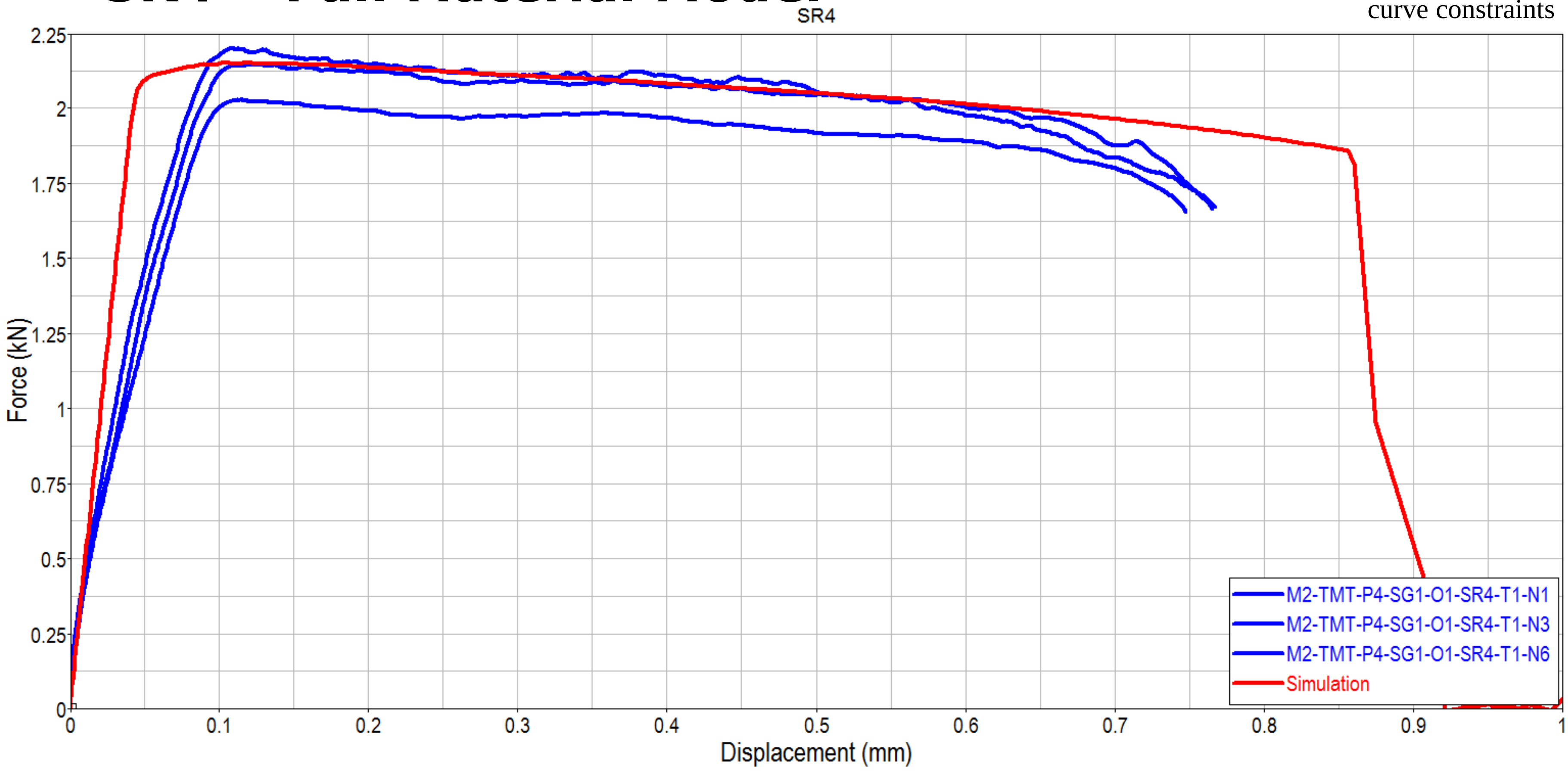
SR3 – Full Material Model




```
*MAT_TABULATED_JOHNSON_COOK_TITLE
MAT_224_Ti64
$      mid        ro         e        pr        cp        tr      beta    numint
         2 4.4300E-6 110.00000  0.342000     526.3       293  0.800000  1.000000
$     lck1      lckt       lcf       lcg       lch       lci
      1000      2000      3000      4000      5000
```

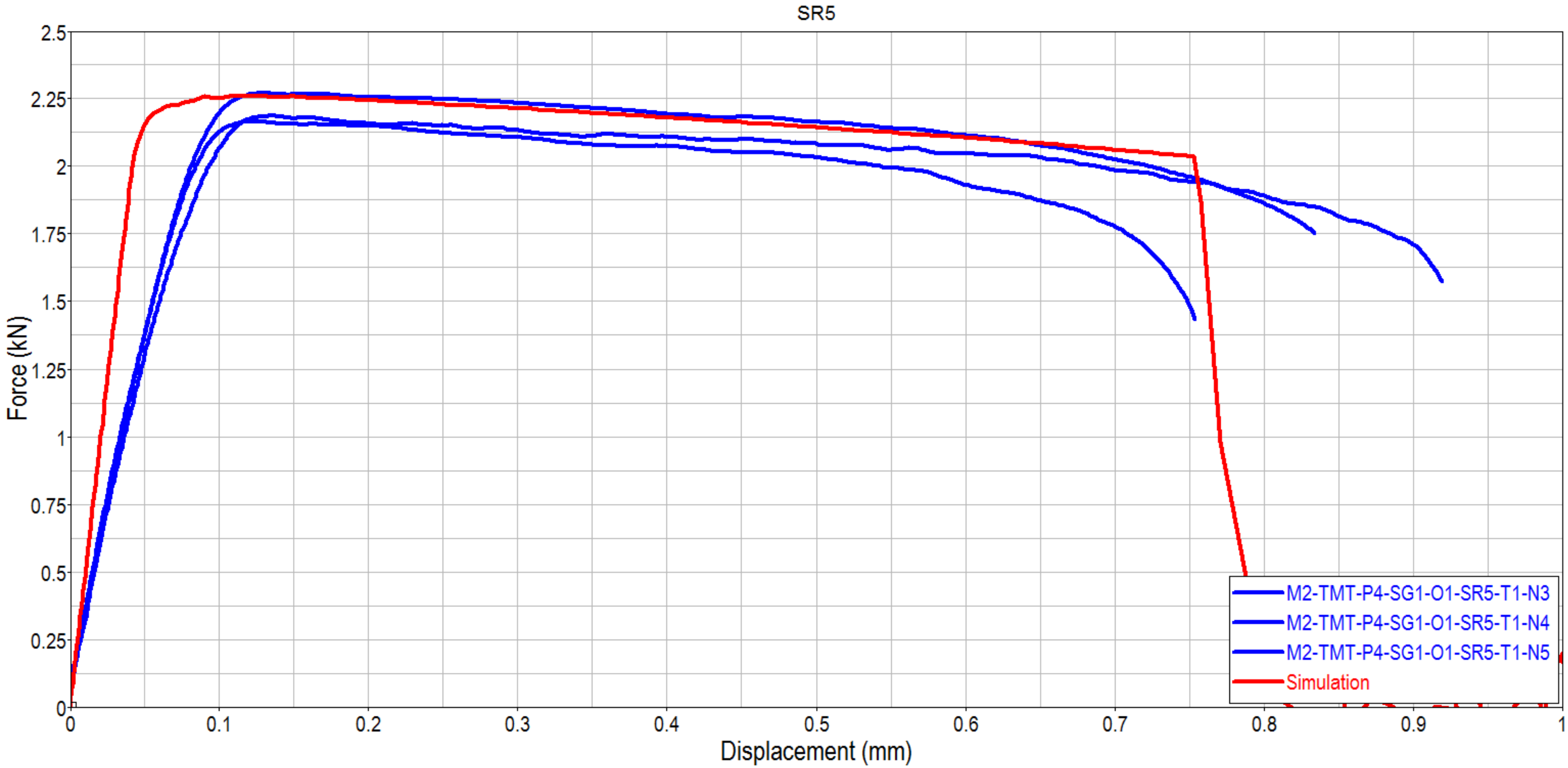
Failure displacement
due to non-monotonic
curve constraints

SR4 – Full Material Model




```
*MAT_TABULATED_JOHNSON_COOK_TITLE
MAT_224_Ti64
$      mid        ro         e        pr        cp        tr      beta    numint
         2 4.4300E-6 110.00000  0.342000     526.3       293  0.800000  1.000000
$     lck1      lckt       lcf       lcg       lch       lci
      1000      2000      3000      4000      5000
```

SR5 – Full Material Model

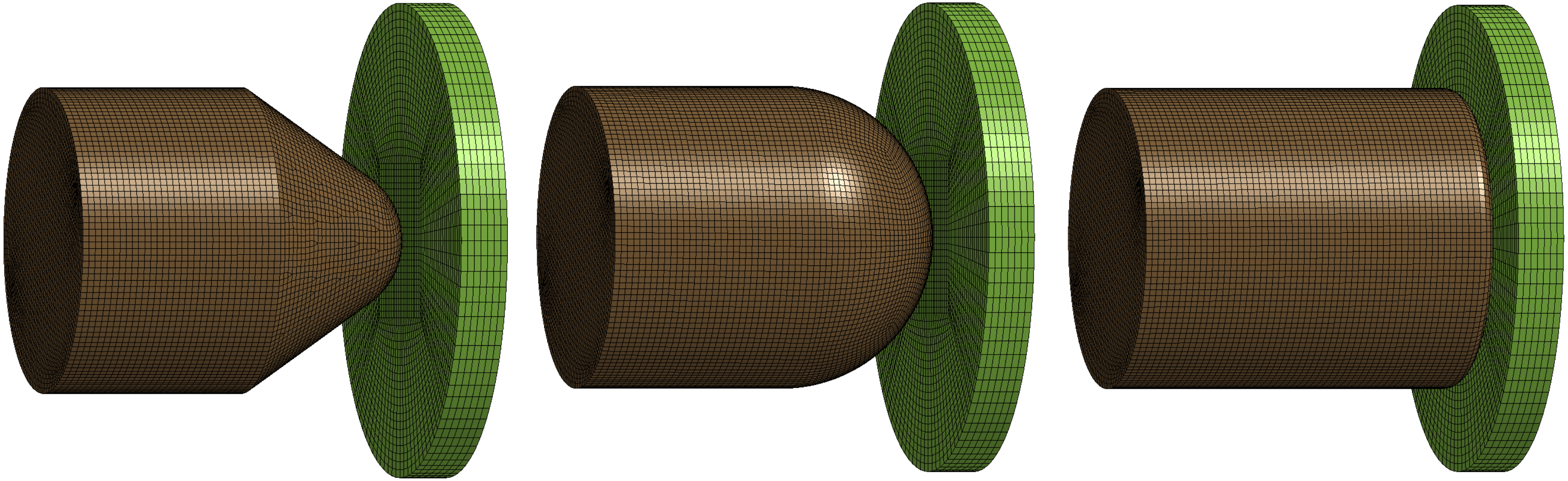



```
*MAT_TABULATED_JOHNSON_COOK_TITLE
MAT_224_Ti64
$      mid        ro         e        pr        cp        tr      beta    numint
         2 4.4300E-6 110.00000  0.342000     526.3       293  0.800000  1.000000
$     lck1      lckt       lcf       lcg       lch       lci
      1000      2000      3000      4000      5000
```

Strain Rate Failure Curve Adjustments

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$              Failure - Strain Rate Curve                 $
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*DEFINE_CURVE
$     LCID       SIDR        SFA        SFO       OFFA       OFFO      DATYP
      4000
$                  A1                    O1
             0.000010                 1.000
             0.001000                 0.750
             2.350000                 0.370
             6.610000                 0.370
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$              Failure - Temperature Curve                 $
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*DEFINE_CURVE
$     LCID       SIDR        SFA        SFO       OFFA       OFFO      DATYP
      5000
$                  A1                    O1
               293.00                 1.000
               473.15                 1.950
               673.15                 1.950
               873.15                 2.950
```

Dynamic Punch Tests



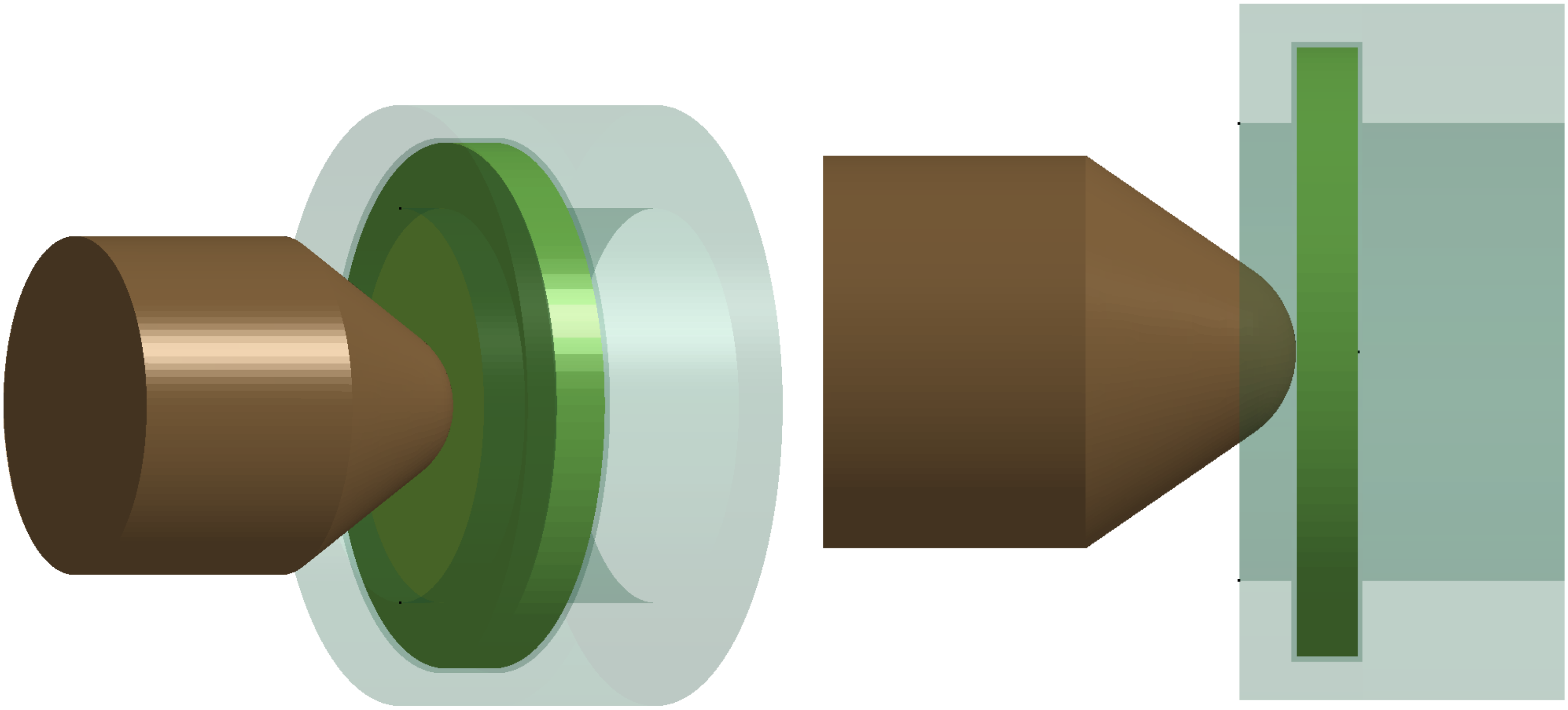
Full Material Model:

*MAT_TABULATED_JOHNSON_COOK_TITLE
MAT_224_Ti64

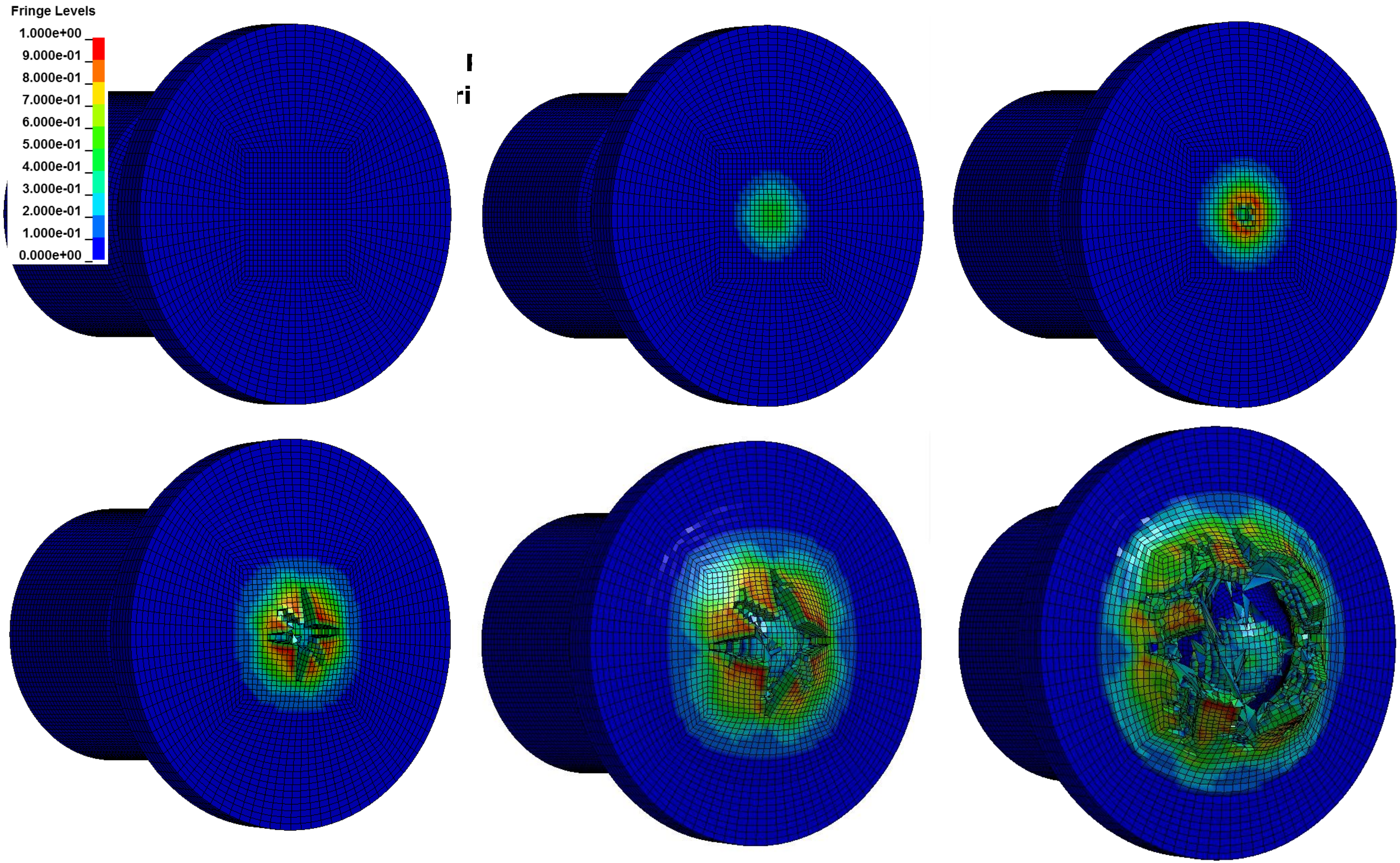
$	mid	ro	e	pr	cp	tr	beta	numint
	2	4.4300E-6	110.00000	0.342000	526.3	293	0.800000	1.000000
$	lck1	lckt	lcf	lcg	lch	lci		
	1000	2000	3000	4000	5000			

Boundary Conditions

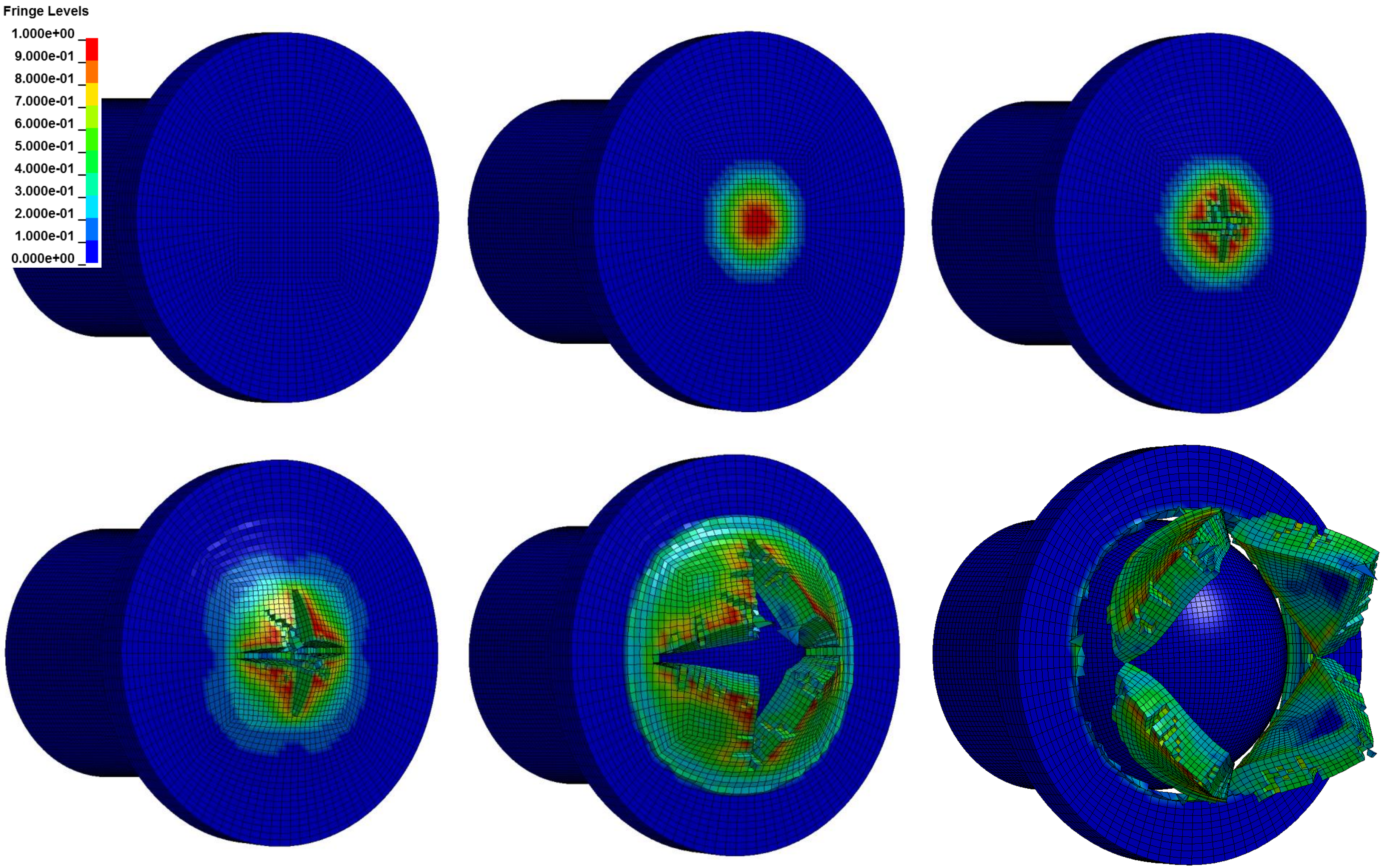
- The adapter and clamp assembly was modeled



Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V



Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

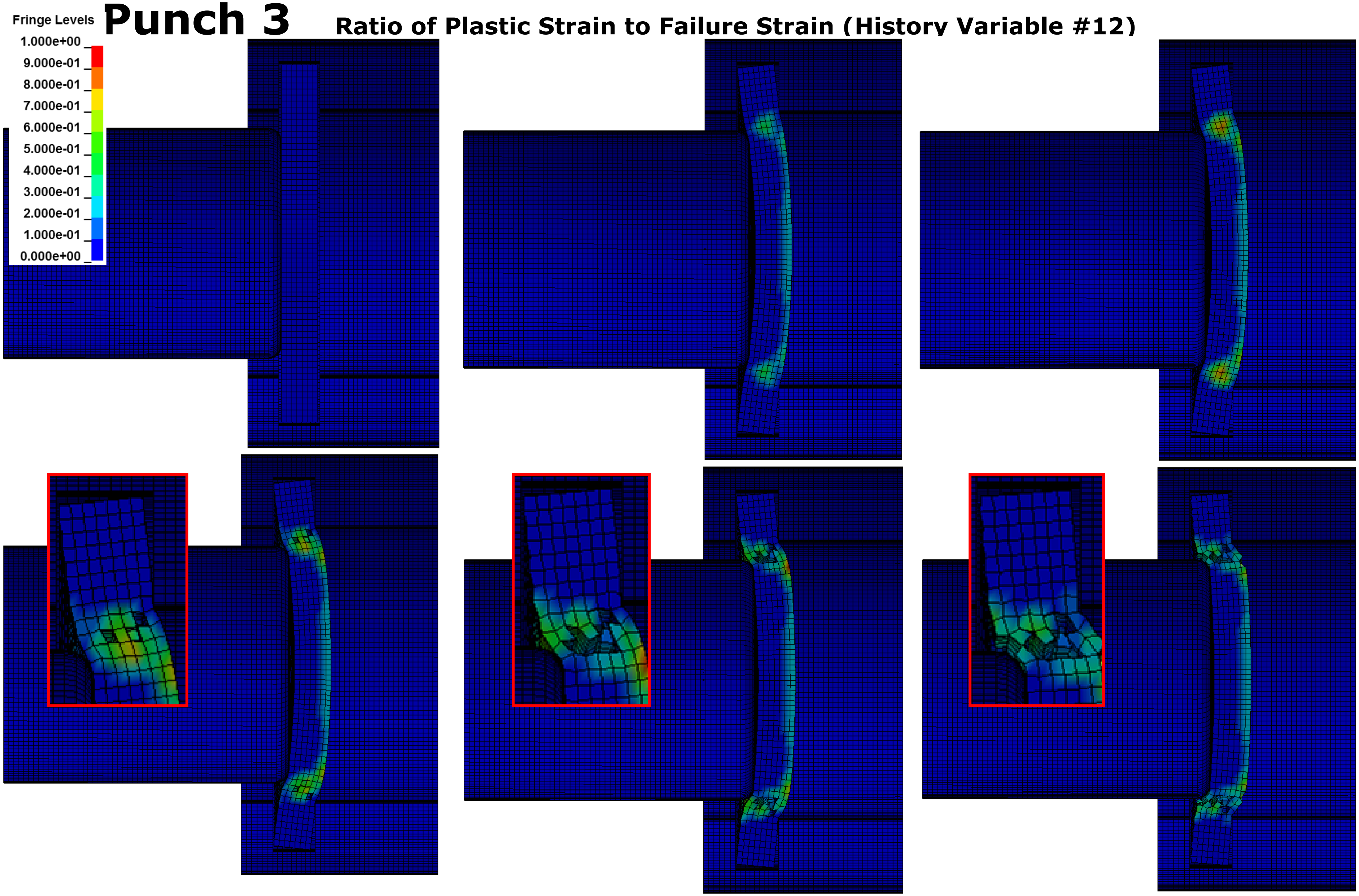


Punch 2 **Ratio of Plastic Strain to Failure Strain (History Variable #12)**

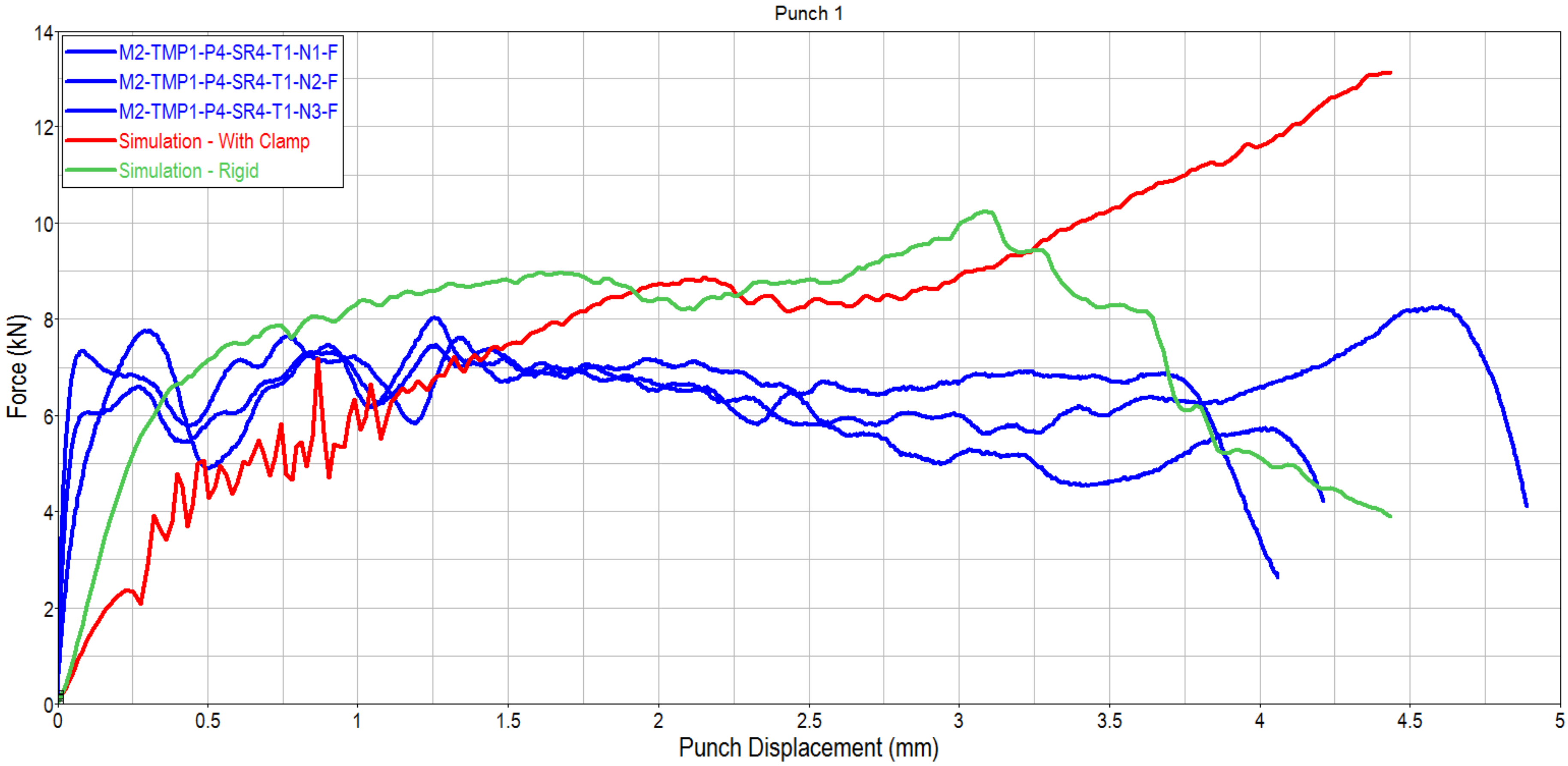
Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

Punch 3

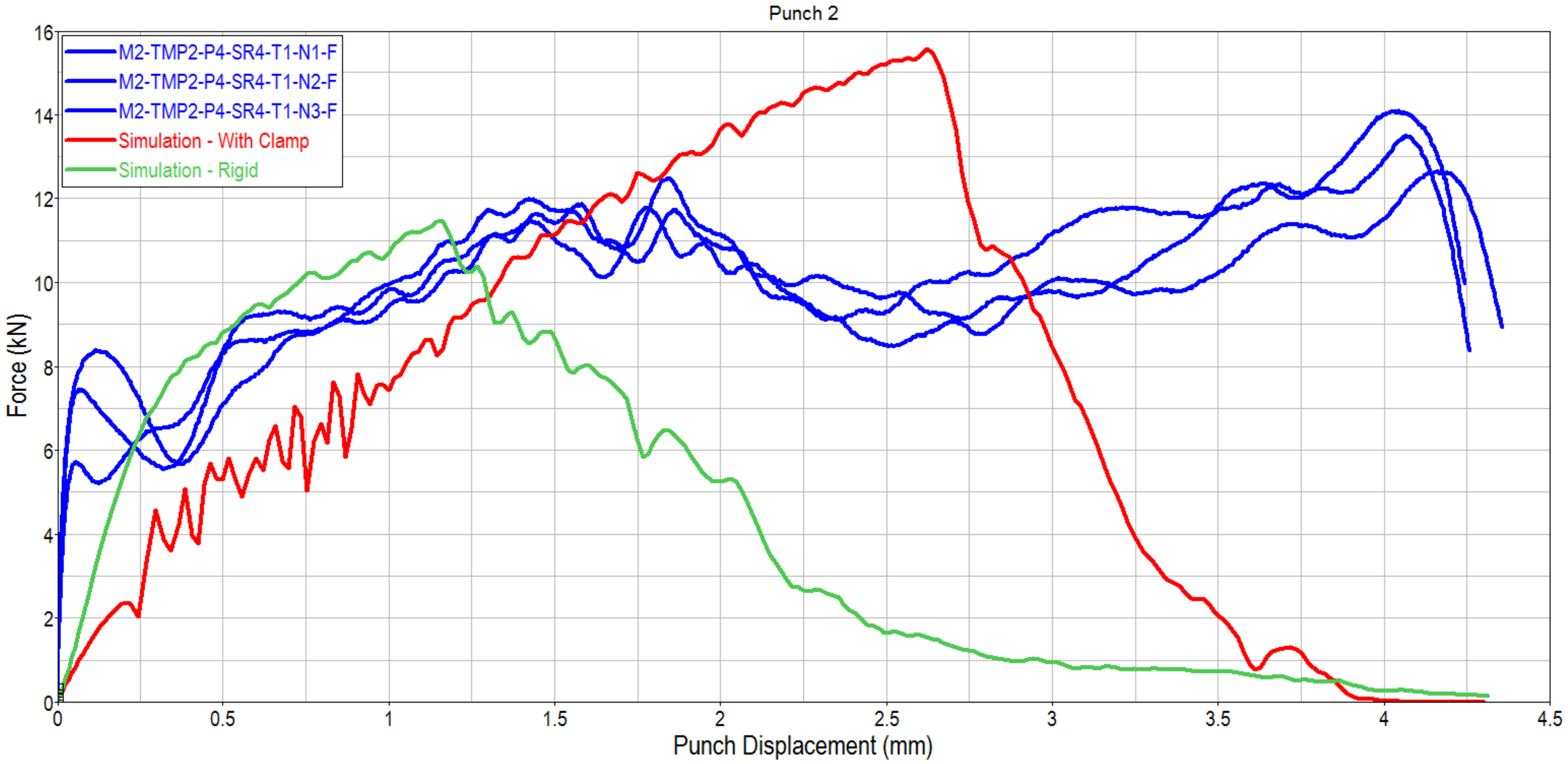
Ratio of Plastic Strain to Failure Strain (History Variable #12)



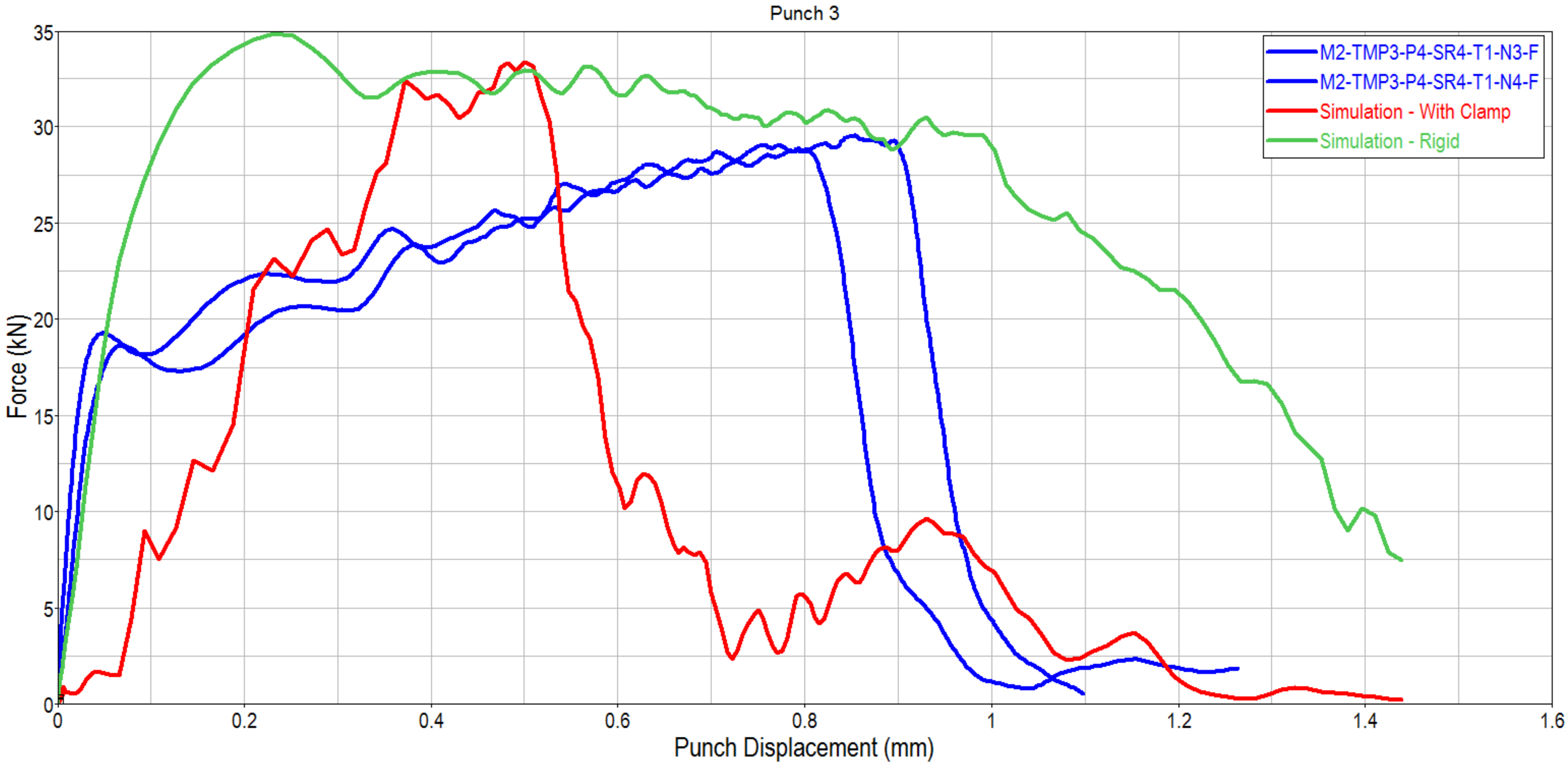
Punch 1 Clamp vs. Rigid



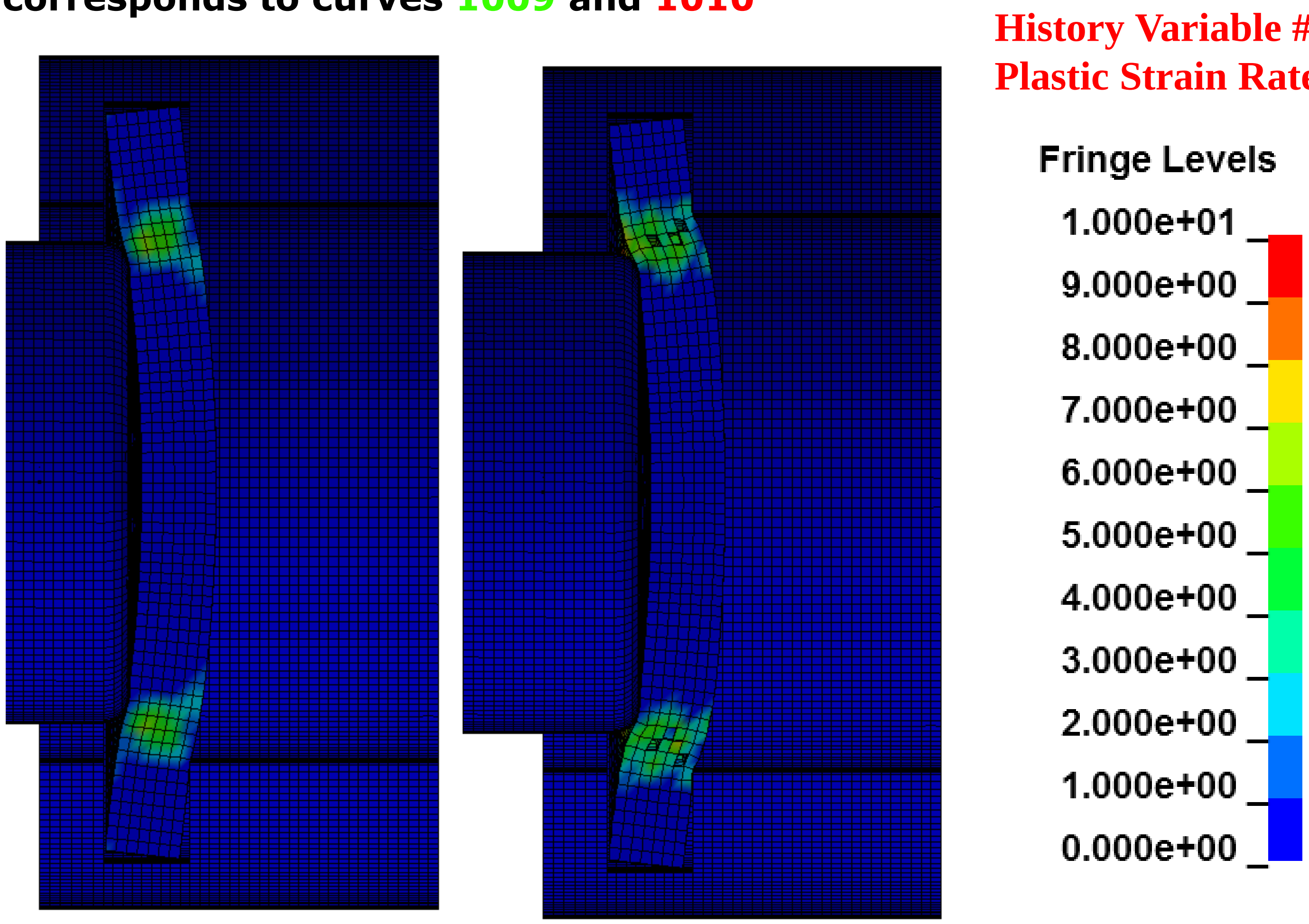
Punch 2 Clamp vs. Rigid



Punch 3 Clamp vs. Rigid

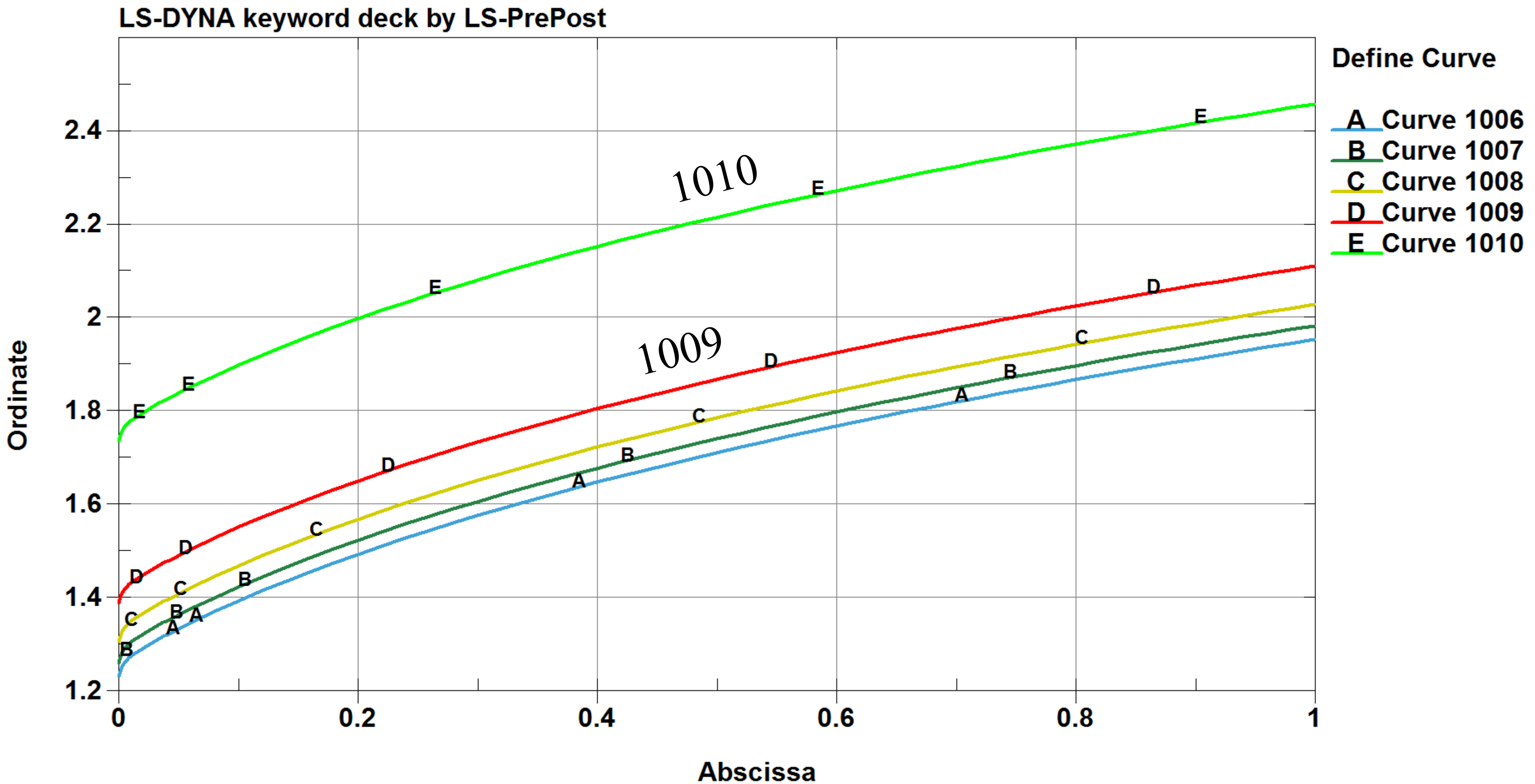


- Strain rates range from 5 1/ms to 10 1/ms
- This corresponds to curves 1009 and 1010



Strain Rates for Punch 3

Yield Curves

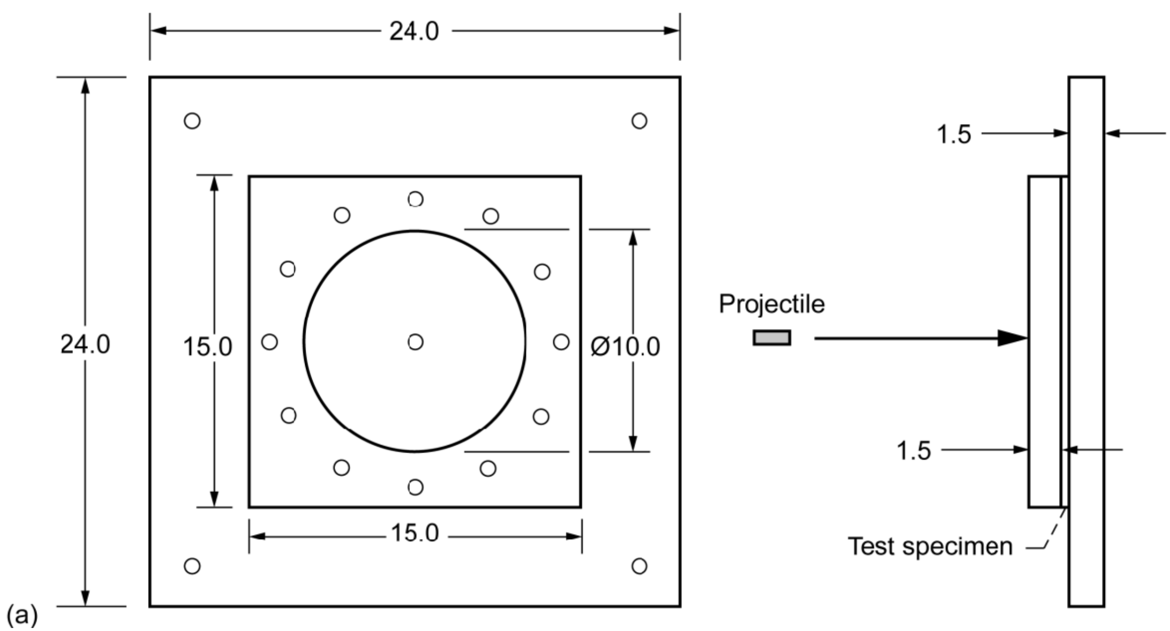


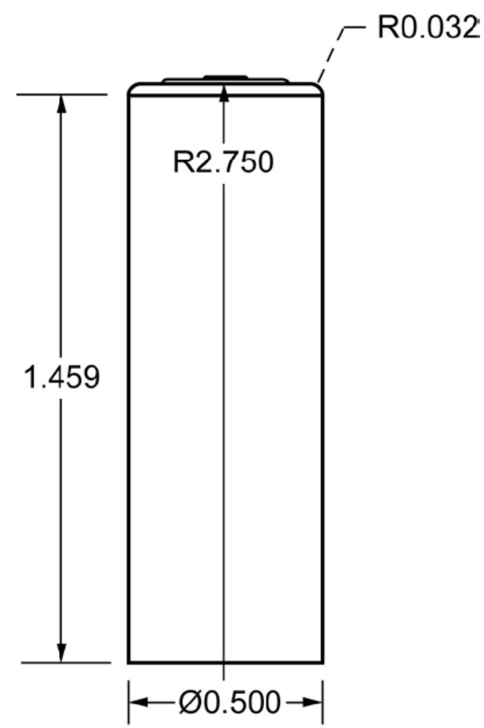
NASA Ballistic Test Series

NASA/TM—2013-217869 DOT/FAA/TC–12/58

Impact Testing of Aluminum 2024 and Titanium 6Al-4V for Material Model Development

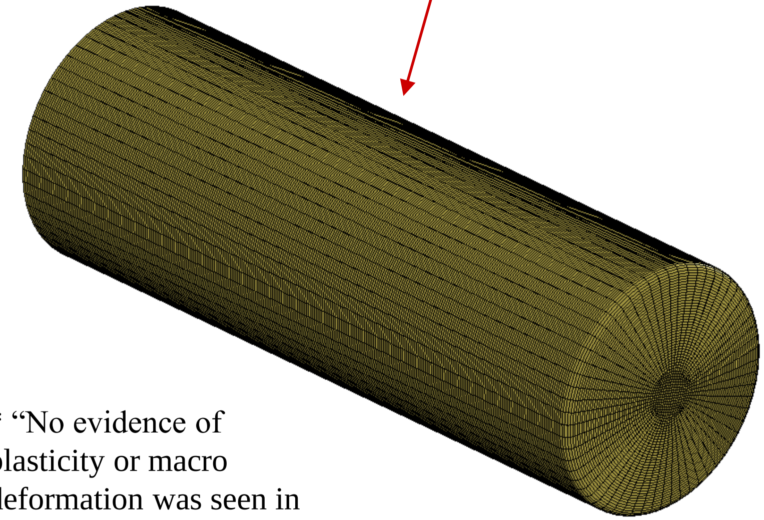
J. Michael Pereira, Duane M. Revilock, Bradley A. Lerch and Charles R. Ruggeri
Glenn Research Center, Cleveland, Ohio



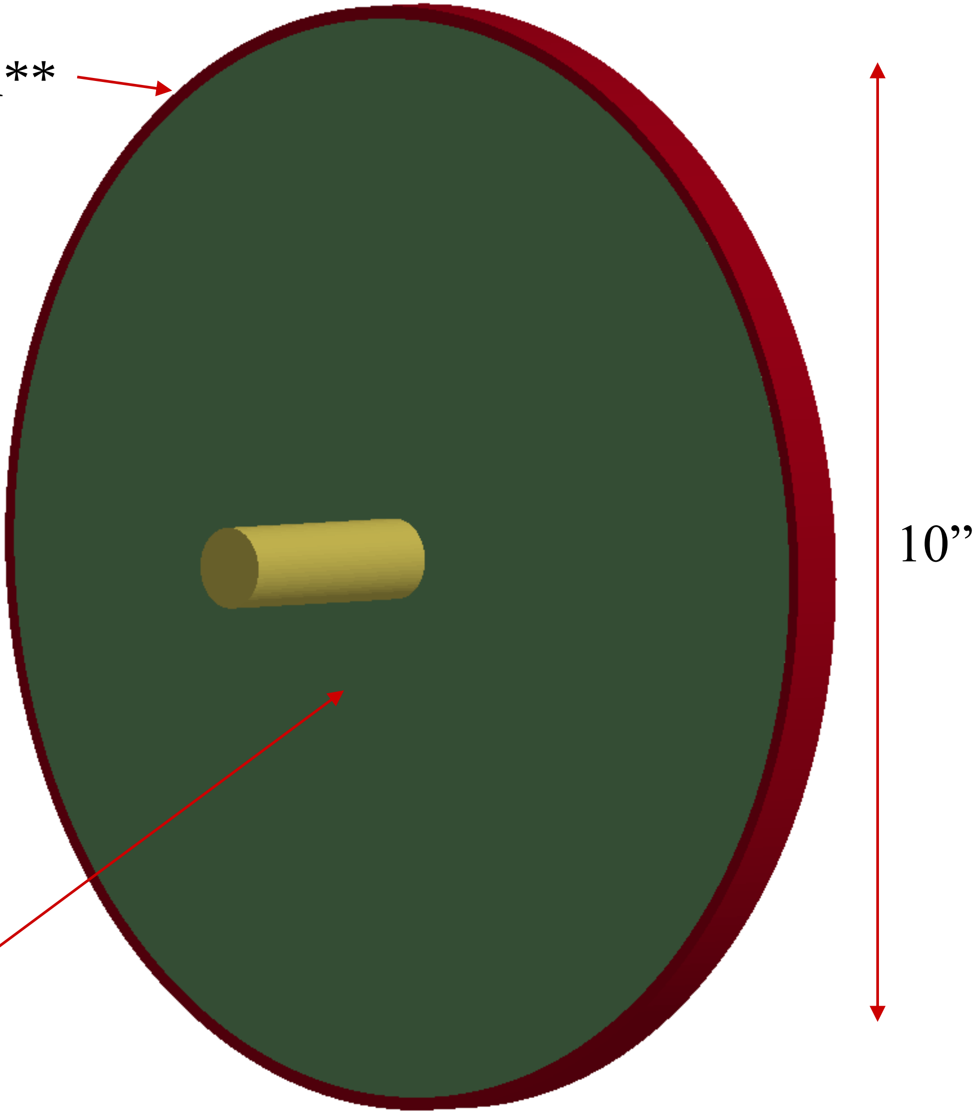


Finite Element Model

MAT_ELASTIC*



Rigid**



MAT_224
0.2 mm mesh
1.8M elements

* “No evidence of plasticity or macro deformation was seen in the hardened A2 projectiles.”

** “This leads to the conclusion that the boundary conditions do not play a role in panels of this thickness (0.14”)”

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

Test	Projectile mass, gram	Projectile impact velocity, ft/sec	Projectile exit velocity, ft/sec
DB177	126.3	896	475
DB178	126.4	865	424
DB179	126.2	713	241
DB180	126.2	646	152
DB182	126.4	527	0
DB184	126.3	581	0
DB185	126.2	597	0
DB186	126.4	578	0
DB192	126.3	630	0
DB193	126.3	629	104
DB195	126.3	616	0

* Assume zero degree impact angle

Triaxialities in ballistic impact tests

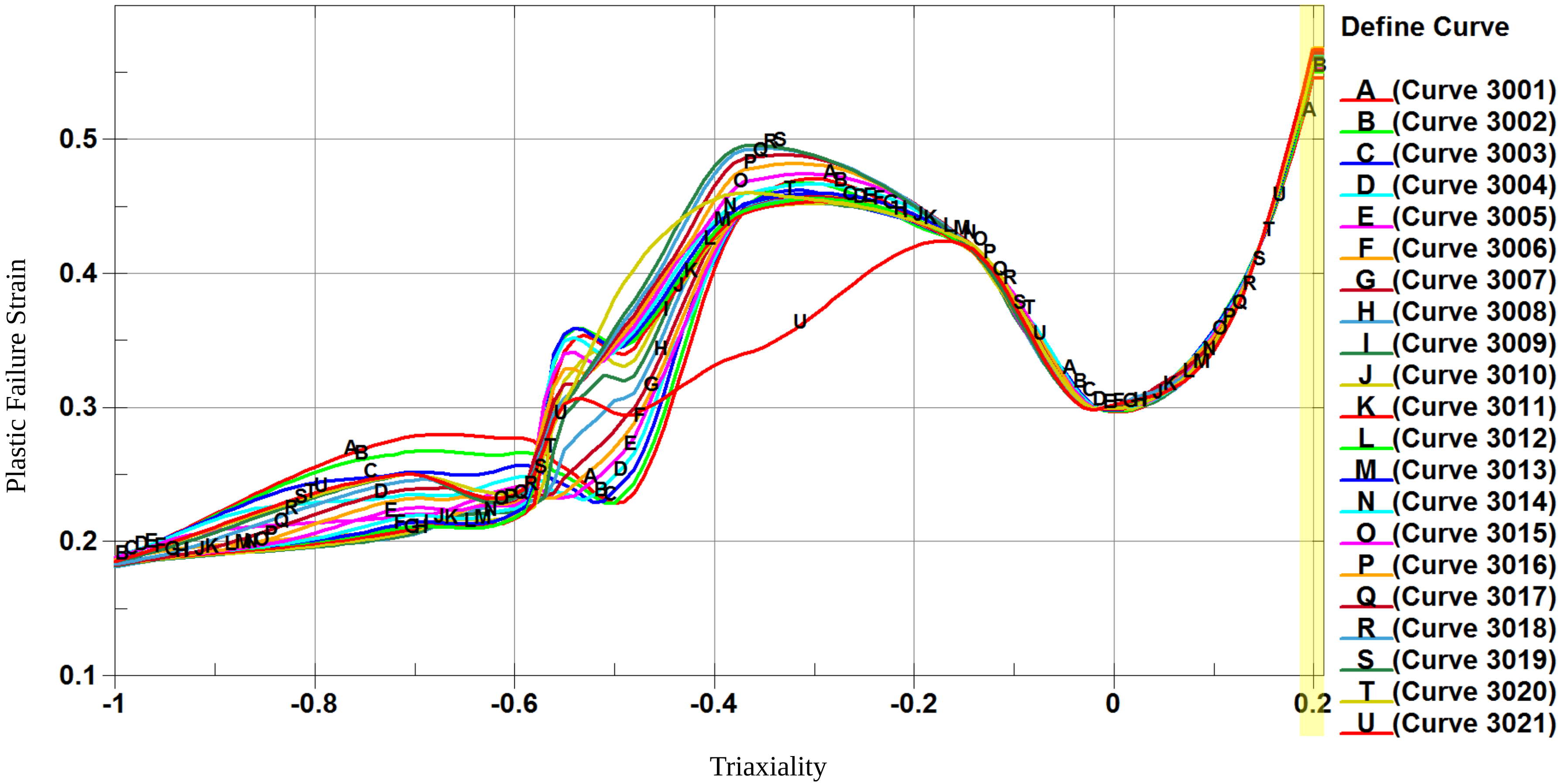
- **Triaxialities in and around the ASB were between 0.2 and 5 showing a very high hydrostatic pressure contents**

$$\boldsymbol{\sigma} = \begin{pmatrix} -p & 0 & 0 \\ 0 & -p & 0 \\ 0 & 0 & -p \end{pmatrix} + \begin{pmatrix} \tau & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\tau \end{pmatrix} \quad p > 0 \; and \; \tau > 0 \quad t = \frac{p}{\tau\sqrt{3}} > 0$$

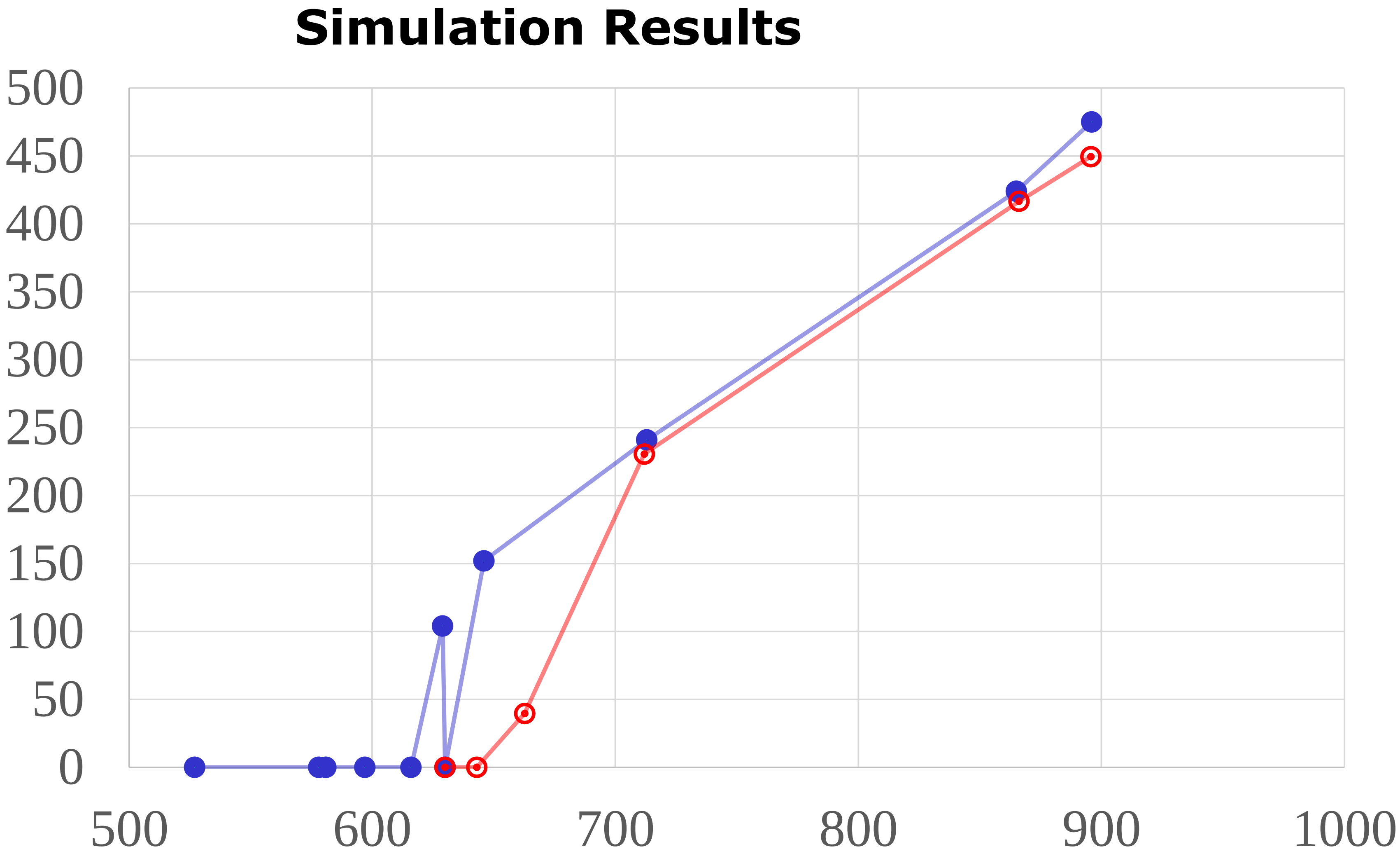
$$if \quad p > \tau \; all \; stress \; components < 0$$

- **Our failure surface had test data for triaxialities up to 0.147 (combined loading test LR4)**
- **The decisive failure in the ballistic impact tests (ASB) was completely in a dark region of the failure surface (triaxialities >0.2)**
- **An update of the failure surface was needed**
- **The assumption that no failure occurs when all 3 principal stress components are negative (triaxiality > 0.3333) is FALSE**

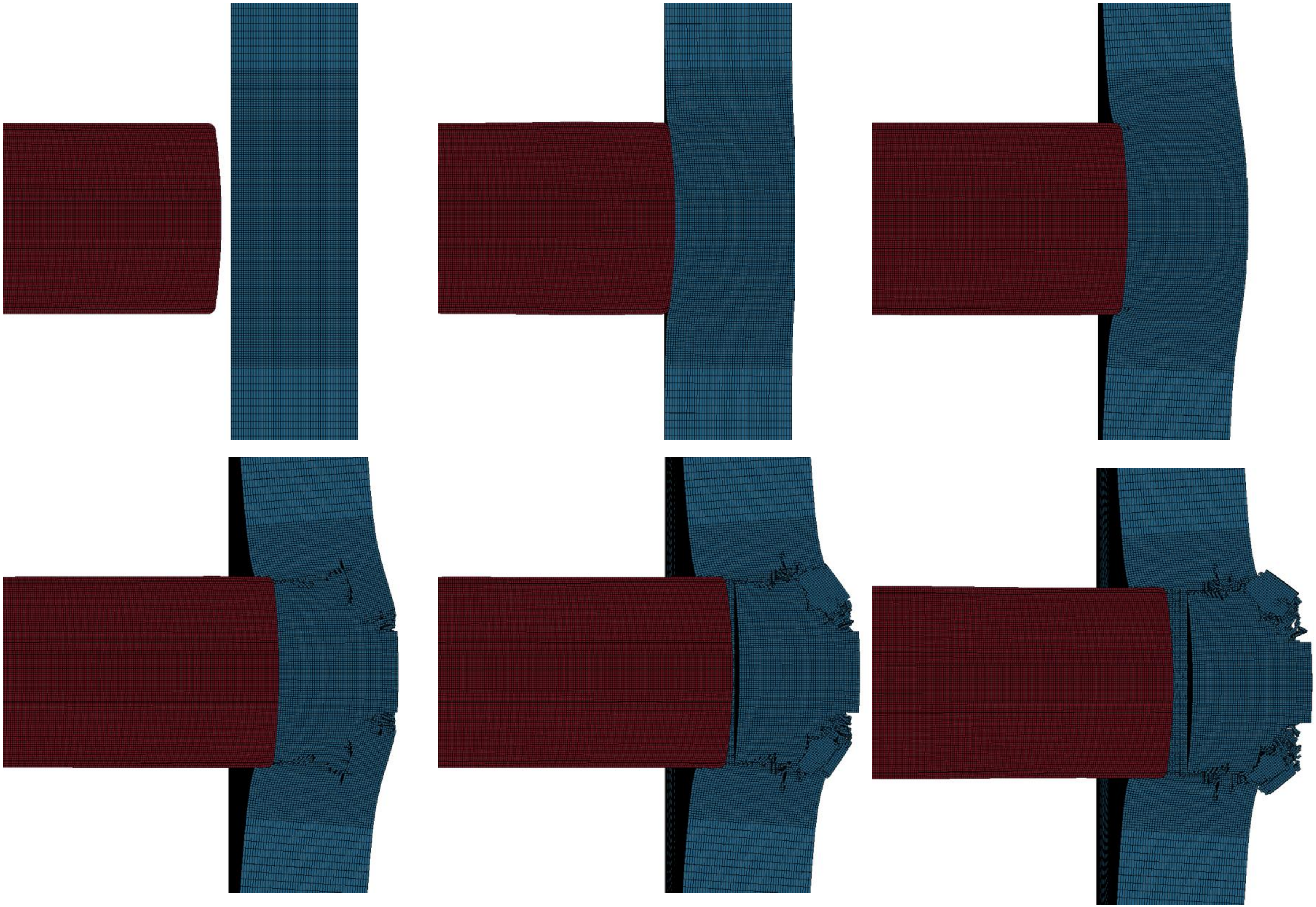
Adjustments to Failure Surface



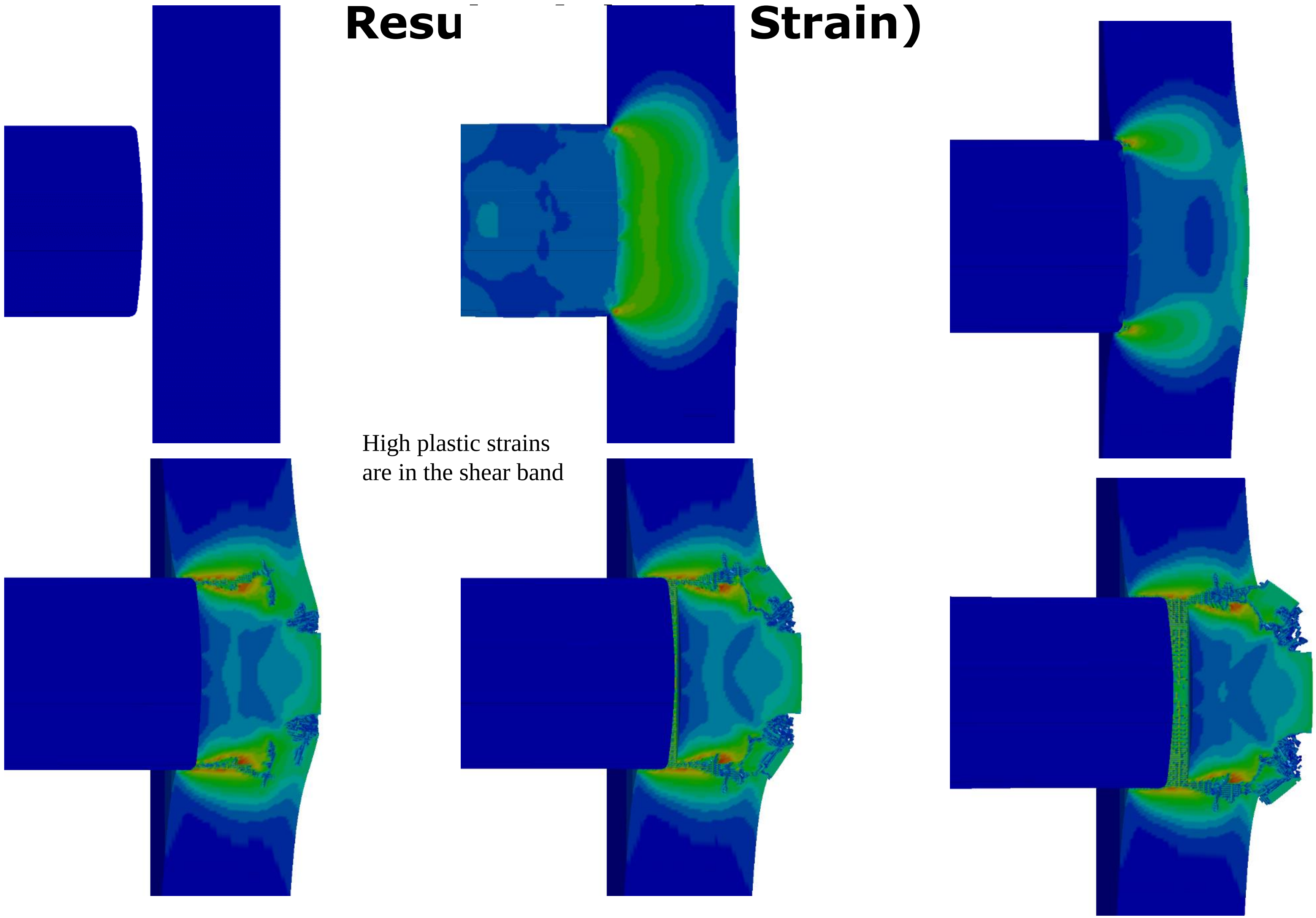
Introduction of a plateau in the failure surface at 60% for triaxialities > 0.2, NO previous tests are affected


Simulation Results
500
450
400
350
300
250
200
150
100
50
0
500
600
700
800
900
1000

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

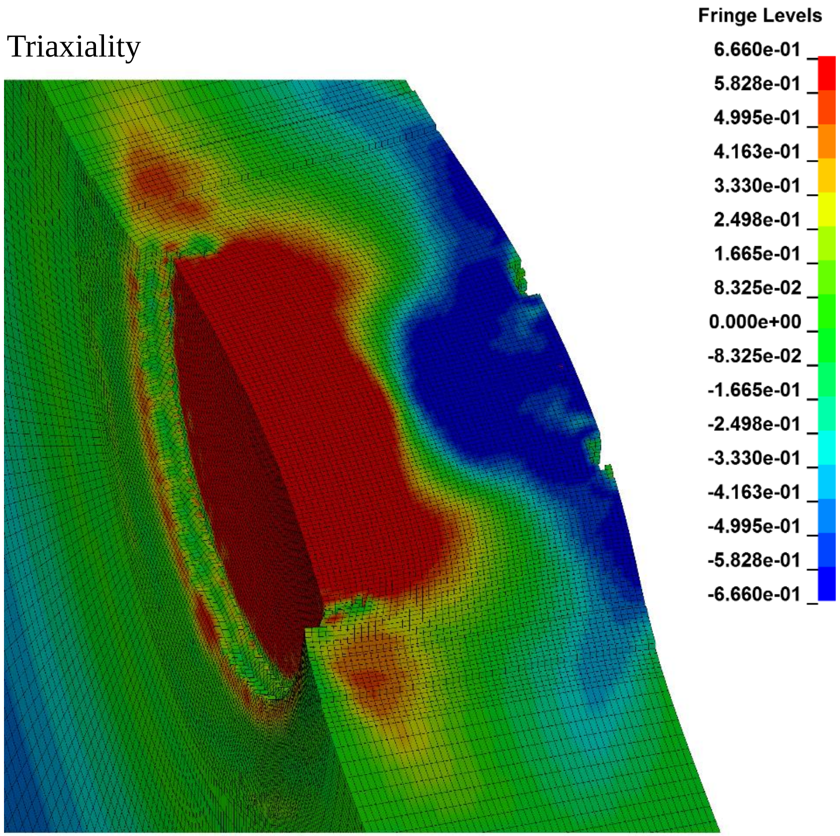


Resu Strain)

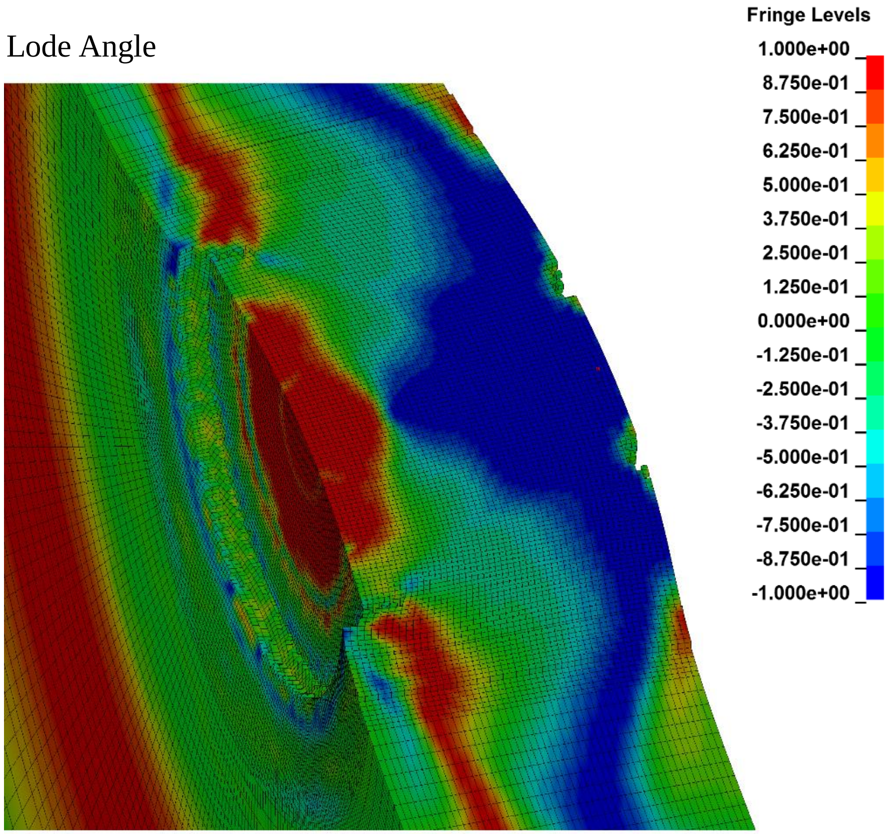


Results (Triaxiality and Lode)

Triaxiality



Lode Angle

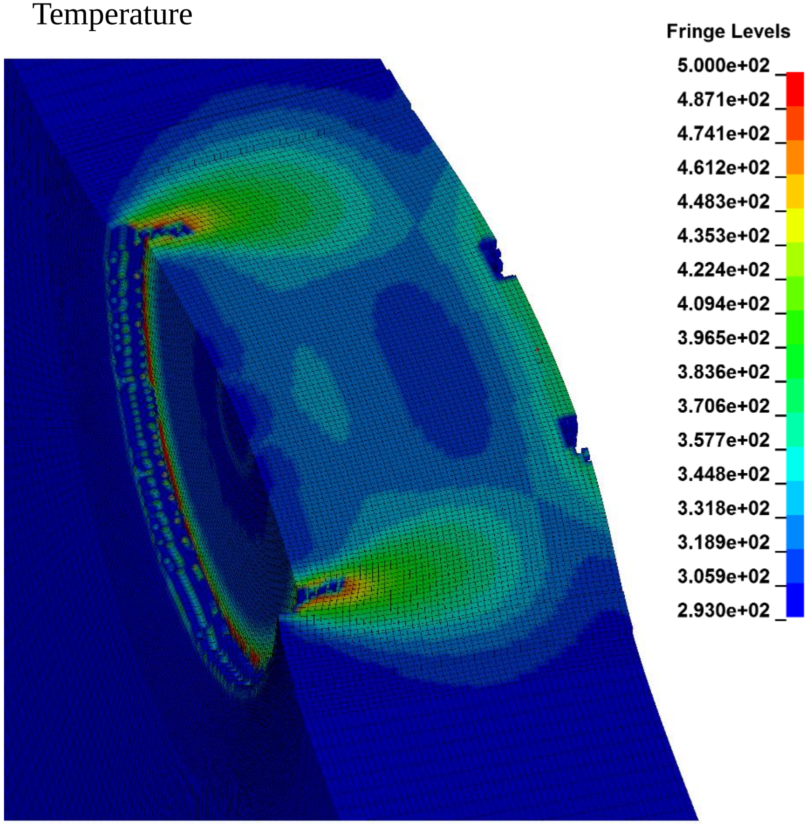


Triaxialities exceed 0.666

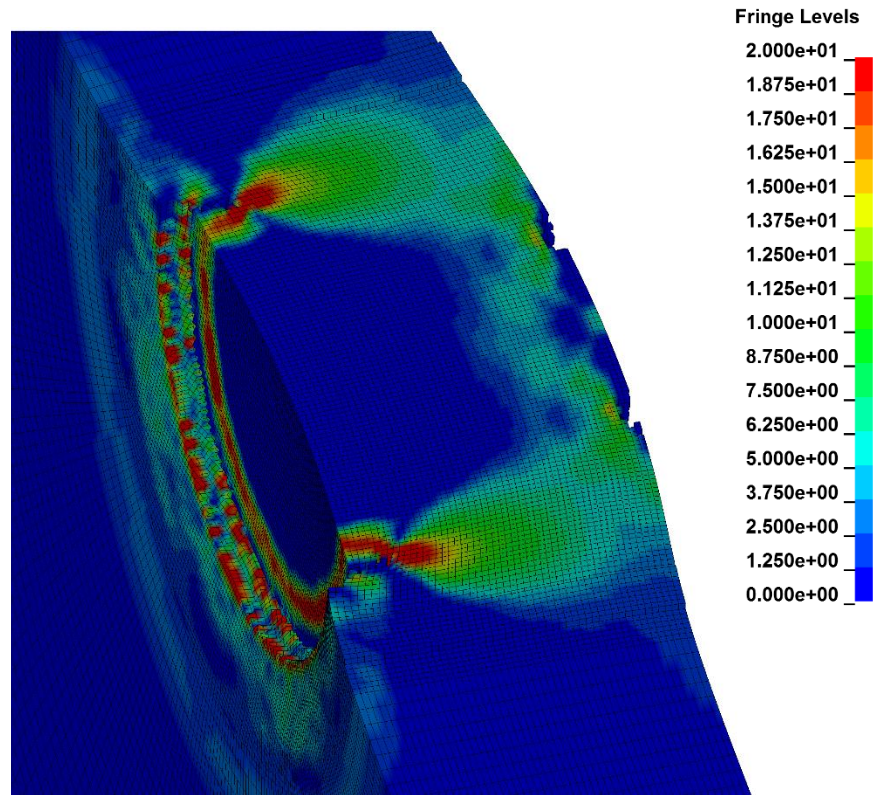
Lode parameters in the ASB between -0.5 and -1

Results (Temperature and Strain Rate)

Temperature



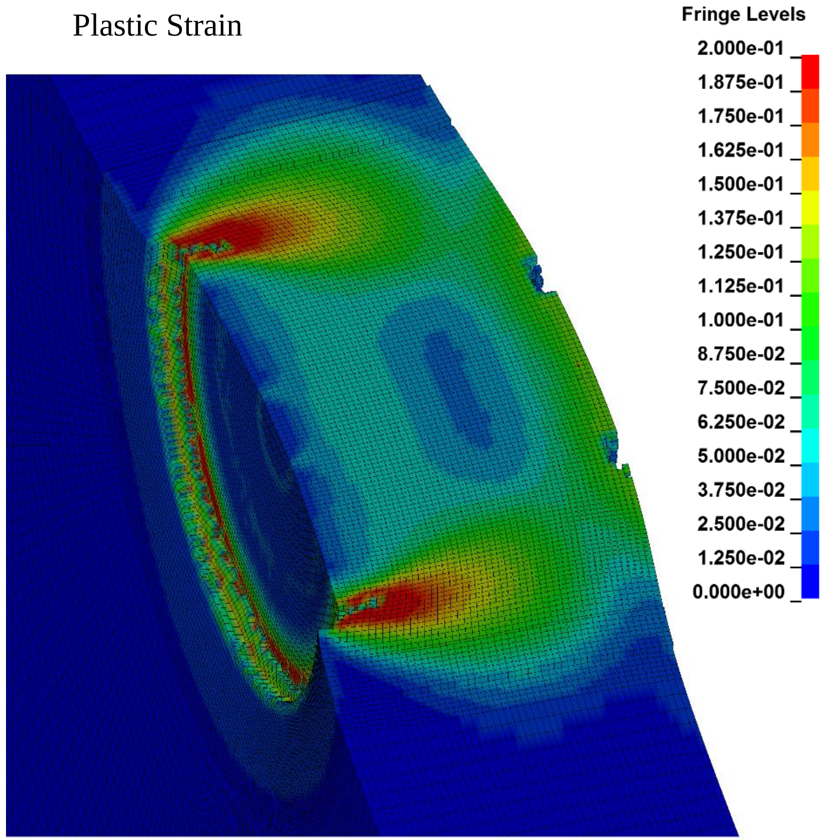
Strain Rate



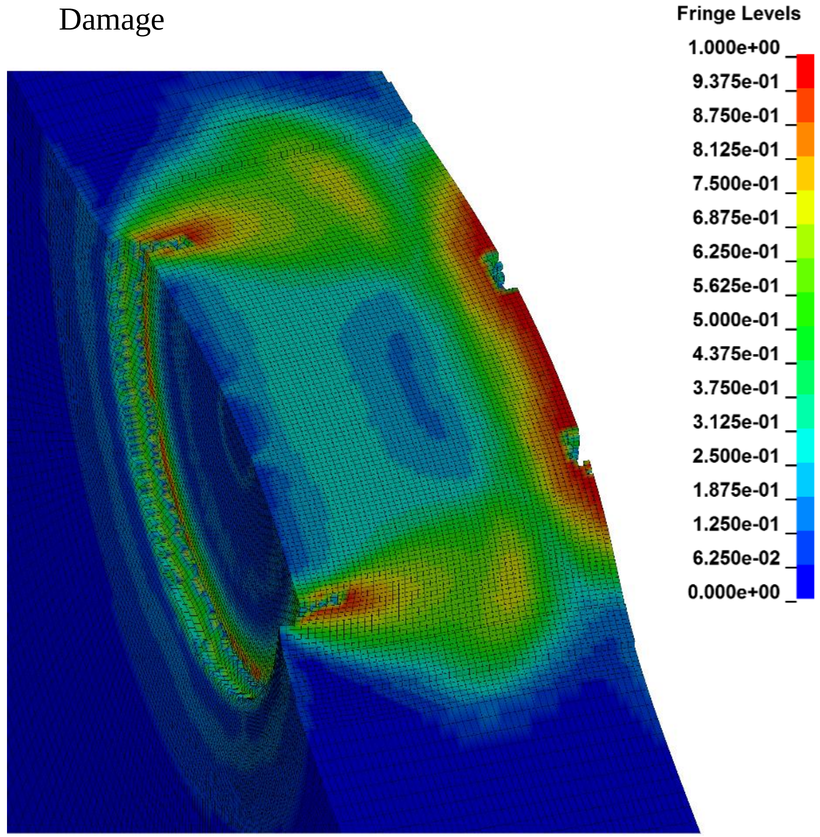
Temperature rise of around 200C in the shear band, negligable in the spall plane
Strain rate values of 20000/s and higher

Results (Plastic Strain and Damage)

Plastic Strain



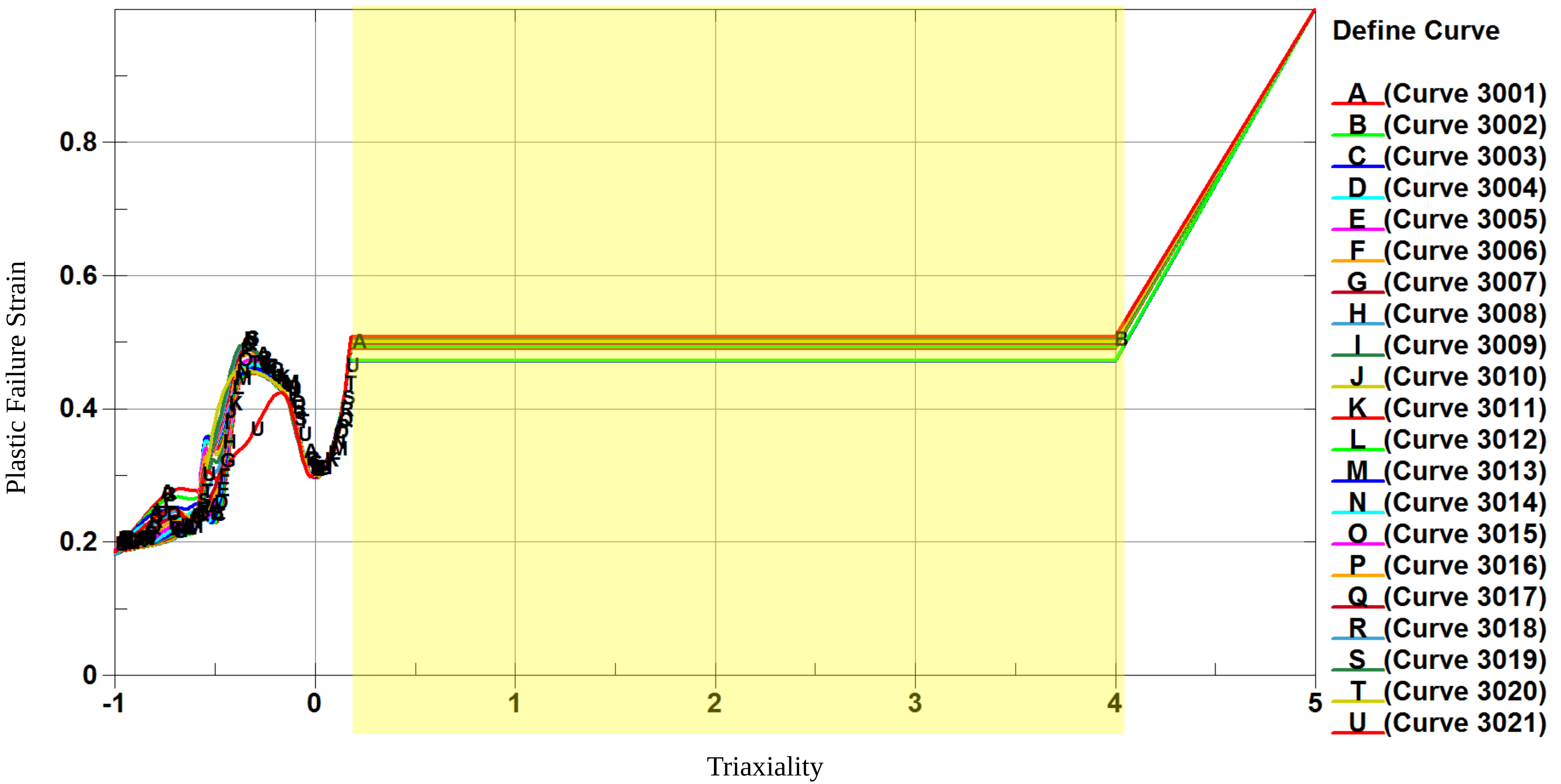
Damage



Discussion of results

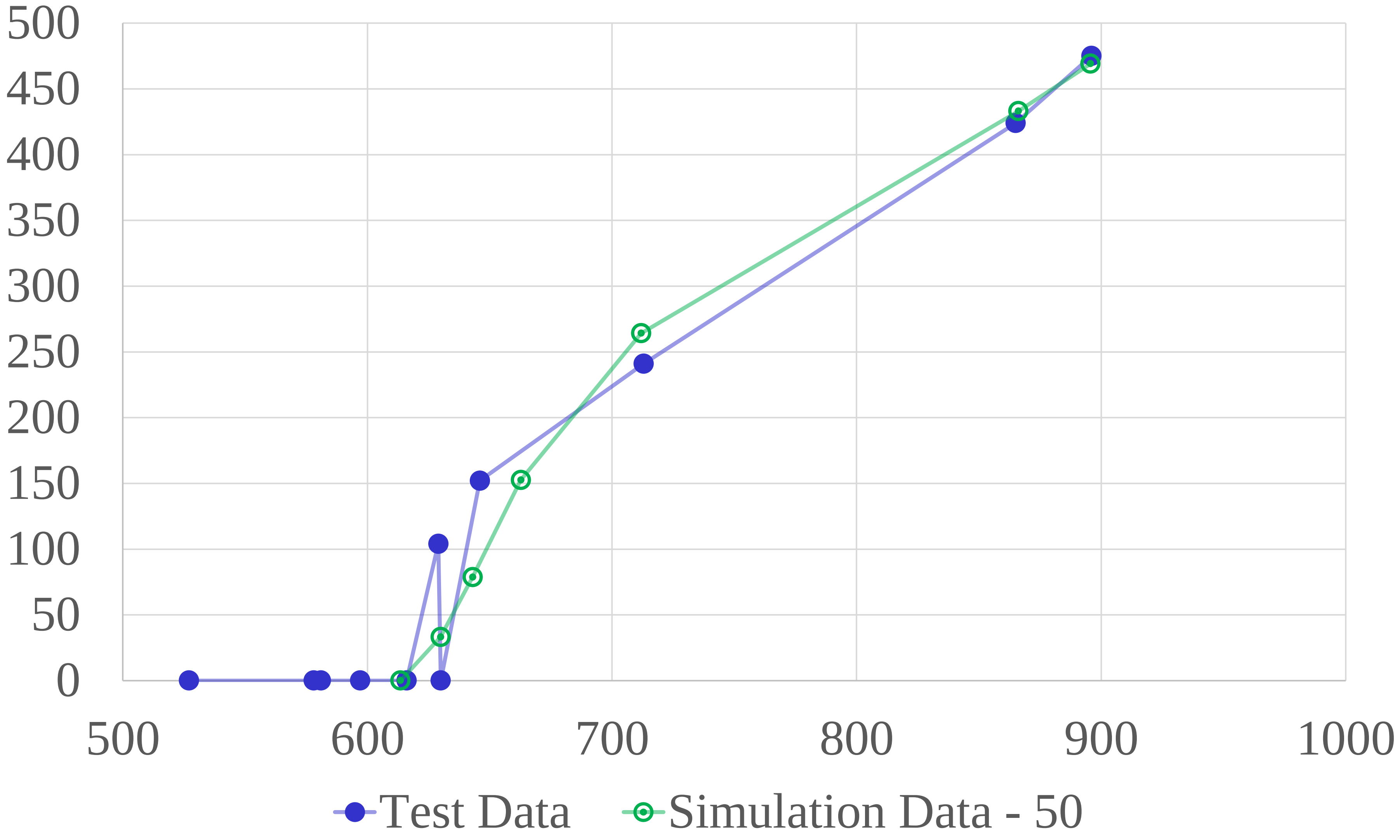
- **Some spalling occurs in the simulation, more then observed in the test, this could be due to the ASB forming somewhat too late**
- **According to Rittel : ‘ the influence of the hydrostatic pressure on the formation as ASB is still an open question’**
- **Our shearband can propagate too slow due to the 0.2mm mesh size, according to Meyers the width of shear bands in Ti-6-4 is between 2 and 20 micron, according to Borvik the mesh size should not exceed the half width of the shear band**

Adjustments to the Failure Surface

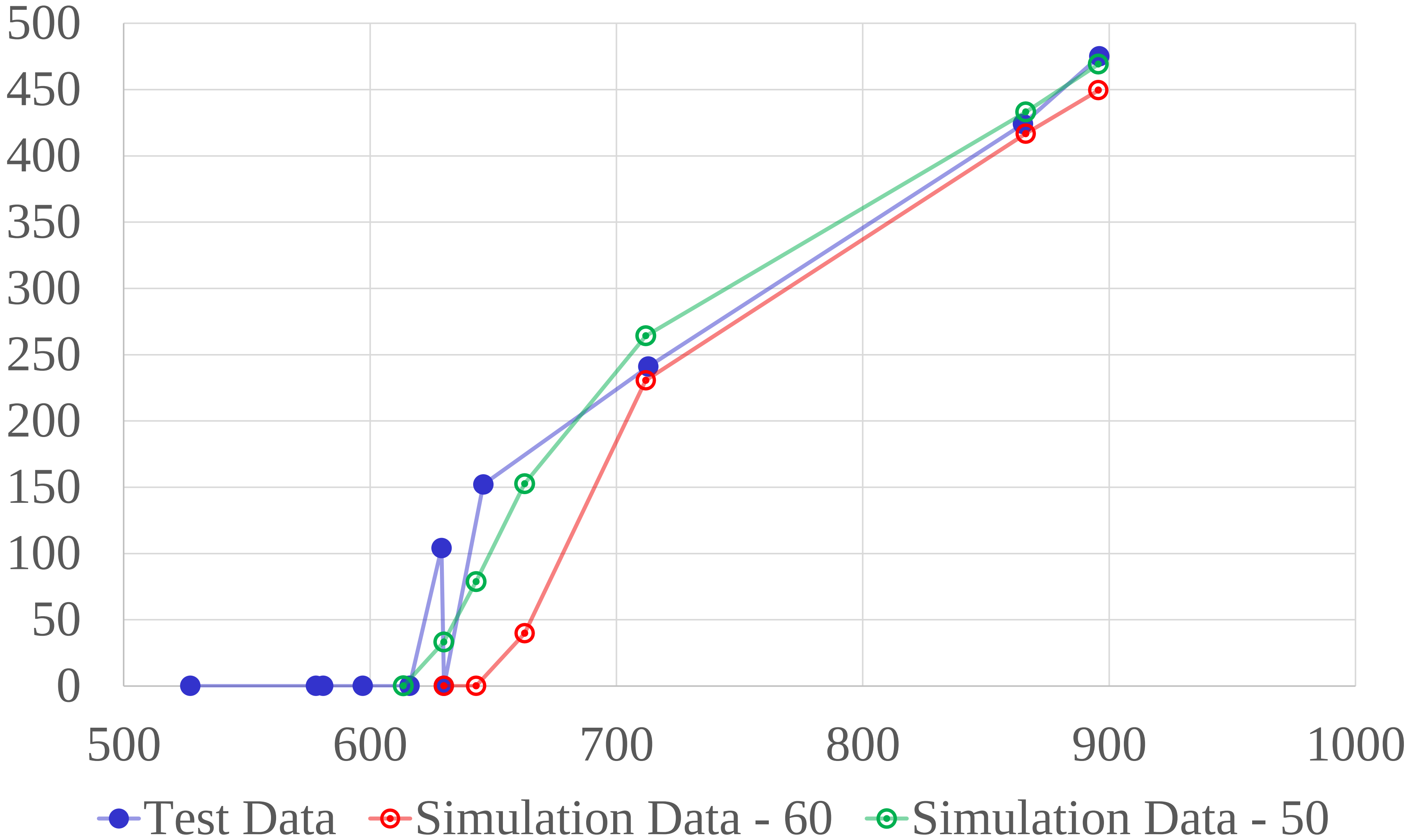


Shift of the plateau from 60% to 55%

Results

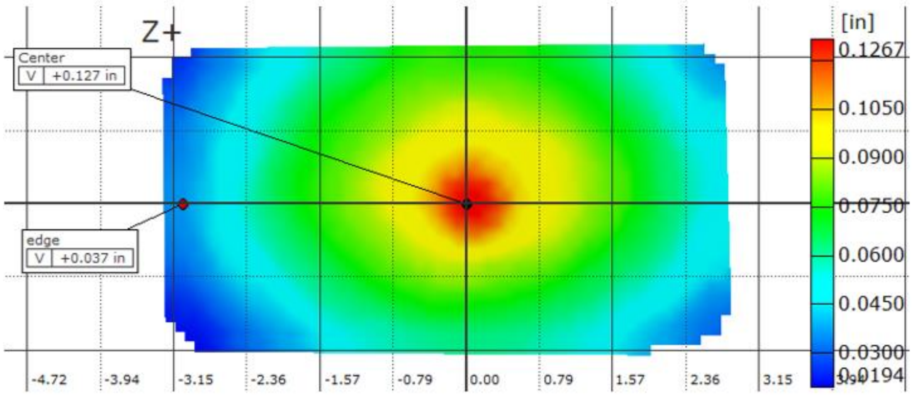

500
450
400
350
300
250
200
150
100
50
0
500
600
700
800
900
1000
Test Data
Simulation Data - 50

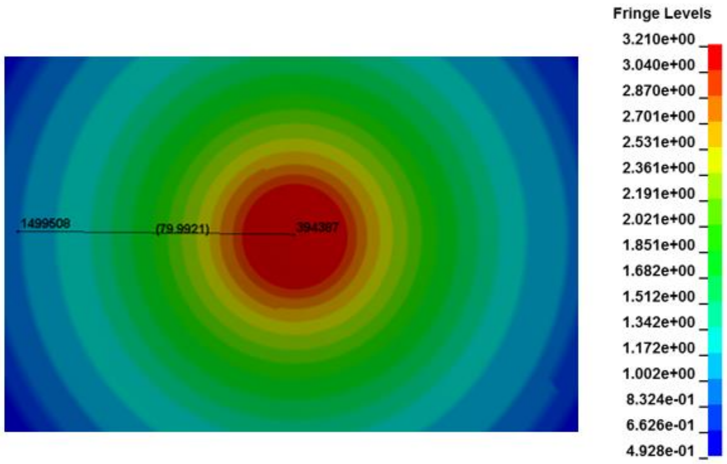
Comparison



500
450
400
350
300
250
200
150
100
50
0
500
600
700
800
900
1000
Test Data
Simulation Data - 60
Simulation Data - 50

Comparison of displacements for DB182 (527 ft/sec)

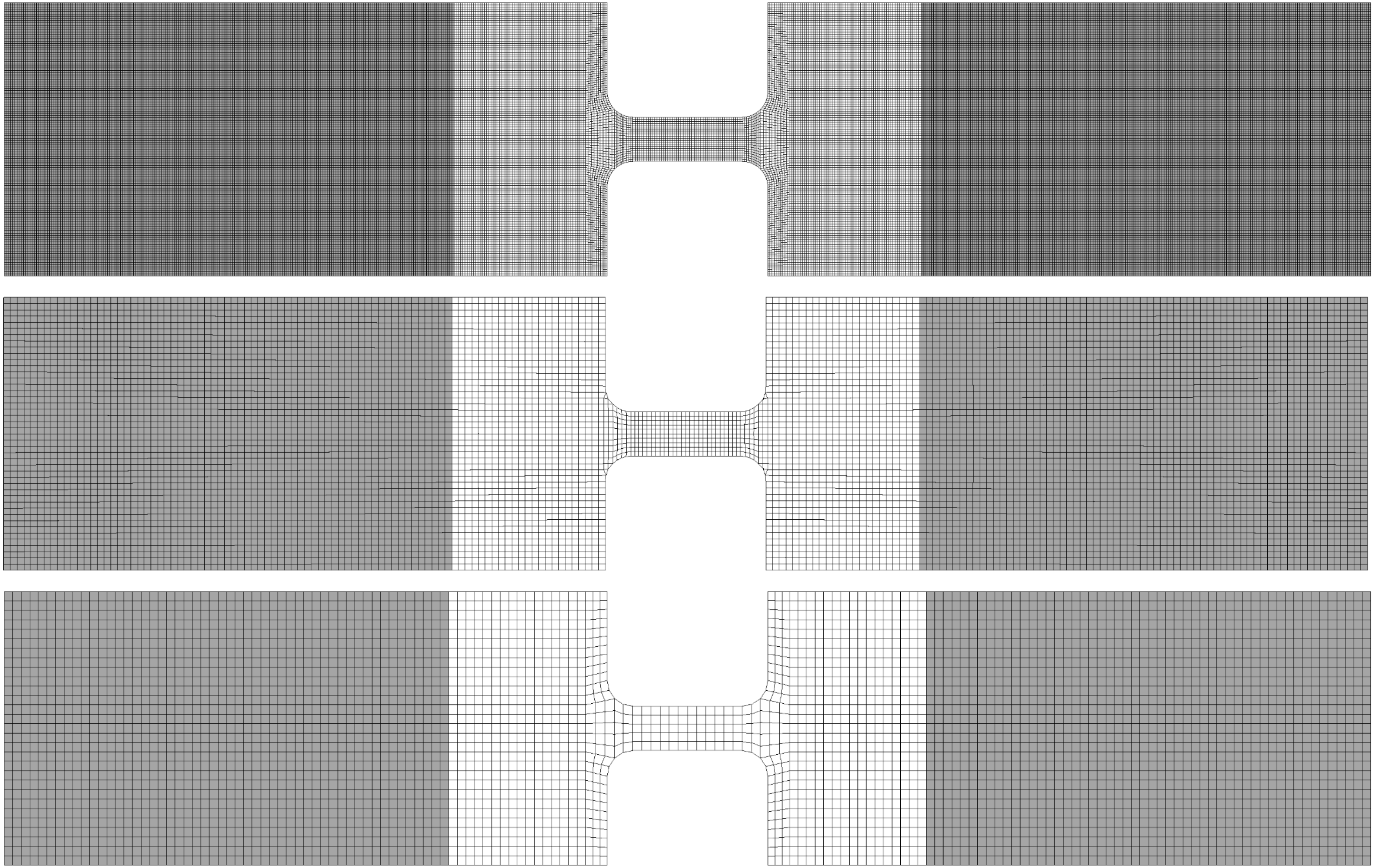




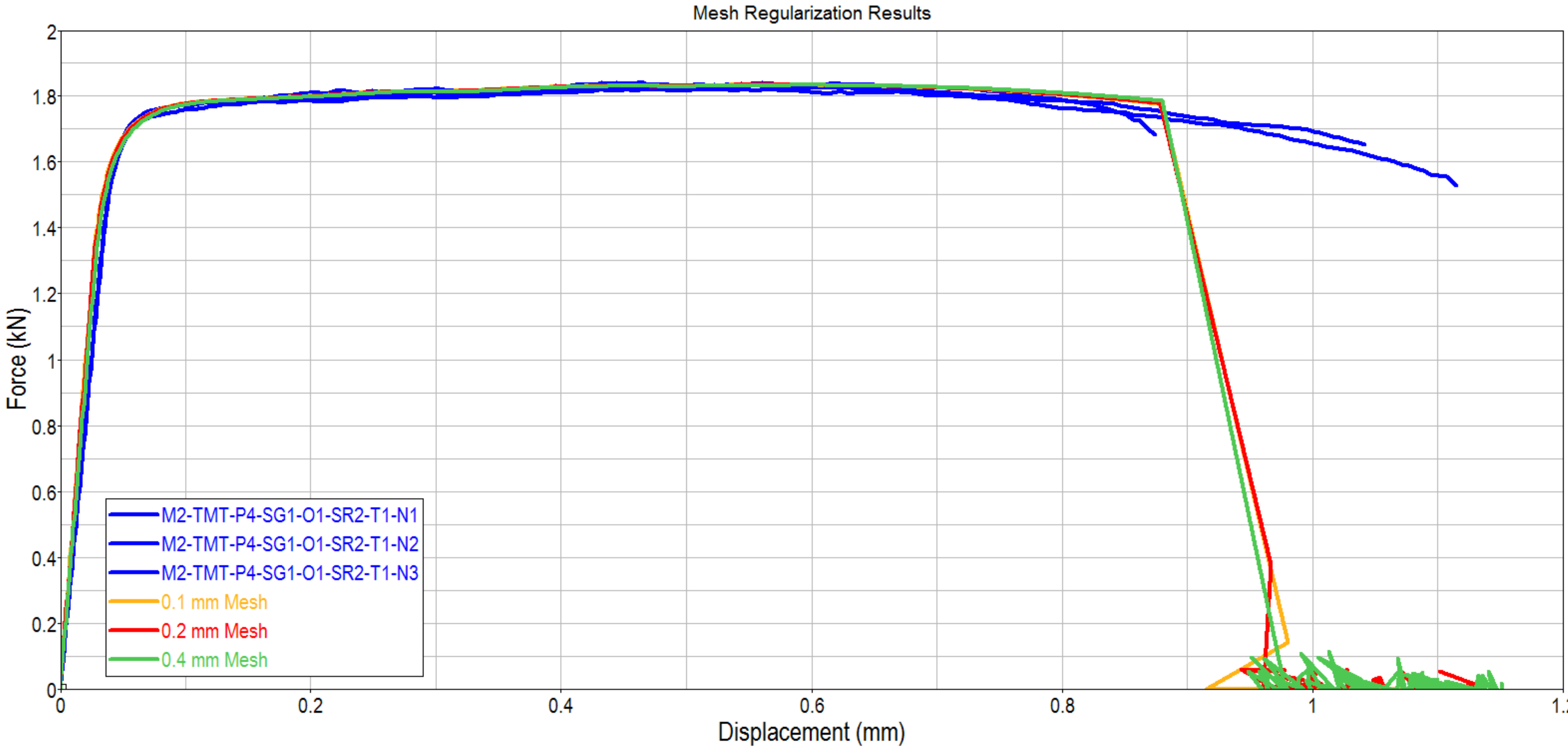
Regularization Curve

- A regularization curve was developed using three mesh sizes
  - 0.1 mm
  - 0.2 mm
  - 0.4 mm
- Each specimen was simulated using the entire Ti-6-4 material model
  - Including failure regularization curve
- The regularization curve was adjusted with each iteration until the failure for each specimen occurred at the same displacement

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V



Regularization Results

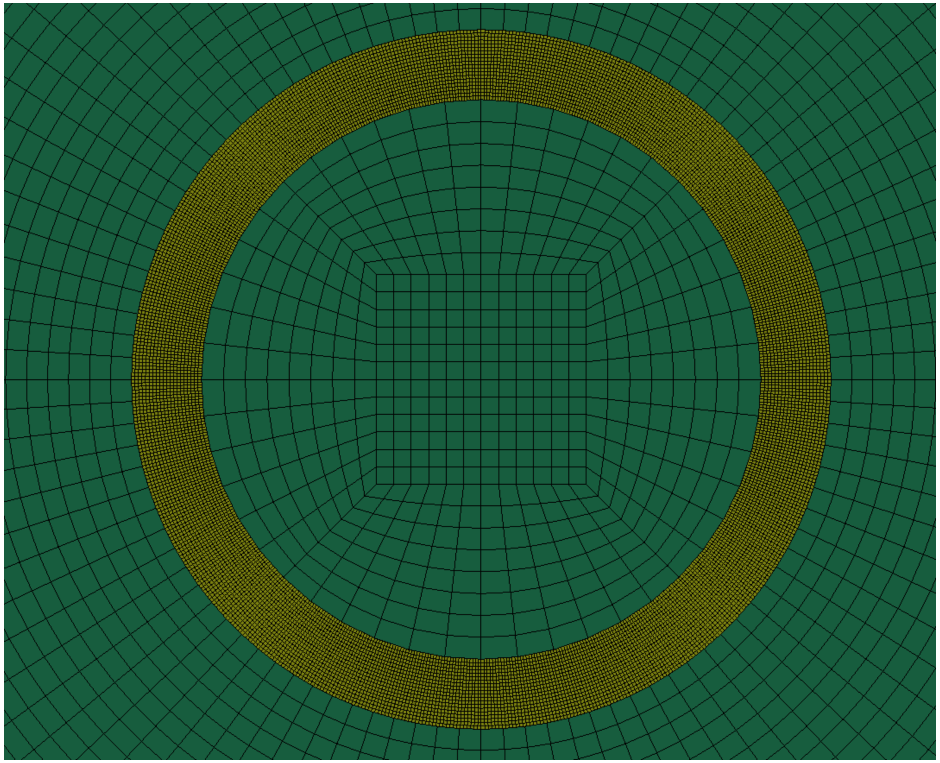


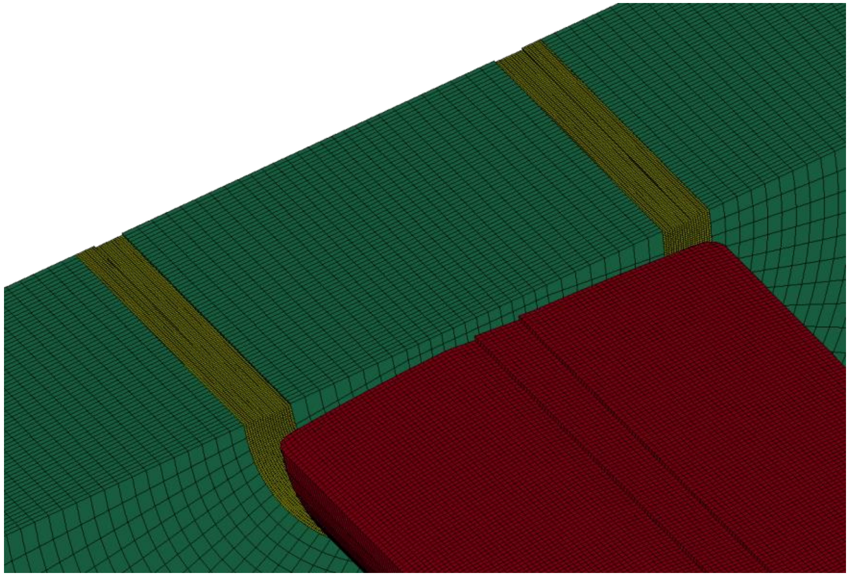
Final Regularization Curve

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$             Failure - Regularization Curve            $
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*DEFINE_CURVE
$#     lcid       sidr        sfa        sfo       offa       offo     dattyp
      6000          0        1.0        1.0        0.0        0.0          0
$           ABSCISSA            ORDINATE
                0.00               1.038
                0.10               1.038
                0.20               1.000
                0.40               0.912
                0.50               0.912
```

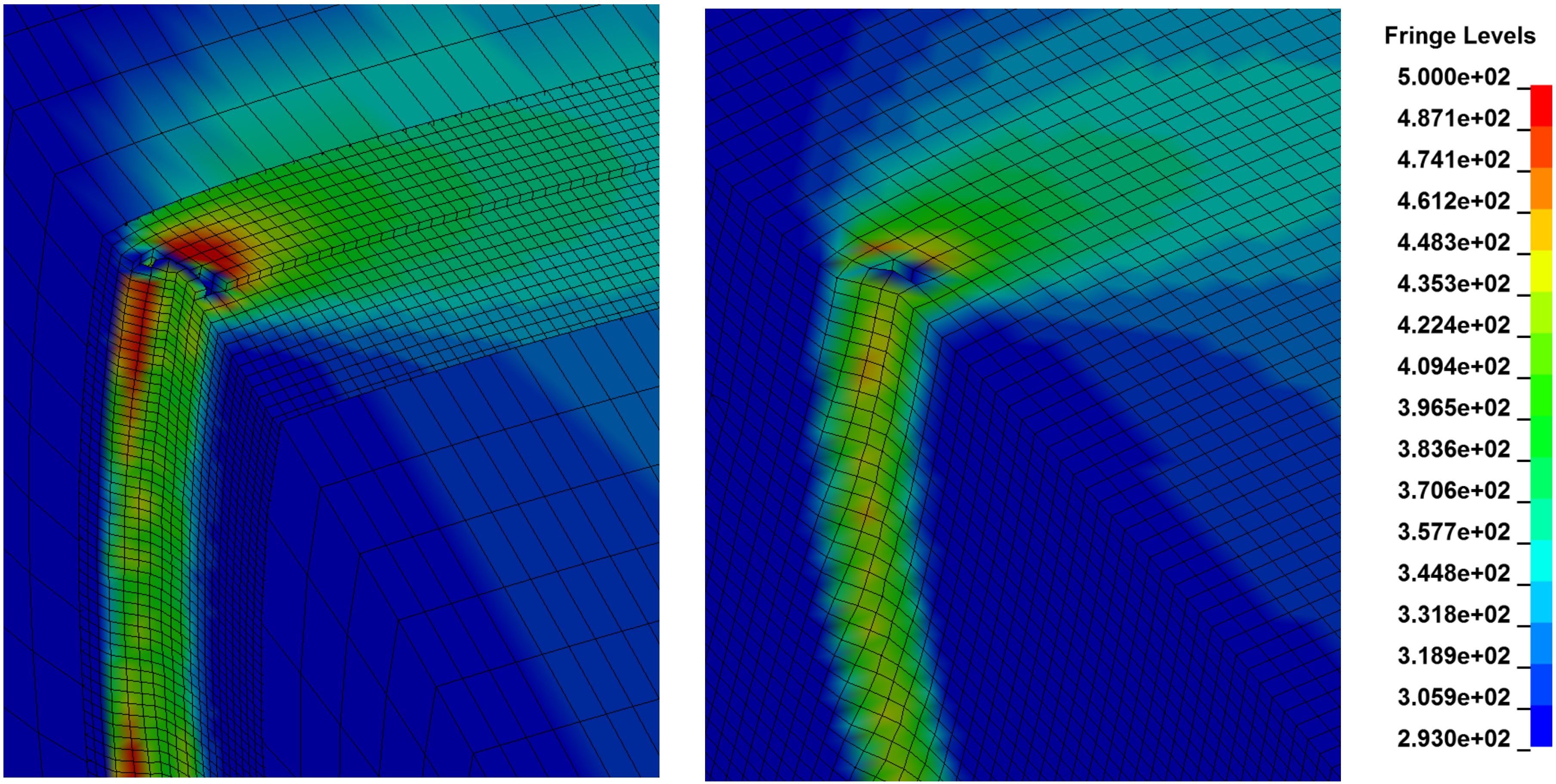
NASA Ballistic Test (0.1 mm mesh)

- NASA Ballistic test plate was re-meshed with 0.1 mm elements in the area of the adiabatic shear band
  - 0.1 mm elements
  - Connected with *CONTACT_TIED_SURFACE_TO_SURFACE
  - 217 m/s impact velocity





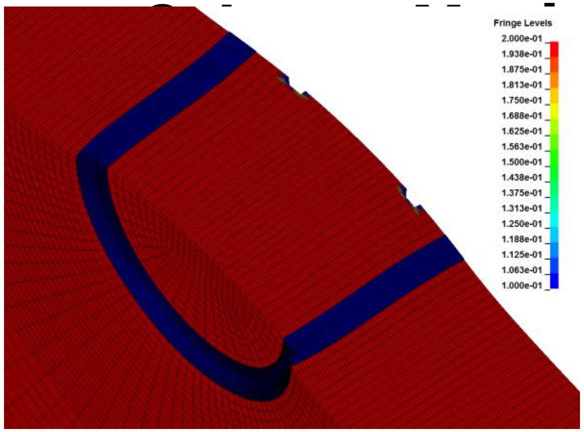
Temperature Comparison (0.02ms)



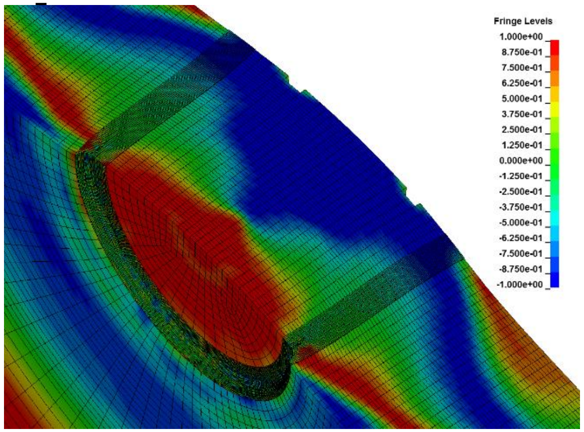
Max Temperature = 634 K

Max Temperature = 569 K

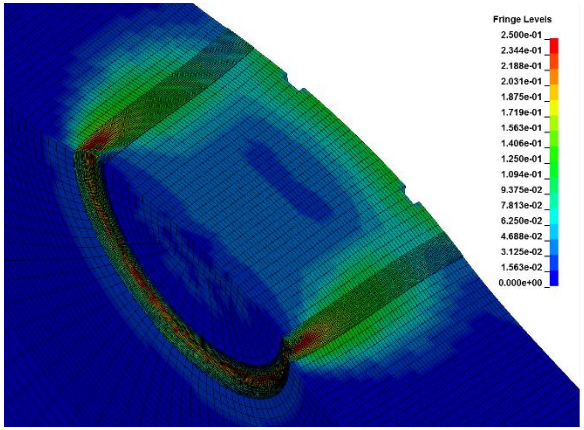
Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V



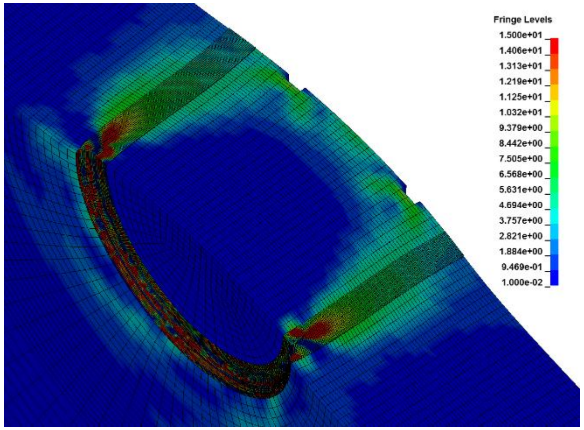
Element Size



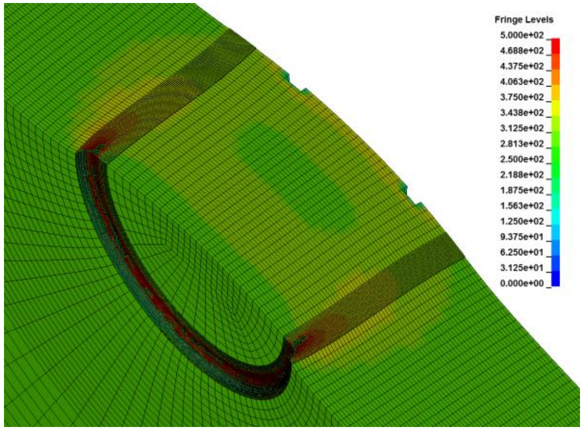
Lode Parameter



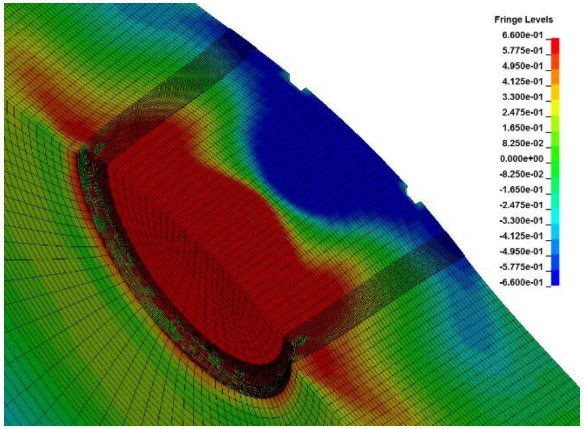
Plastic Strain



Strain Rate

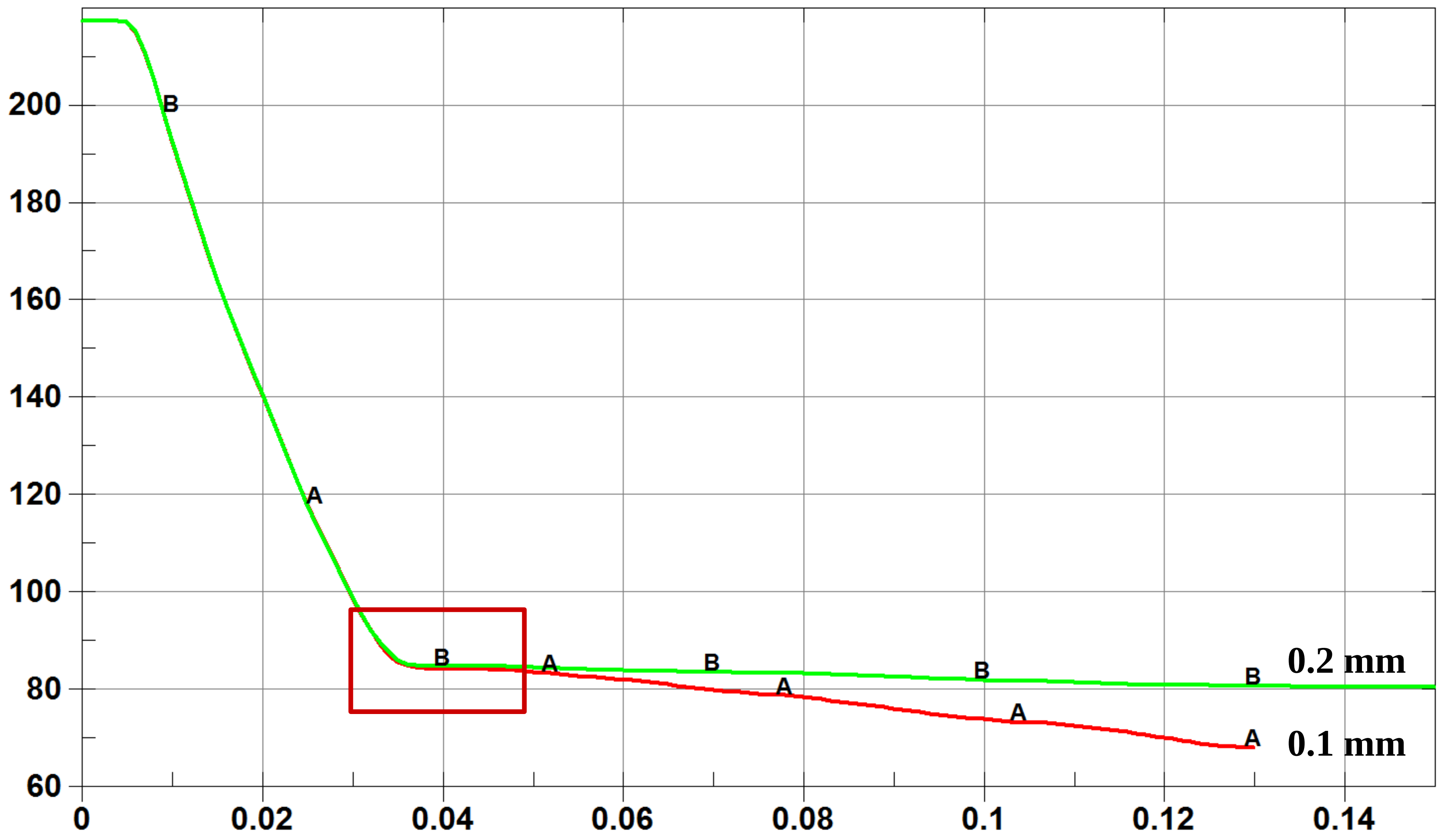


Temperature

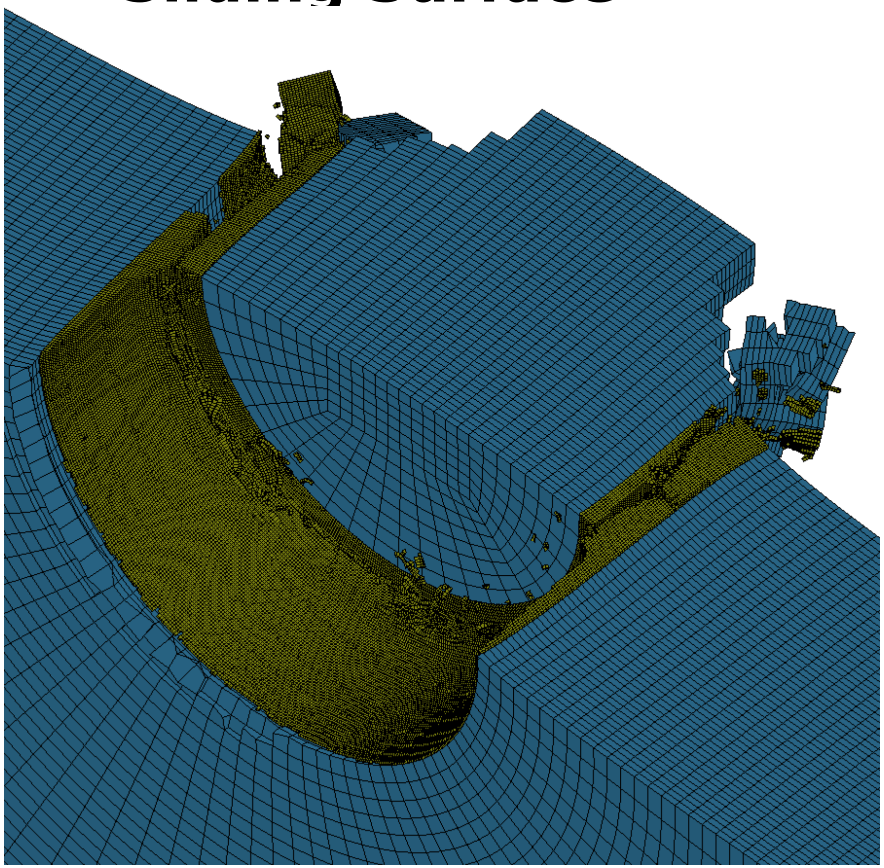


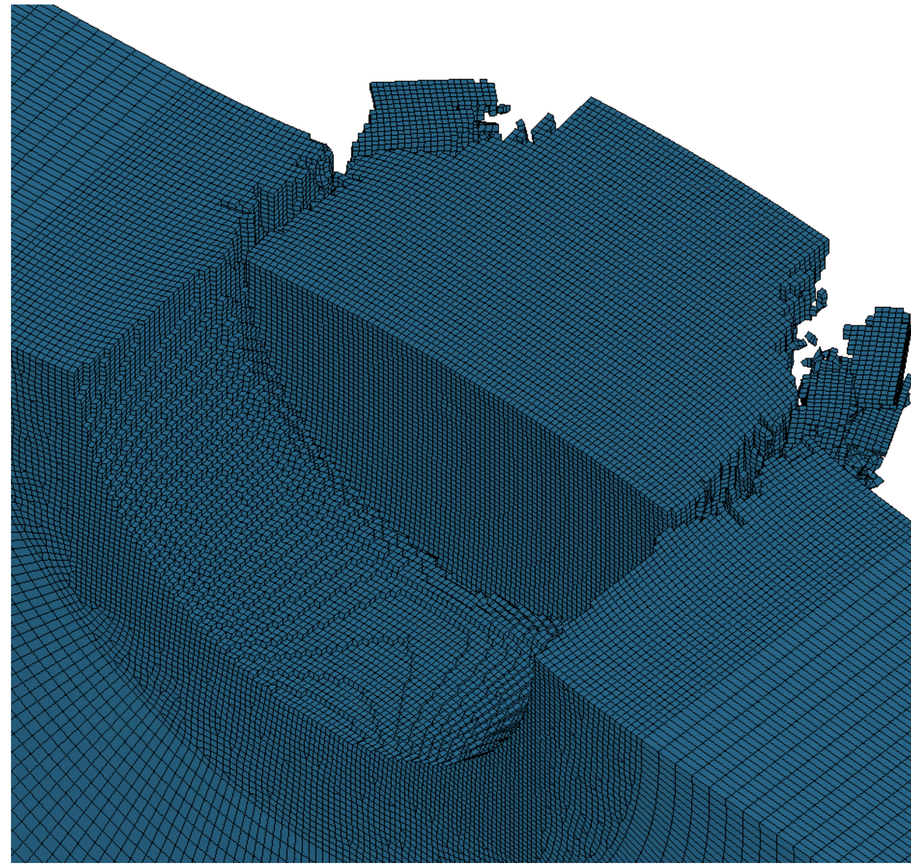
Triaxiality

Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V

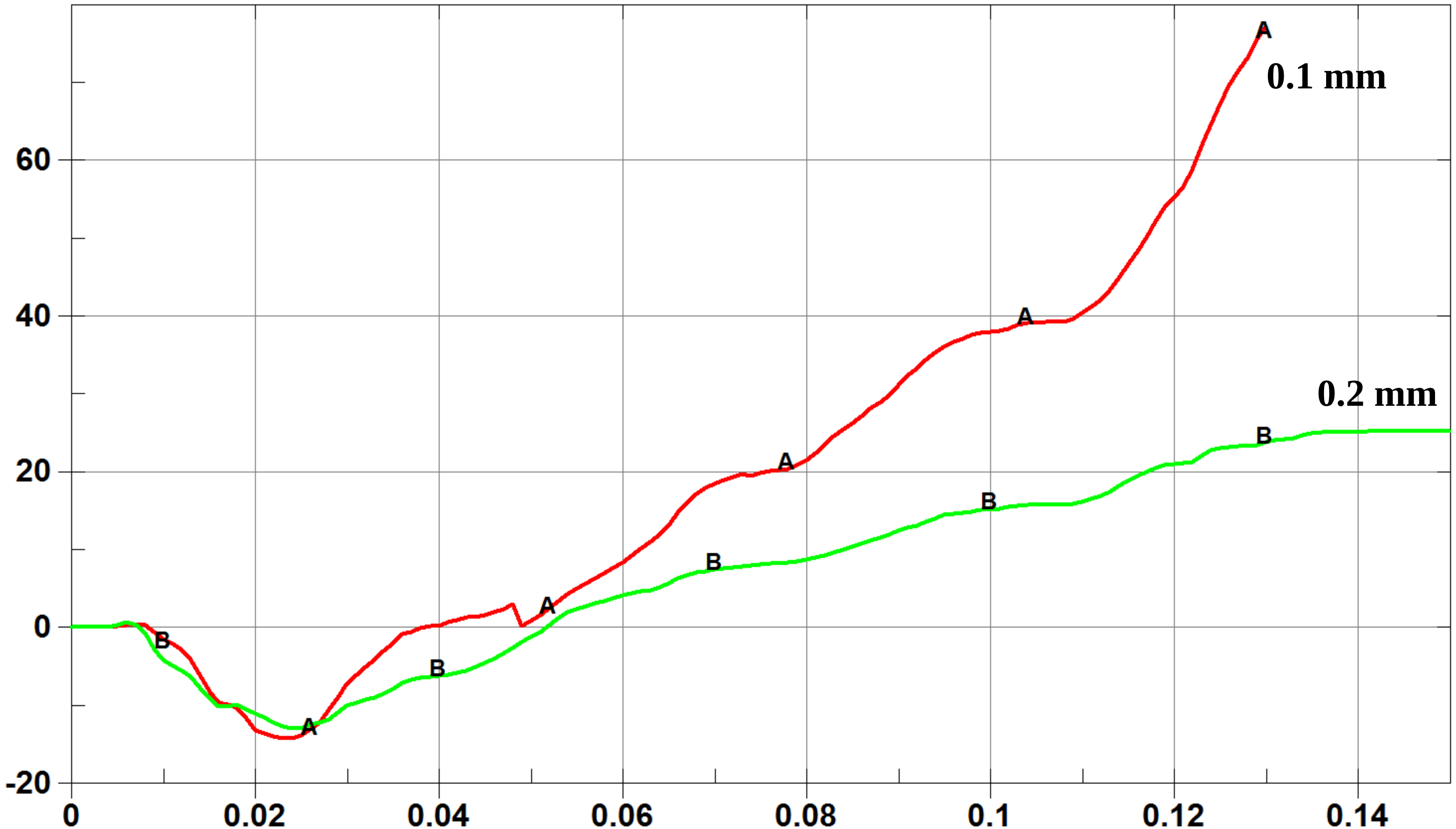


Sliding Surface





Numerical Simulation of Dynamic Failure : ballistic tests on Titanium-6Al-4V



Conclusions

- **The mechanisms of plastic instability and failure can be very different under static and dynamic loads**
- **Whereas regularization is often not needed to model shear failure under quasistatic, isothermal conditions, the situation may be different under high dynamic loads**
- **In the present study the mesh size was much larger then the width of the physical ASB, still a shear failure occurred in the simulation and realistic exit velocities could be obtained**
- **It is wrong to assume that no failure will occur in the region of stress space where triaxialities have large positive values, more attention will be given to this part of the failure surface in the future**