Experience with Material and Fracture Modeling at FCA US LLC

Dr. Anantharam Sheshadri[1*], Hamid Keshtkar[1], Ashutosh Patil[1], Paul Du Bois[2 *]
[1]FCA US LLC, Auburn Hills, MI
[2] Consulting Engineer, Northville, MI

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Contents

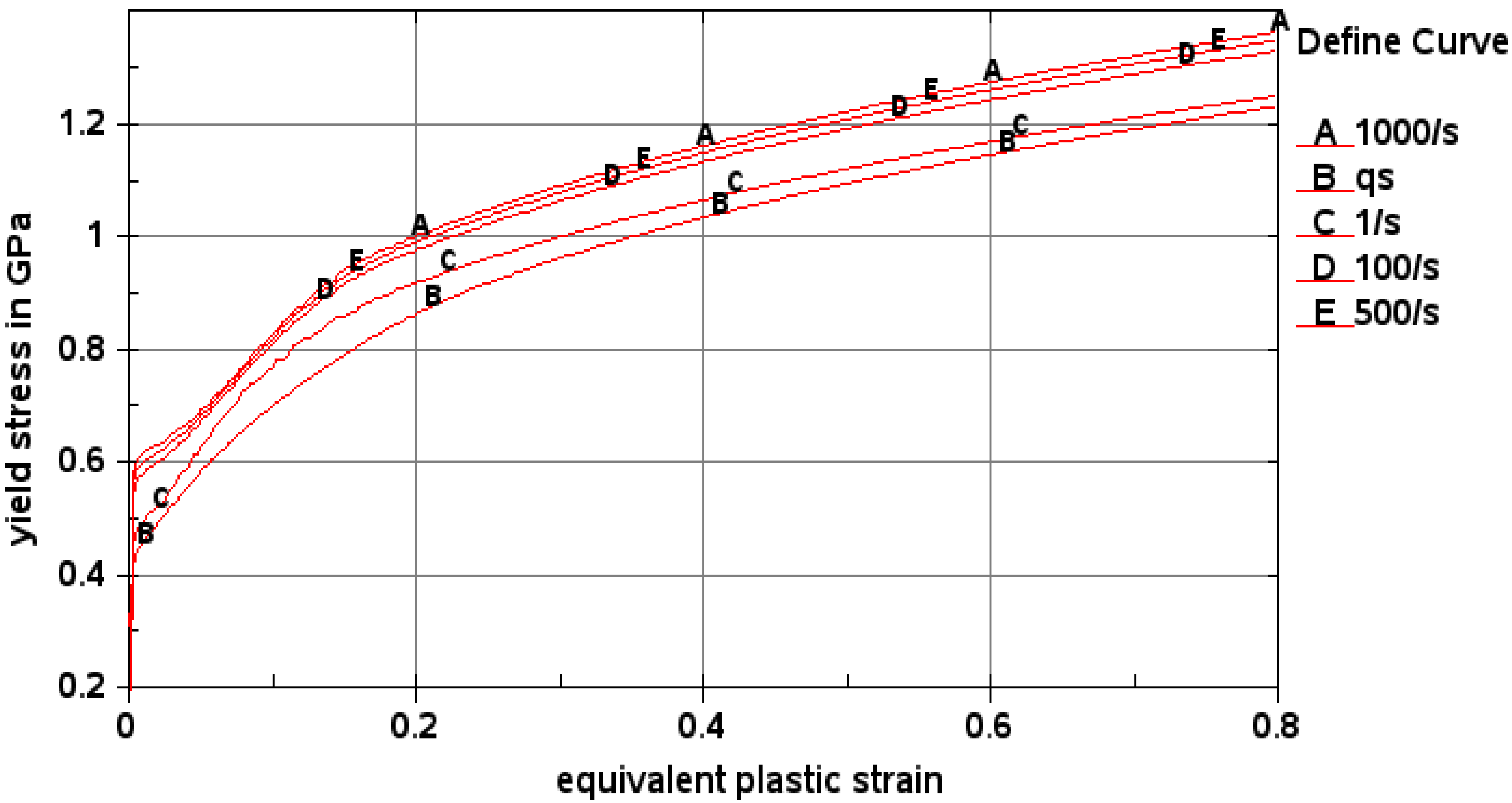
Framework – Material Fracture Modeling

FIAT CHRYSLER AUTOMOBILES

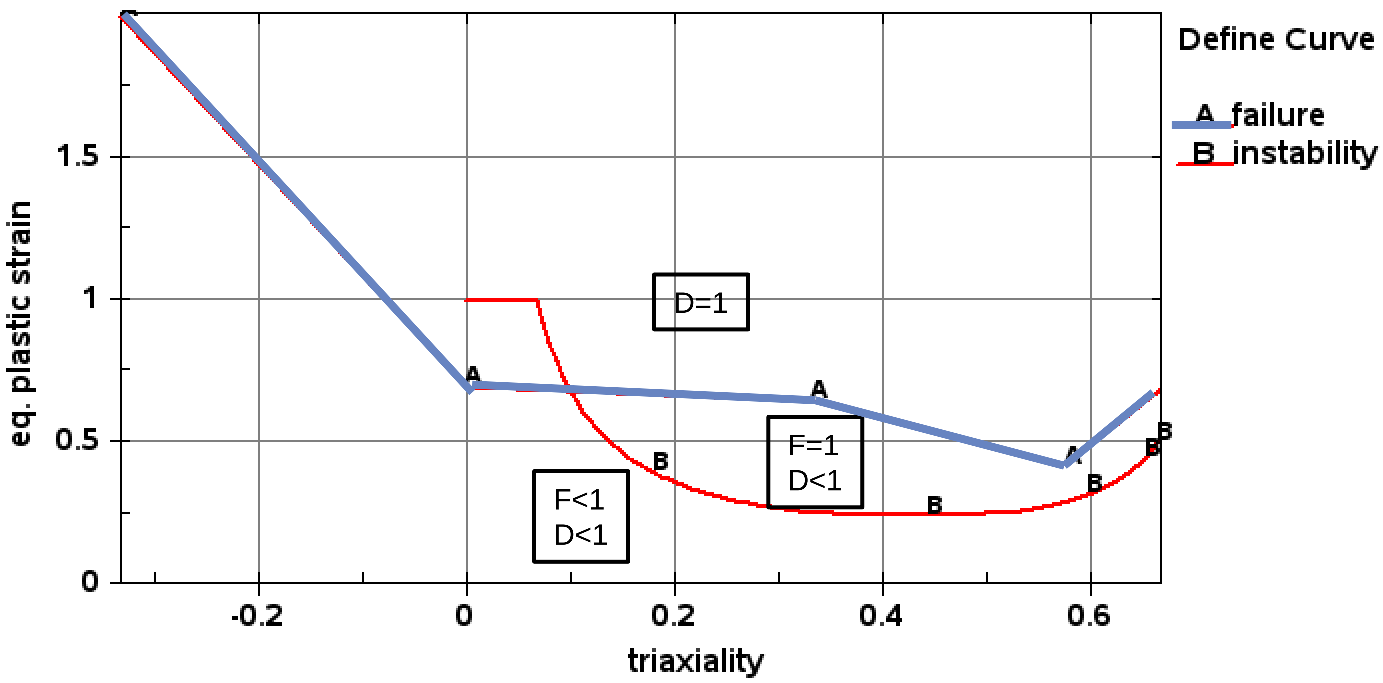
Material Fracture Modeling

- 2D Shell
  Plane stress – sheet, extrusion (upto 2.5mm*)
  - Isotropic
    Elastoplasticity: Mat24
    Failure: Gissmo/Triaxiality
  - Anisotropic
    Elastoplasticity: Mat36E
    Failure MAGD/Triaxiality
- 3D Solids
  Thick Ribs, Cast, Thick extrusions
  - Isotropic
    Elastoplasticity: Mat24
    Failure Gissmo/Triaxiality with Lode (Future Challenge)
  - Anisotropic
    No application encountered yet. No methodology available yet.

- MAT_024 is used for metallic sheets with 0.8<R<1.2
- isotropic, isochoric, quadratic and associated tabulated visco-plasticity

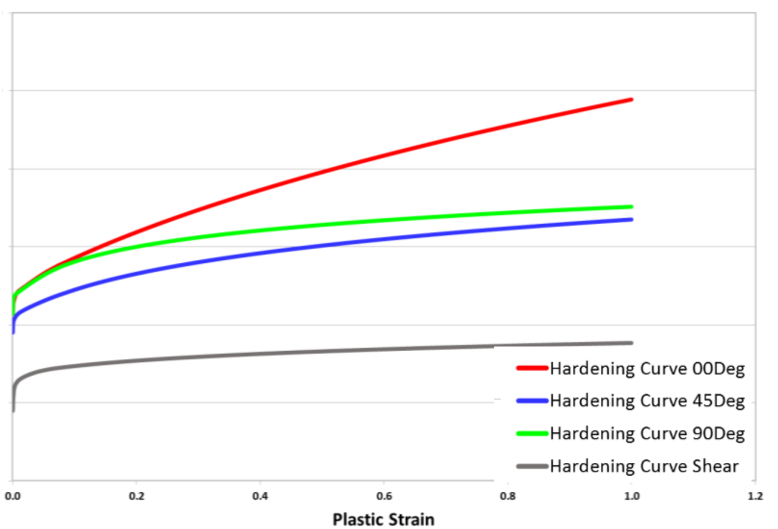


- MAT_ADD_EROSION to model failure
- increment instability and damage variables



- If F=1 we have localization of plastic deformation, damage coupling, severe thinning etc.…

- For large or small R-values / directional differences in strength
- MAT_036E (Fleischer-Borrvall-Andrade)
- orthotropic, isochoric, non-associated, higher order, tabulated visco-plasticity with non self-similar hardening based on the principle of work-hardening



Sample Dir.	0 Degrees	45 Degrees	90 Degrees	Shear	Biaxial*
R - Value	0.47	2.5	1.9	0.92	1.0

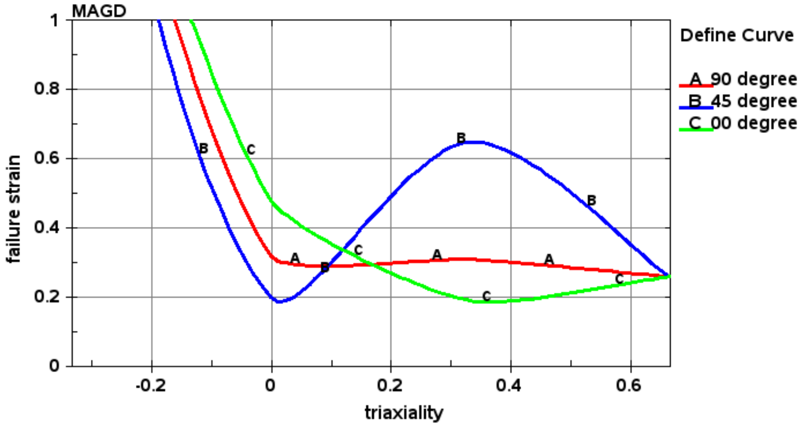
$$f = \sigma_{vm} - \alpha_{00}\sigma_y^{00}(\varepsilon_p) - \alpha_{45}\sigma_y^{45}(\varepsilon_p) - \alpha_{90}\sigma_y^{90}(\varepsilon_p) - \alpha_s\sigma_y^{s}(\varepsilon_p) - \alpha_b\sigma_y^{b}(\varepsilon_p)$$

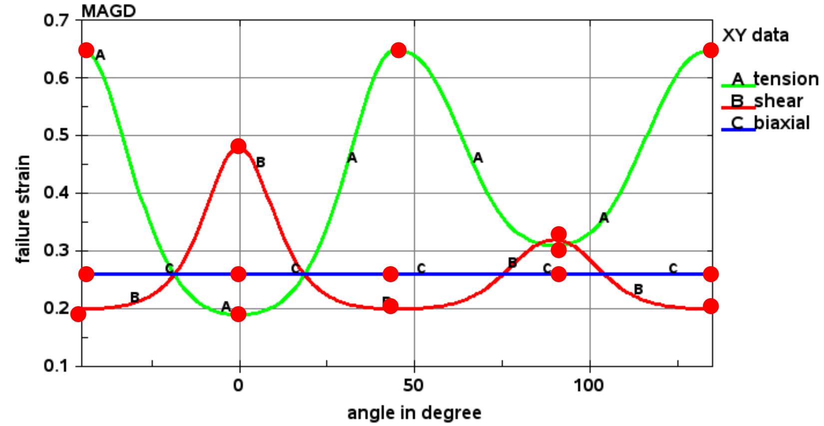
Can only consider shear in the 0 degree direction!

- chosen over more traditional models for orthotropic metals because of the non self-similar feature, essential to model deformation as we approach failure

Methodology - orthotropic

- MAT_ADD_GENERALIZED_DAMAGE to model failure
- choose settings IFLAG1=2, IFLAG2=1 and IFLAG3=1



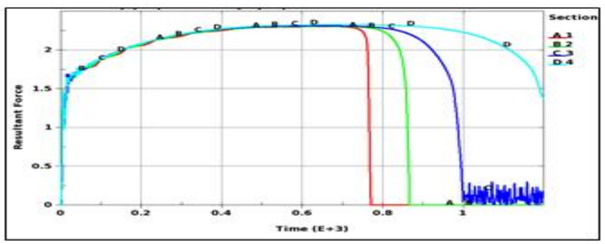


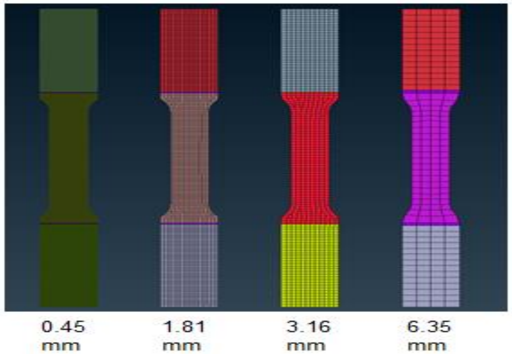
- 3 GISSMO models for loading in 00/45/90 degrees to the rolling direction with monotonic interpolation for intermediate angles

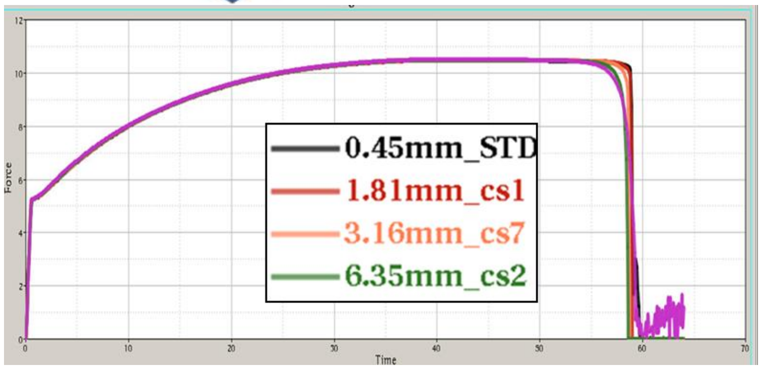
- Model is consistent in the isotropic limit only for DMGEXP=1

Methodology – Regularization - Need

- Need for regularization :
  - Crash analyses mostly modeled with shell elements – does not change in the near future
  - Convergence (similar FD) after necking for different mesh sizes is not guaranteed
  - Mesh sizes used for material characterization and that for actual applications can be very different
  - Models used in applications are not meshed perfectly uniform
  - Consequently failure parameters are mesh dependent

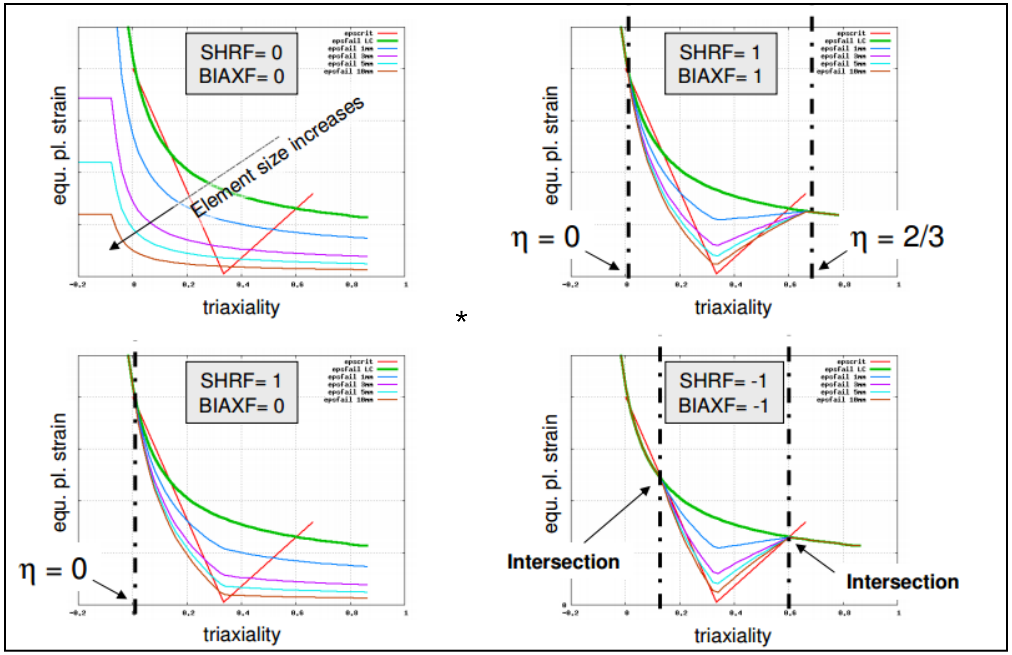


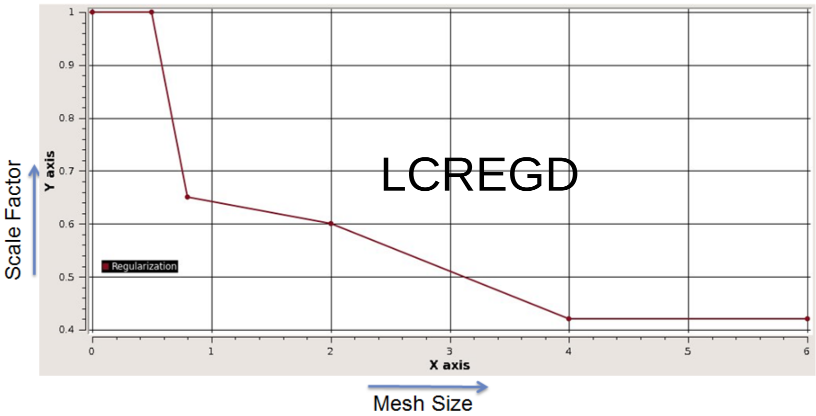




Methodology – Regularization - Tools

- Regularization tools in GISSMO/MAGD :
  - LCREGD is the regularization curve, this allows to regularize the displacement at failure
  - FADEXP<0 references a mesh size dependent fading exponent, this allows to regularize the FD curve beyond the maximum
  - SHRFAC and BIAXFAC allow for the definition of a triaxiality dependent regularization, shear failure is usually assumed to be brittle





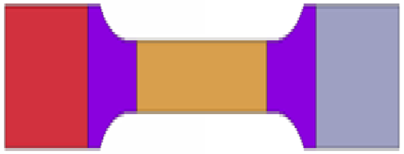
*Reference:

Current Simulation Technique for the Modeling and Failure Prediction of Aluminum Extrusions with LS-DYNA in Crash Applications
Filipe Andrade[1], André Haufe[1], Markus Feucht[2], Merdan Basaran[2], Paul Du Bois
LS-DYNA Nordic Users' Forum 2012 – Göteborg

Methodology – Regularization – Sample Design

- Regularization is required for mesh sizes of 0.5 to 6 mm.
- smooth representation of the deformed geometry : minimum 4 elements for a 90 degree bend are needed
- Geometry of the sample limits the maximum element size that can be regularized.
- Base regularization performed on a tensile test where the diffuse neck corresponds to a 180 degree bend and the diameter of the neck is comparable to the sample width
- 6 to 8 elements over the width are needed to achieve convergence with respect to displacement
- 4 mm element size requires a sample width of 24/32 mm, this exceeds the standard ASTM sample

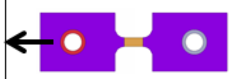
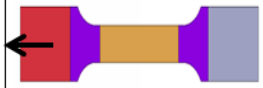
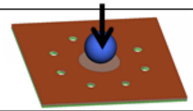
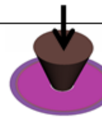
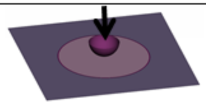
Standard ASTM sample



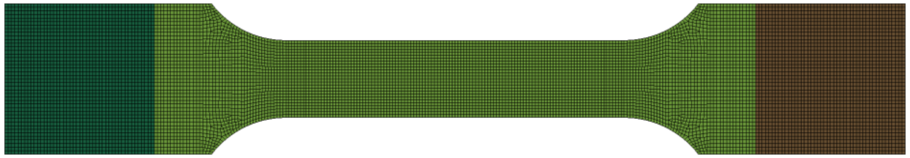
Regularisation sample

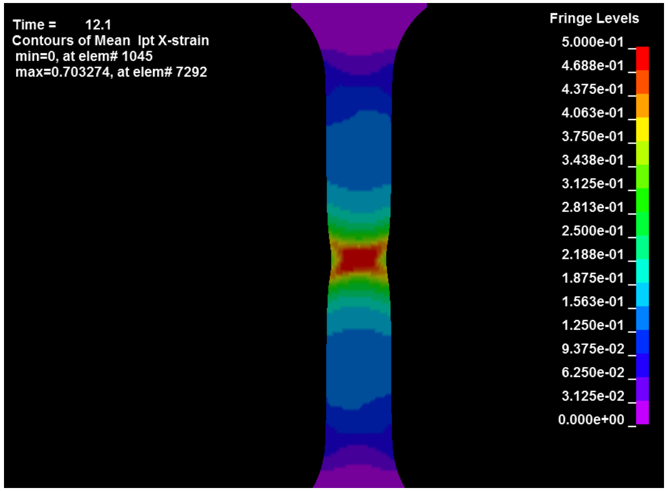
- Regularization samples (1” wide) are a part of standard testing requirements

Material Characterization Testing Requirements

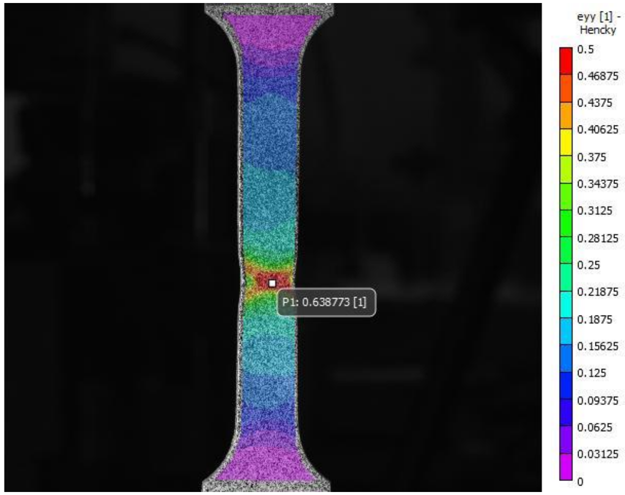
		Number of Tests*	Specimen
Test-1: Tension Mini	Qs - 1/s - 50/s - 350/s (Rolling, @ t1)	4	
Test-2: Tension ASTM E8	Qs - (Rolling-Transverse-Diagonal, @ t1) & (Rolling, @ t2 t3)	5	
Test-3: Tension Regularization	Qs - (Rolling, @ t1)	1	
Test-4: Notch	Qs - (Rolling-Transverse-Diagonal, @ t1)	3	
Test-5: Punch (Biaxial)	Qs @ t1	1	
Test-6: Shear	Qs - (Rolling-Transverse-Diagonal, @ t1)	1	
		15	
		** 3 good repeats*	
Validation Test-7: Cone Push	Qs - @ t1 t3	1	
Validation Test-8: Drop Tower	Qs - No failure (eg 6 mph) & Clear failure (eg 10 mph), @ t1 t3)	4	
		** 3 good repeats*	

1. Match Quasi-Static tensile test FD by inputting true stress-strain curve with adapted “n” values as per swift hardening. Keep Fadexp=8





CAE

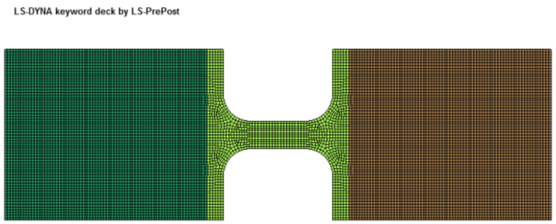


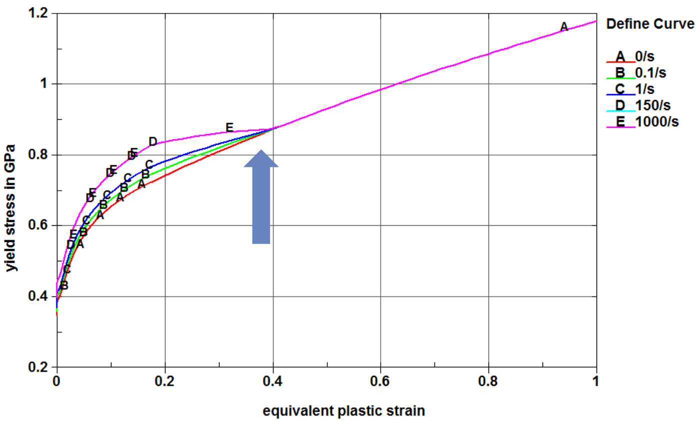
TEST with DIC

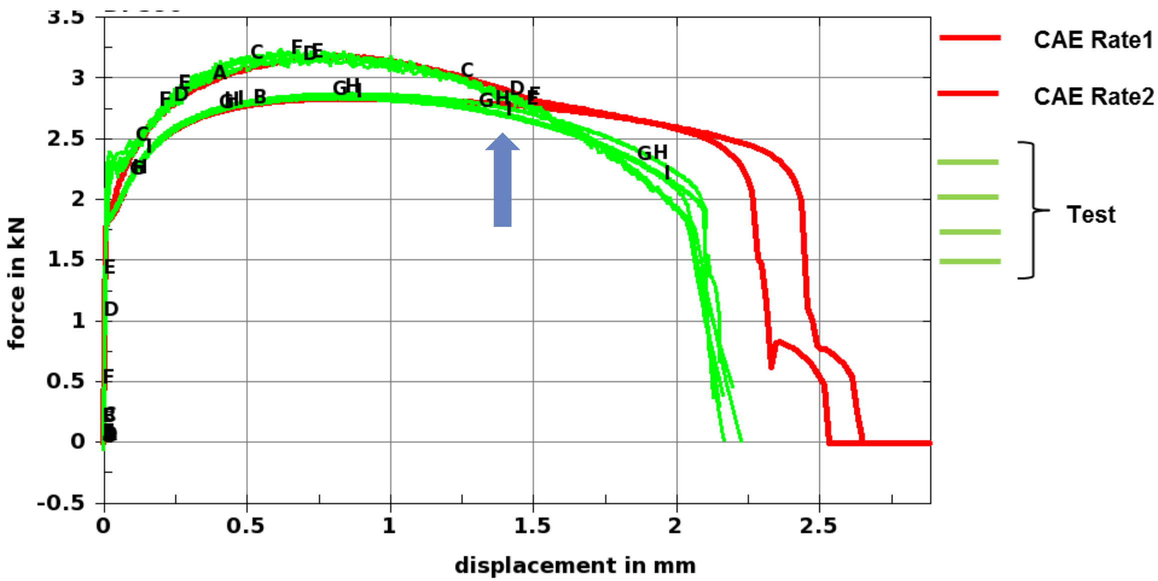
Mesh size = VSGL
Match strain field and f-d curve
Model virtual extensometer and exact sample geometry

Calibration Procedure – Part 1 – Dynamic yield curves

2. Match high rate FD by adding rate-dependency. Try with scaling true-stress with respect to rates. Otherwise adapt the high rate curves post necking until match of FDs is achieved.



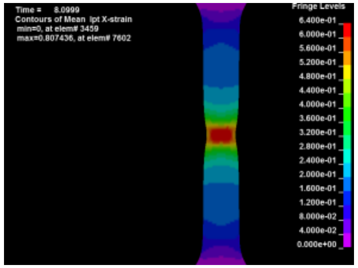


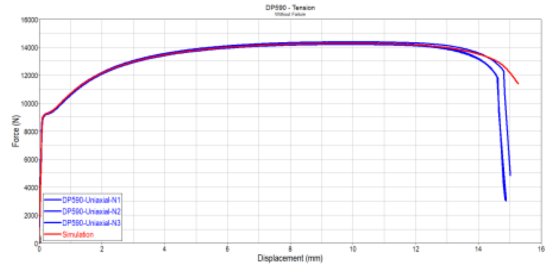


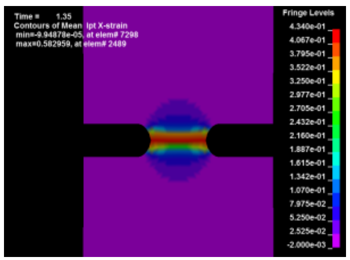
At high strain rates thermal softening reduces the strength, matching f-d may be hard due to our reluctance to use cross-over curves in the TABLE

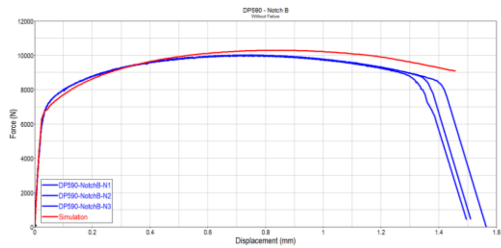
A QS tensile test on a mini-sample is essential as rate effects cannot be derived from experiments performed on different samples

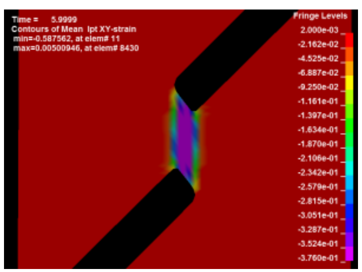
Calibration Procedure – Part 2 – Failure Curve

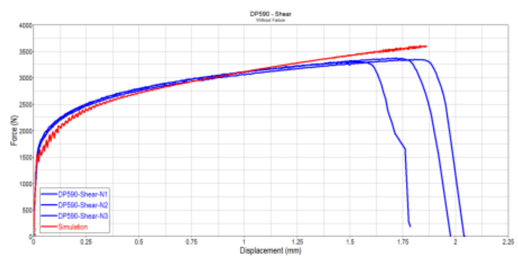


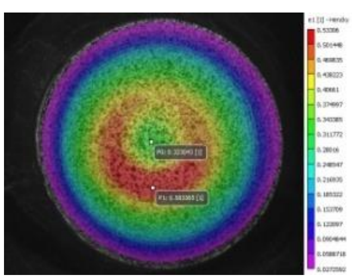


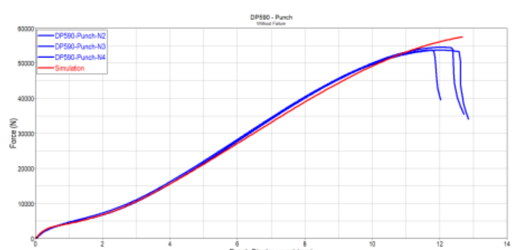








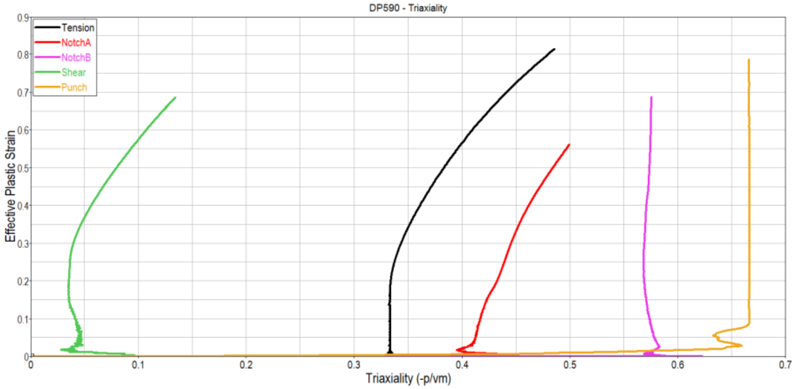




CAE

Start by running simulations of all failure tests up to failure displacement and achieve a reasonable match

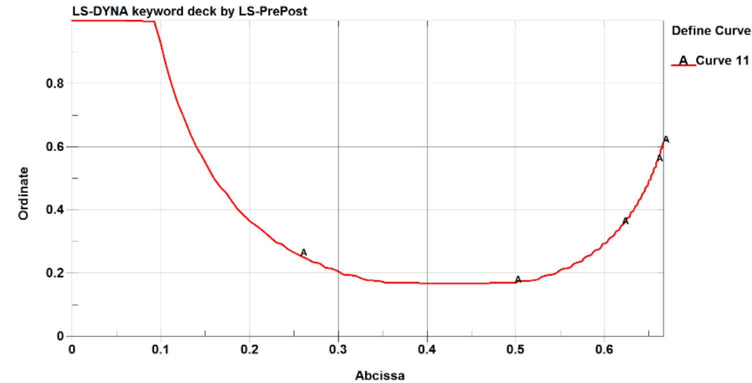
Calibration Procedure – Part 2 – Failure Curve

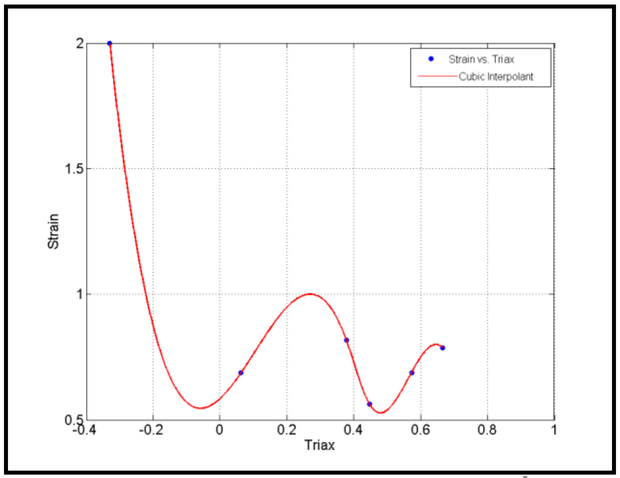


Specimen	Element ID	Simulation Time (ms)	Displacement (mm)	Triaxiality	Effective Plastic Strain
Tension	2280	8.11	14.5	0.378	0.817
Notch A	7014	2.33	2.30	0.447	0.562
Notch B	7399	1.37	1.35	0.573	0.688
Shear	5649	5.93	1.70	0.063	0.686
Punch	3990	8.32	12.5	0.660	0.787

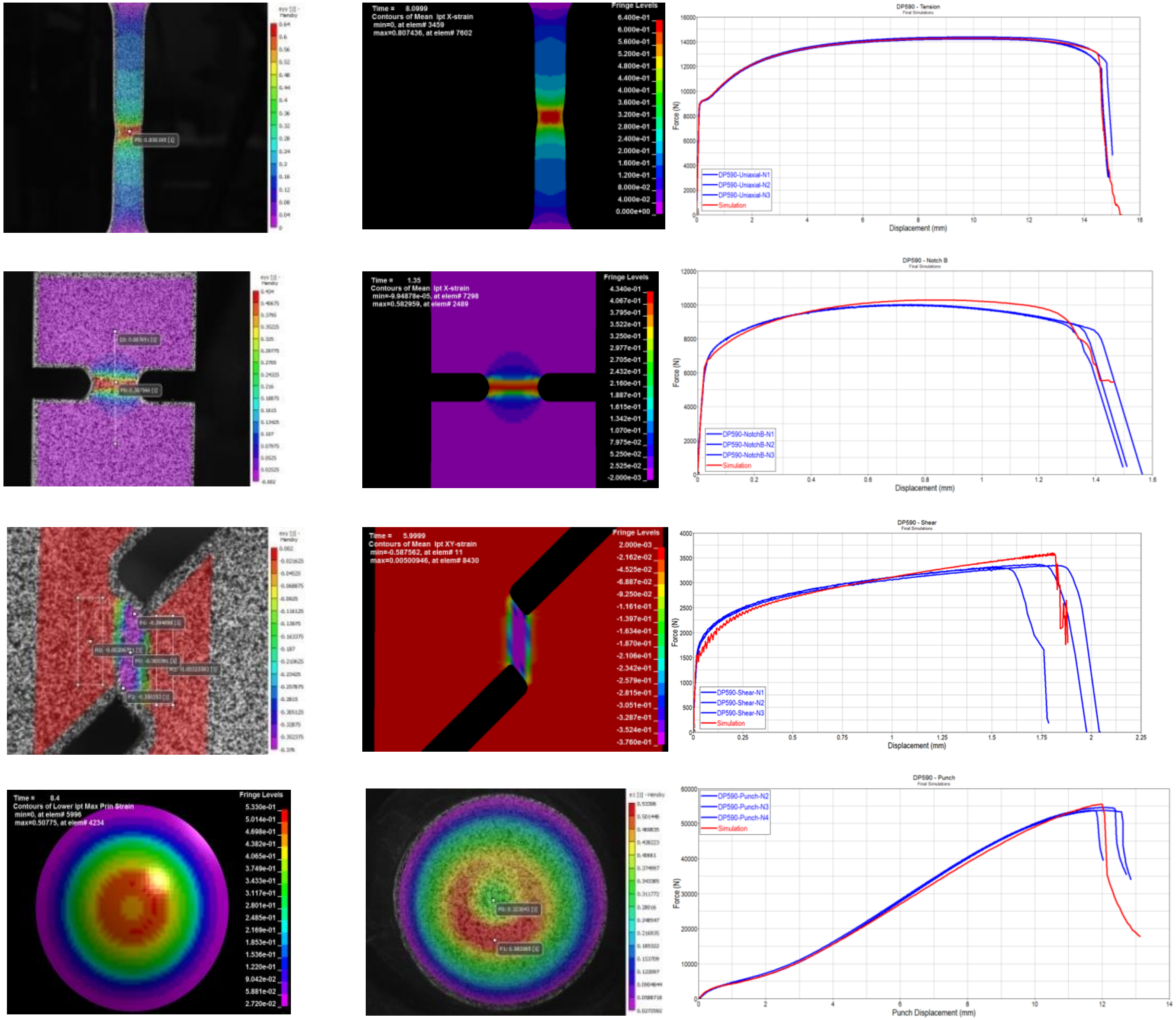
Derive initial failure curve from computed load paths and measured DIC failure strains

Add instability curve (Swift)





Calibration Procedure – Part 2 – Failure Curve

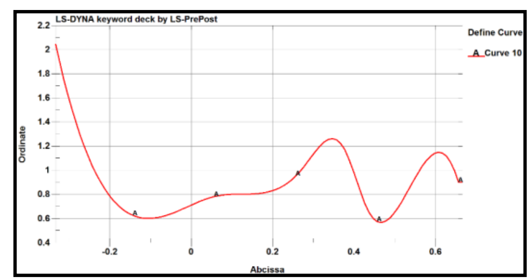


Test

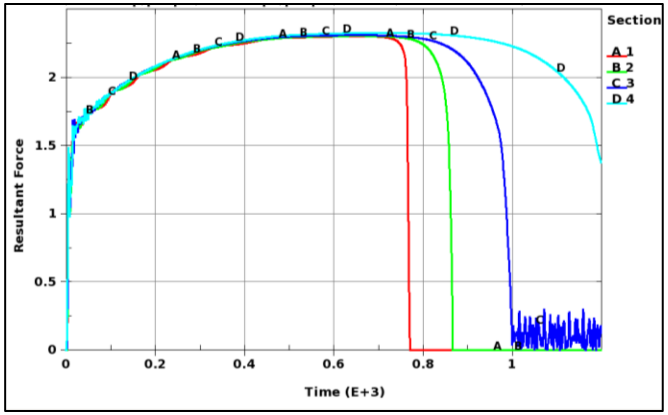
CAE

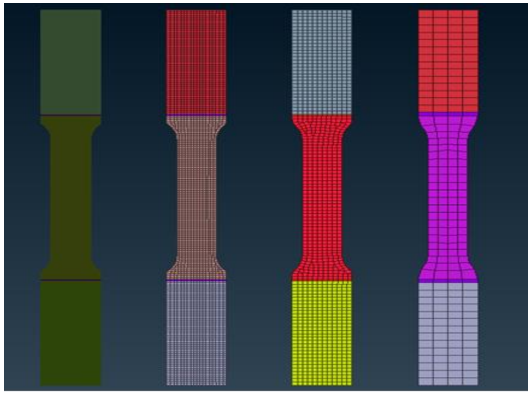
Iteratively achieve the final shape of the failure curve LCSDG

Also match reasonably the failure displacement and the DIC strain field

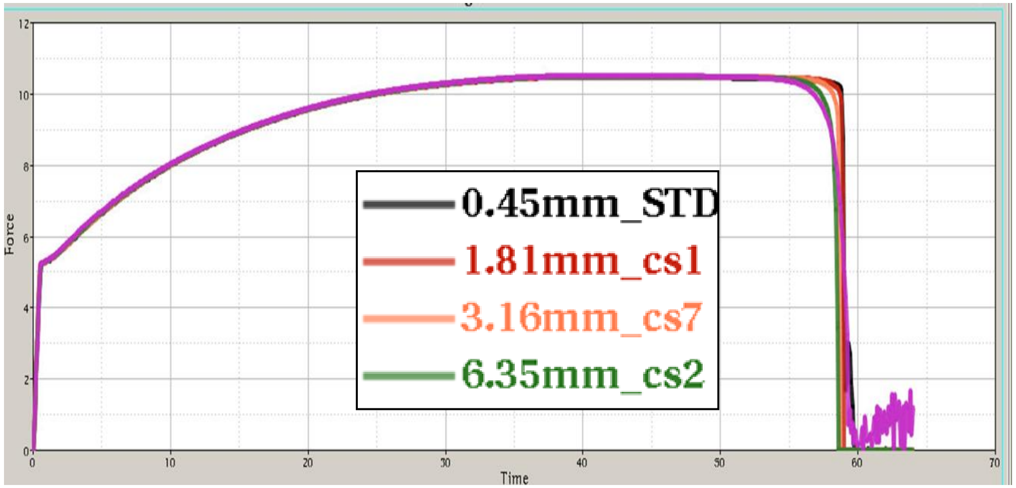


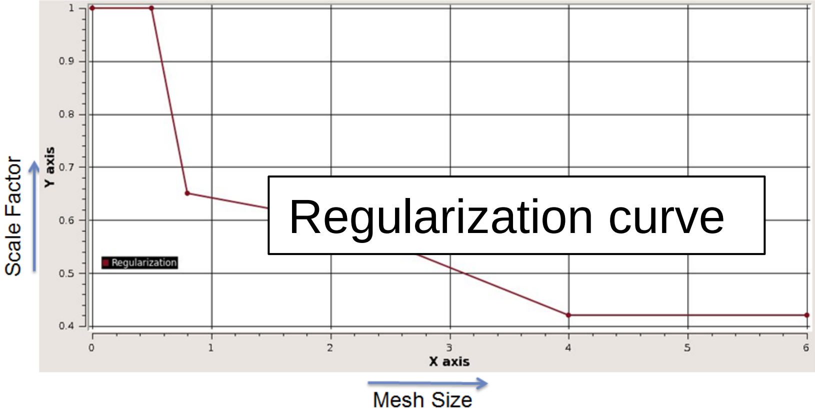
Calibration Procedure – Part 3 – Regularization



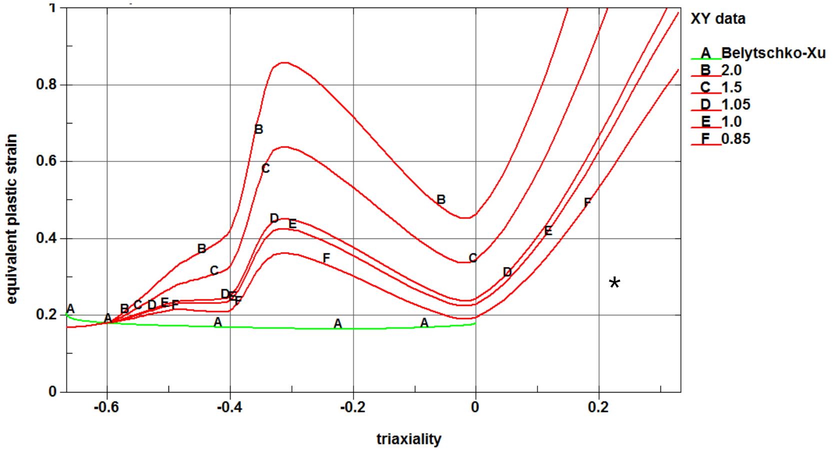


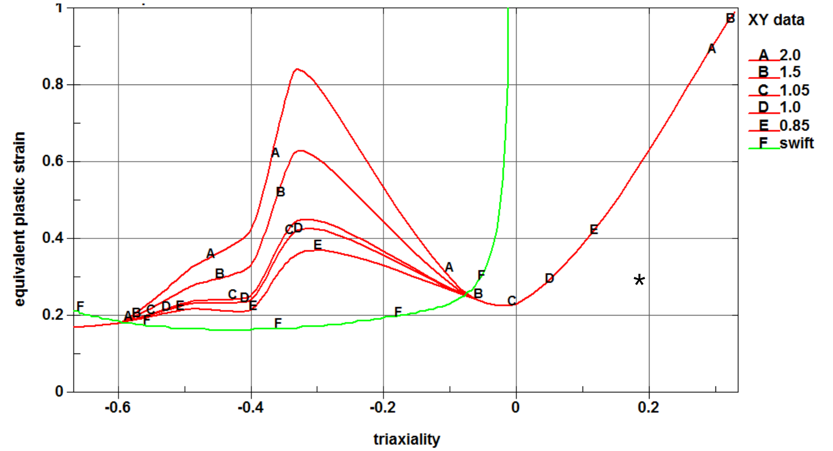
0.45 mm | 1.81 mm | 3.16 mm | 6.35 mm





Calibration Procedure – Part 3 – SHRFAC and BIAXFAC





Typical SHRFAC=0 and BIAXFAC=-1

Typical SHRFAC=-1 and BIAXFAC=-1

Shape of the shear f-d curve usually justifies assuming brittle failure in shear and thus SHRFAC=-1

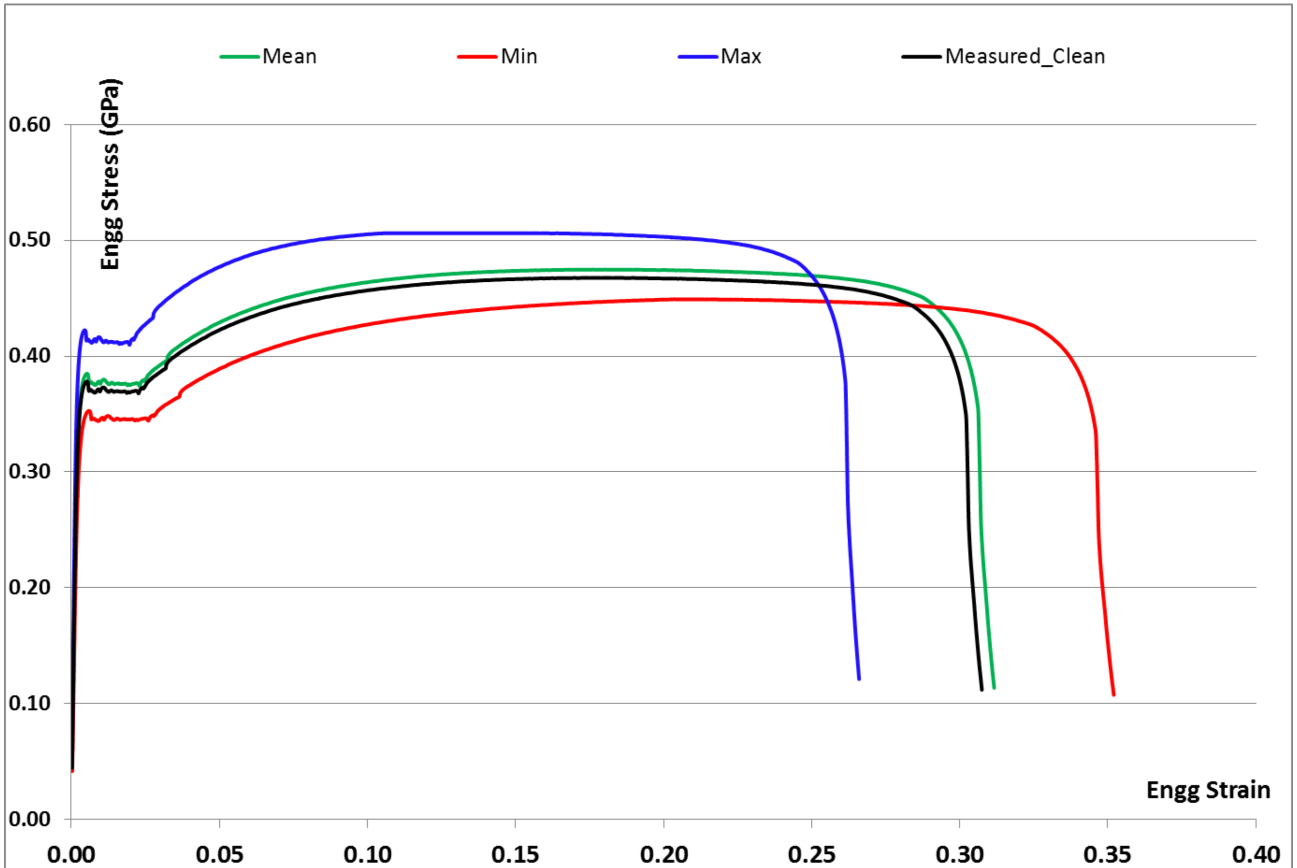
Not always true under biaxial conditions

*Reference:

Increasing predictability in crashworthiness simulation: pushing the limits
Paul Du Bois
Markus Feucht
LS-DYNA German Users' Forum 2012 – Ulm

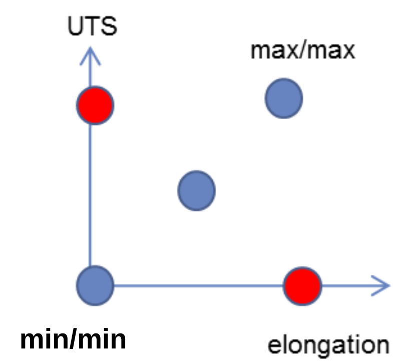
Scatter & Variability

Take material variability into account by using statistical data from the Material supplier. Fabricate curves to create min/max/mean and measured Gissmo models



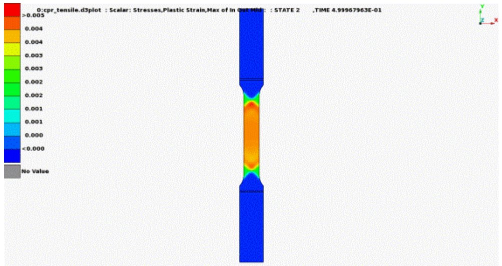
	Yield0.2%	UTS	%Elon
min	0.34	0.43	0.23
max	0.42	0.51	0.35
mean	0.38	0.47	0.29

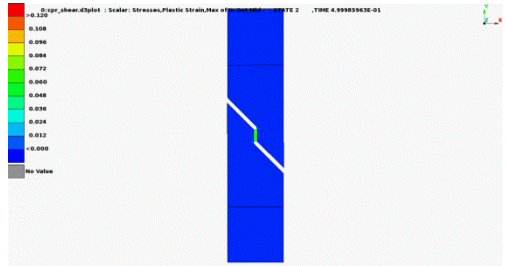
Statistical data lack Information about Shape of the yield curves

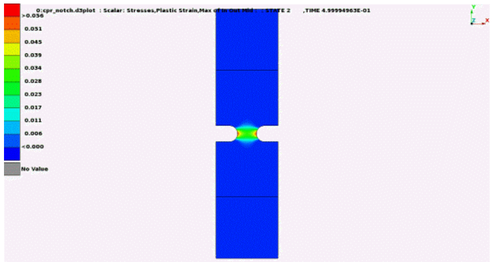


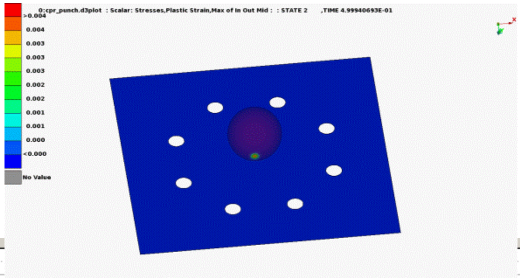
Some Examples

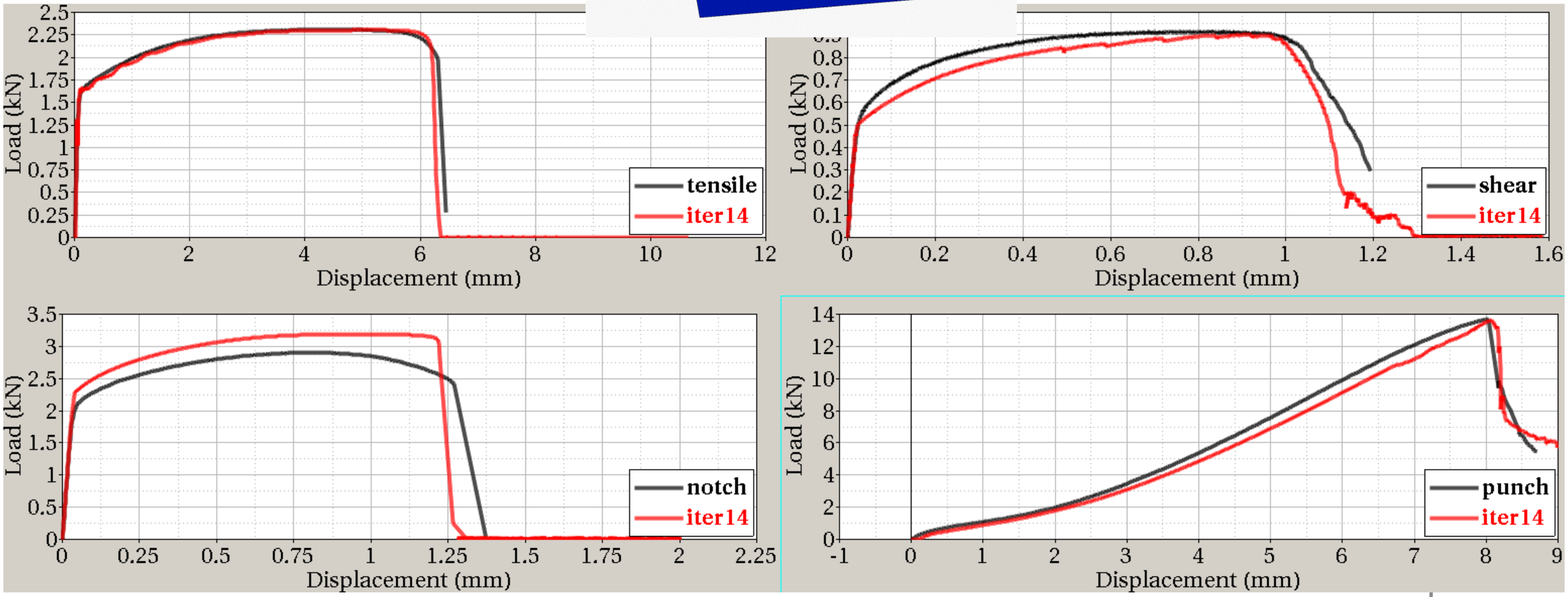
Material1 - Coupon Correlation



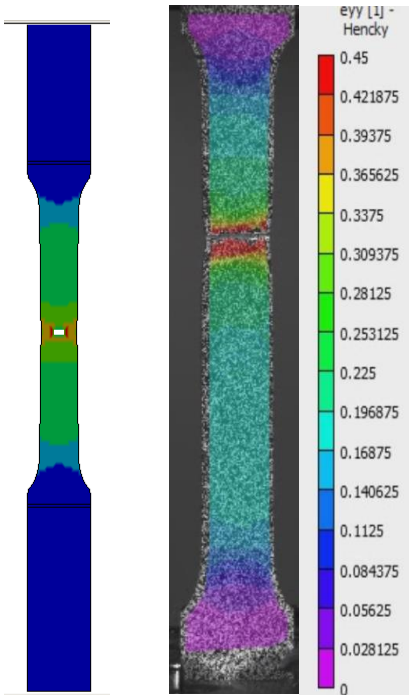




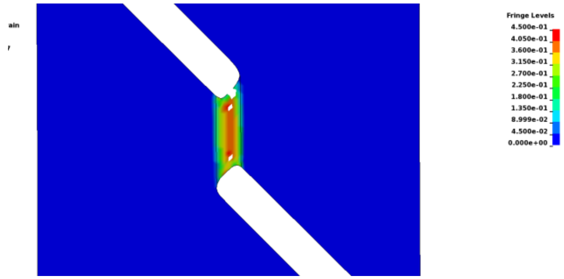


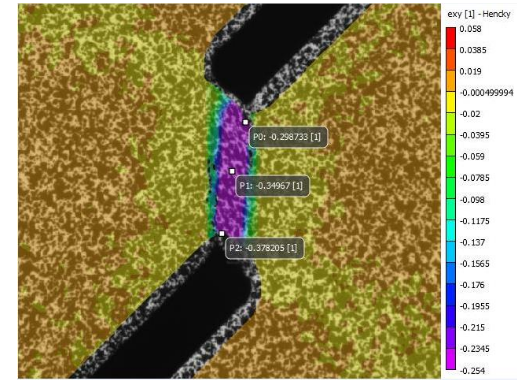


Material1 - DIC Correlation

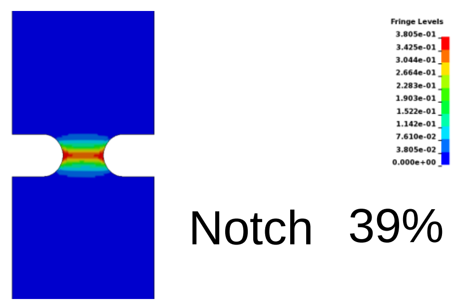


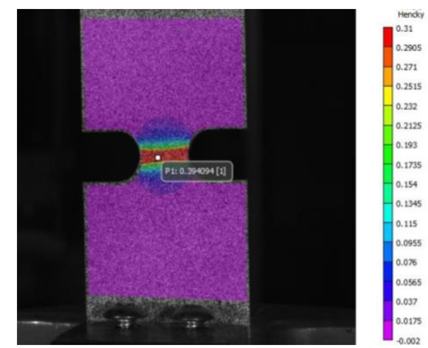
Tensile 45%





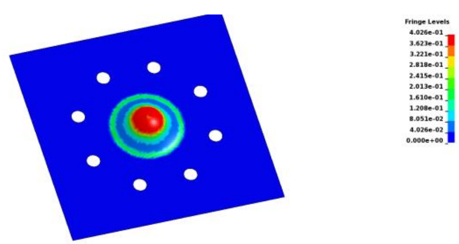
Shear 40%

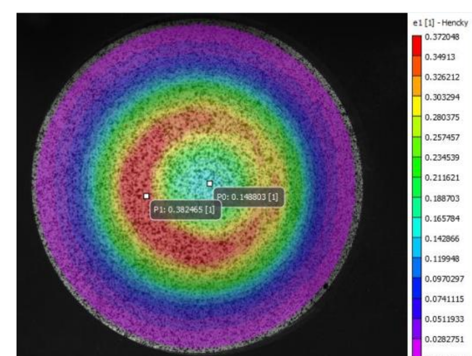




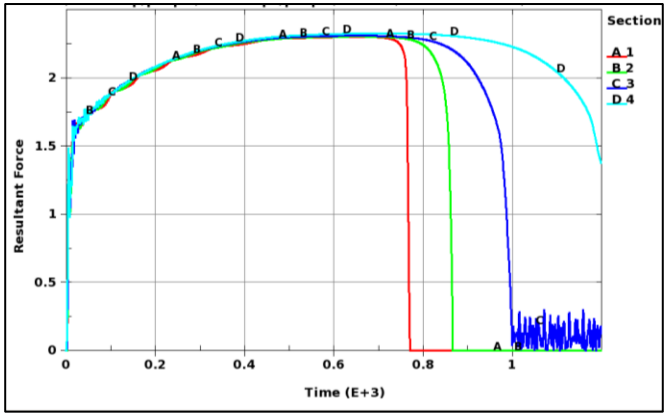
Notch 39%

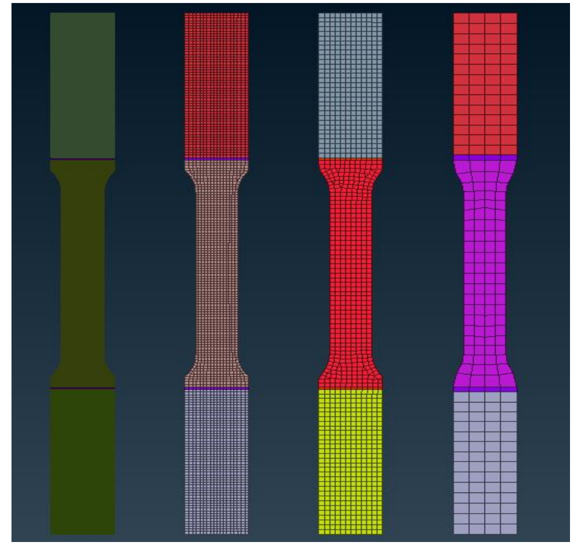
Biax 40%



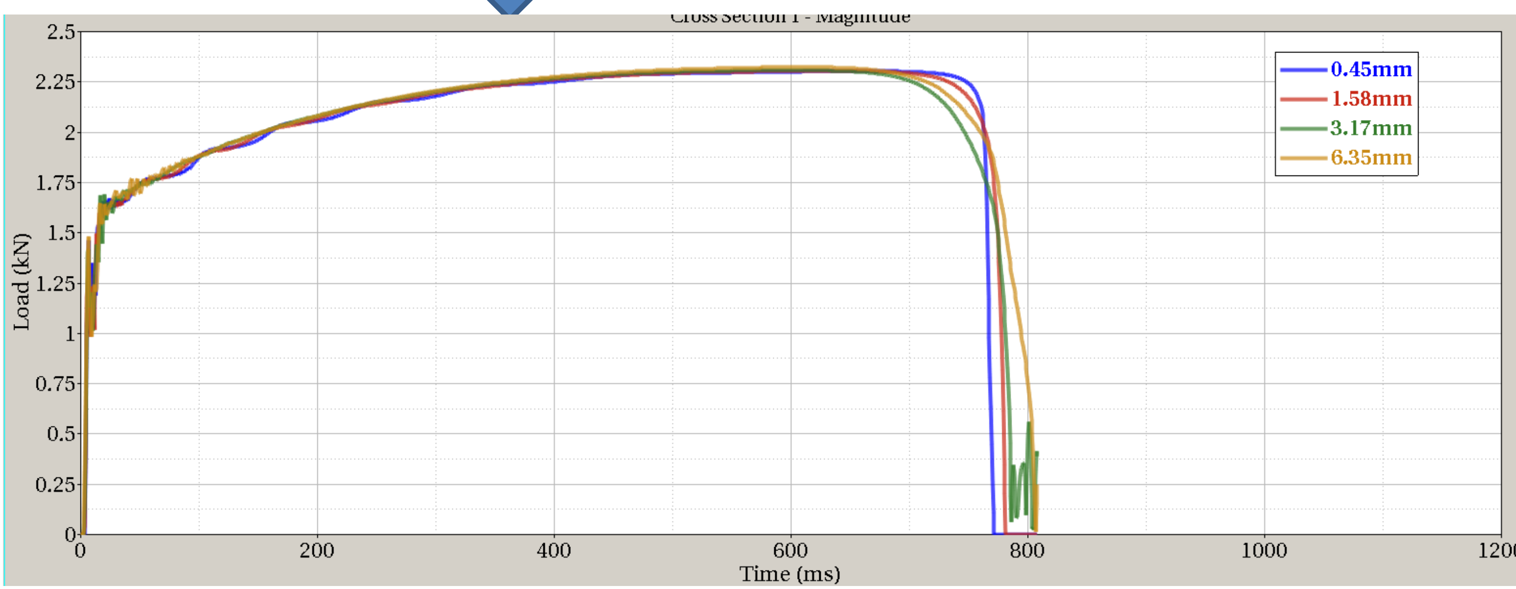


Material1 - Regularization (Mesh Dependency)

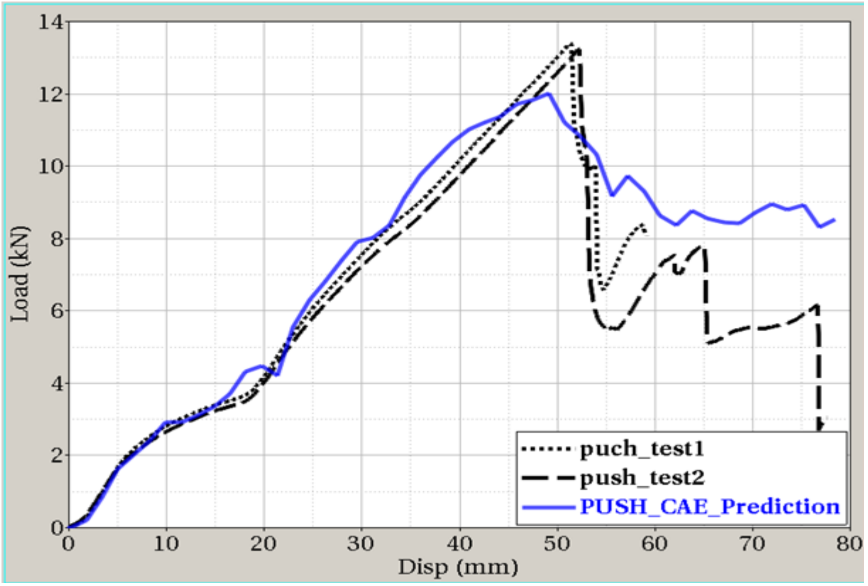


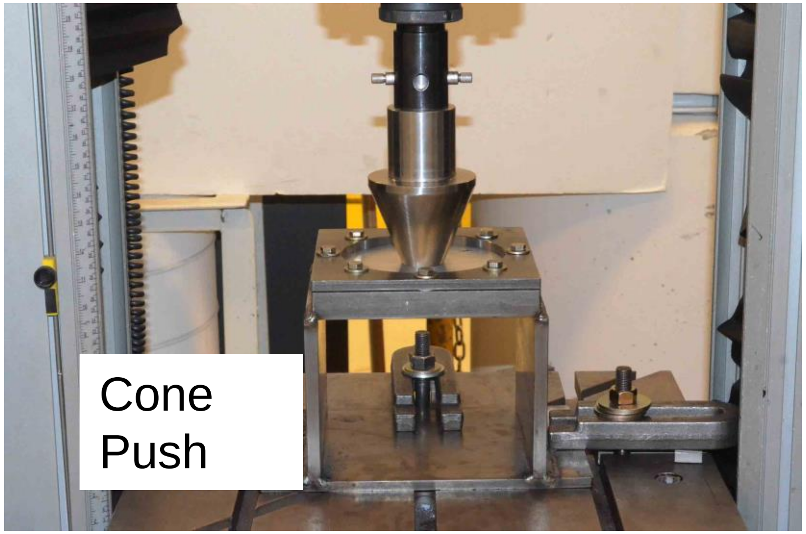


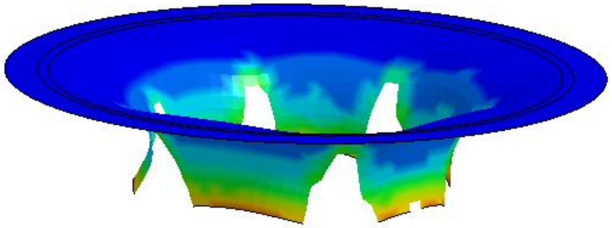
0.45 mm | 1.81 mm | 3.16 mm | 6.35 mm

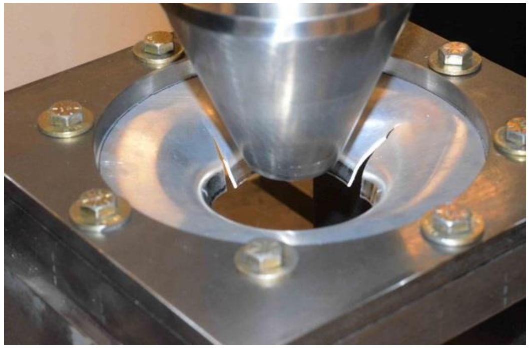


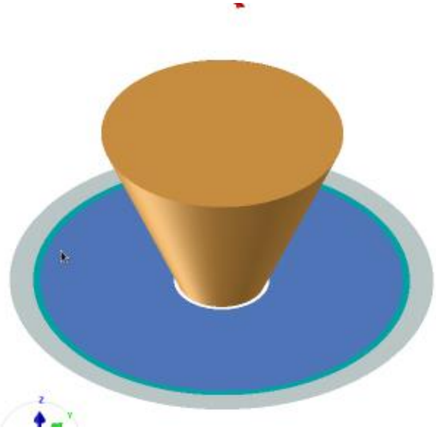
Material1 – Cone Push test-CAE correlation



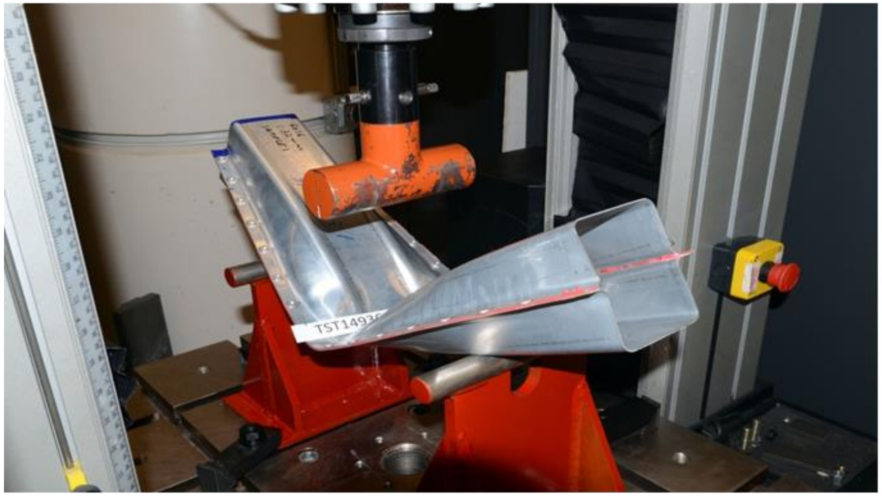


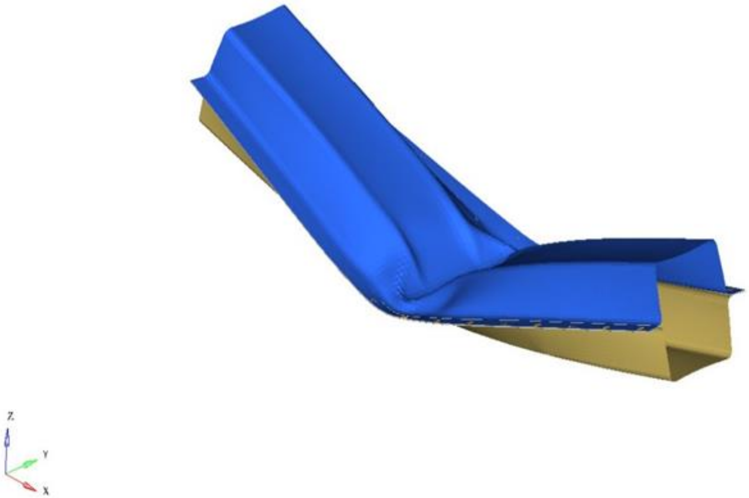


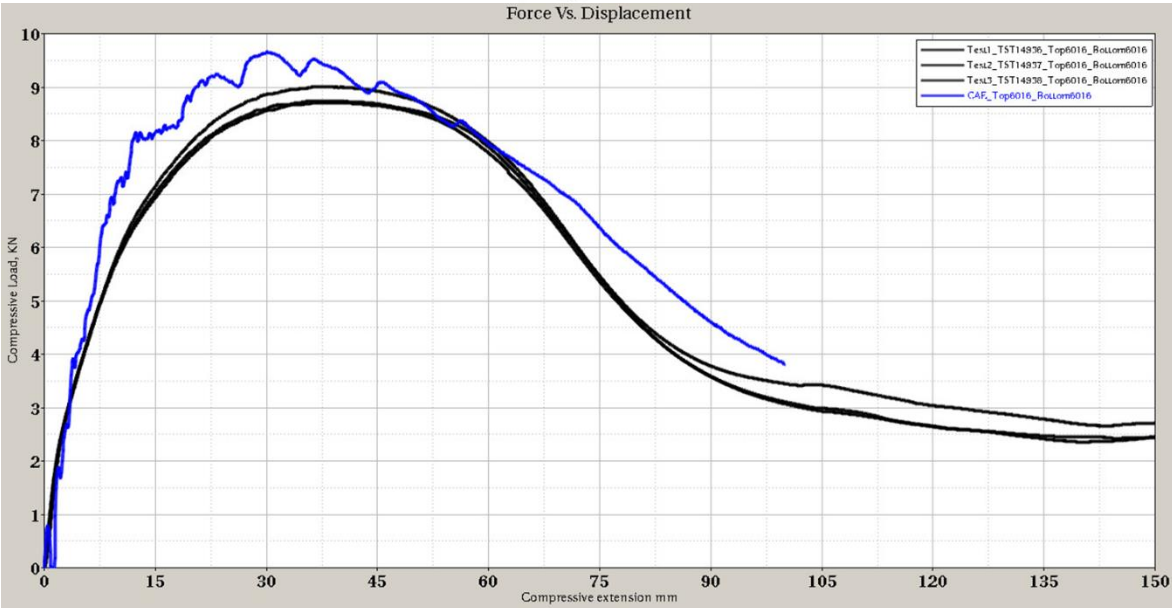




Material1 – 3pt bend test-CAE correlation



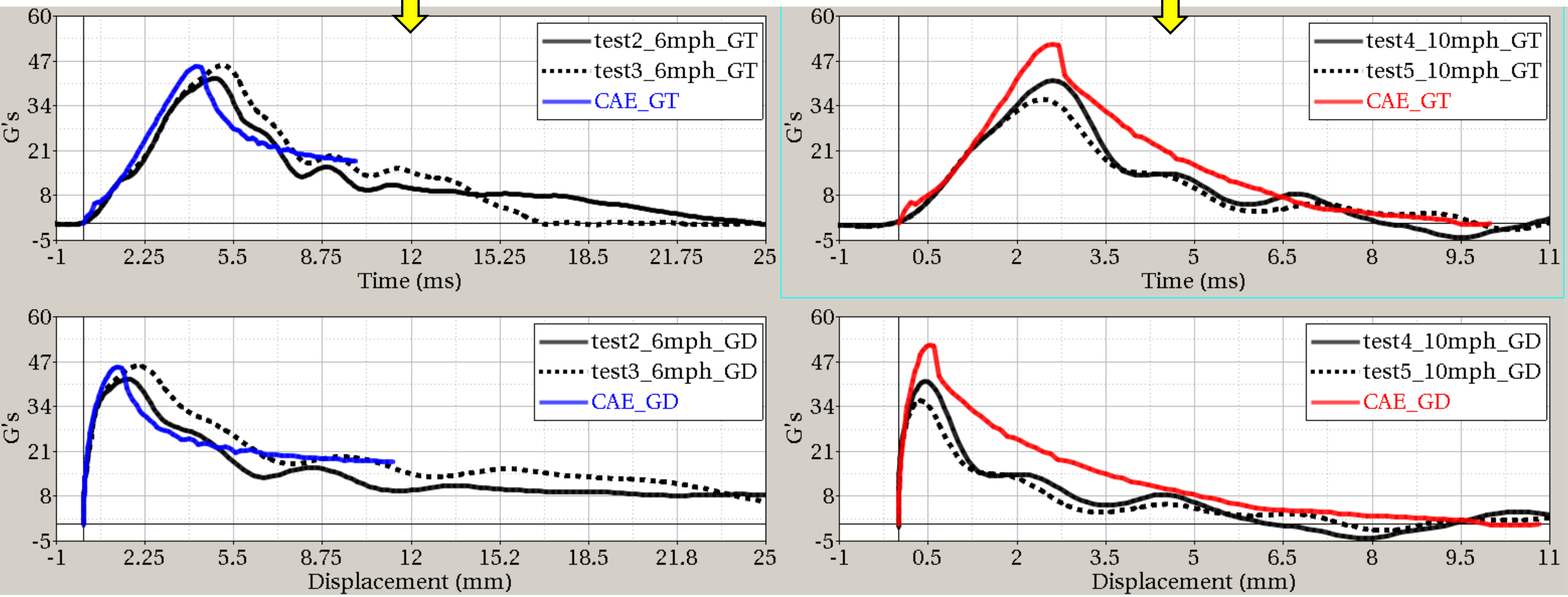


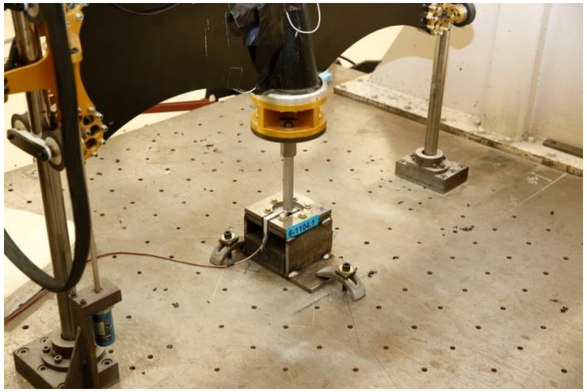


Material1 – Drop tower test-CAE correlation

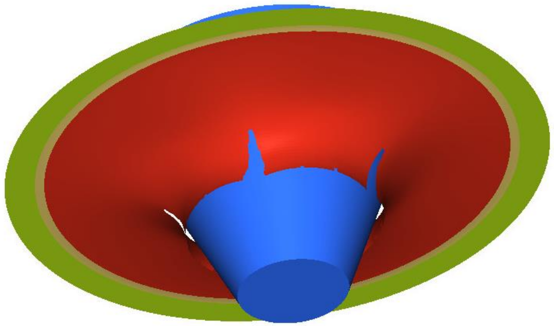
6 mph

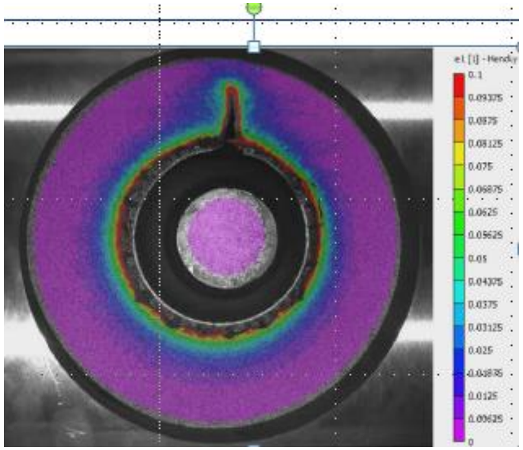
10 mph



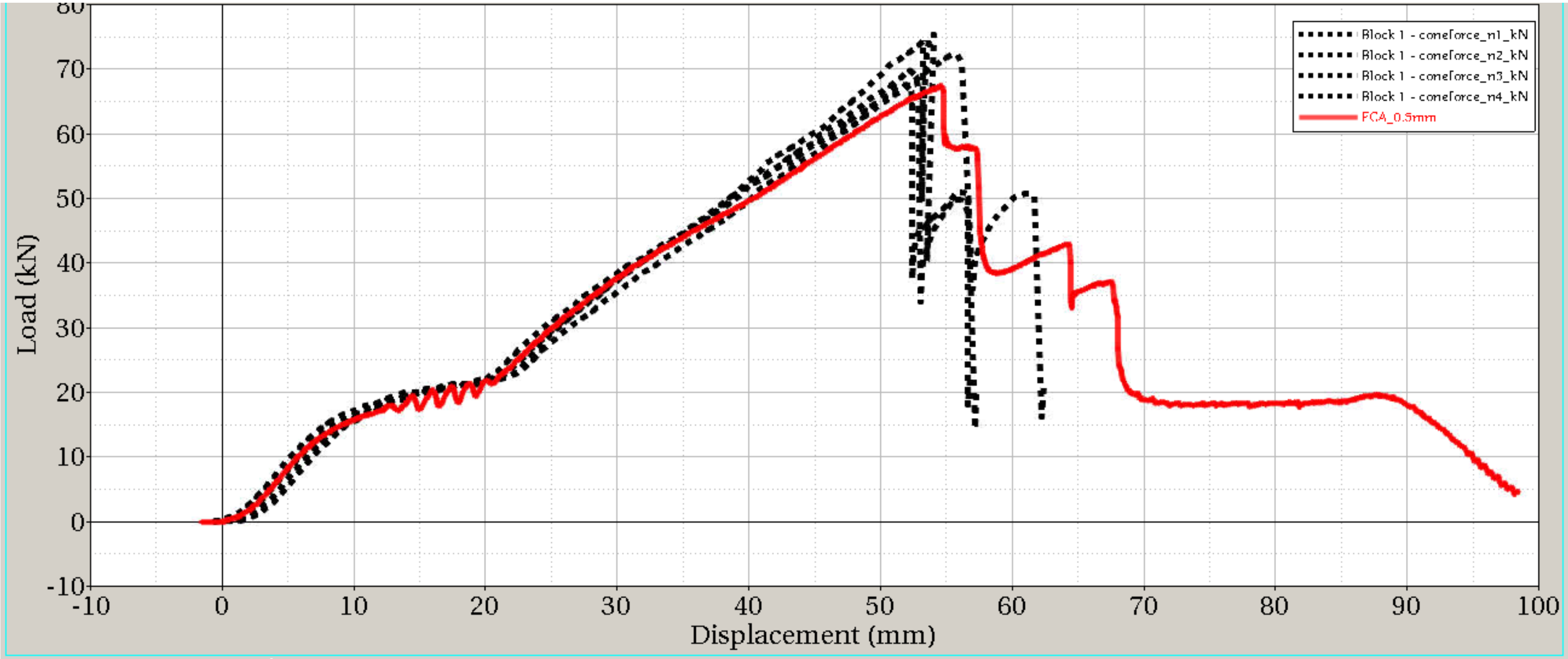


Material2 – Cone Push

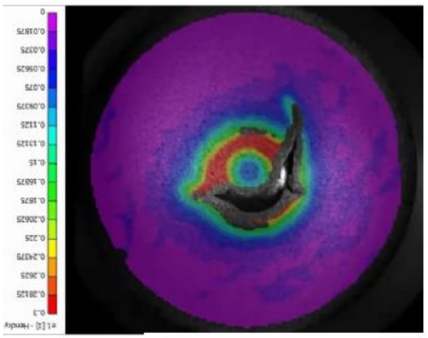


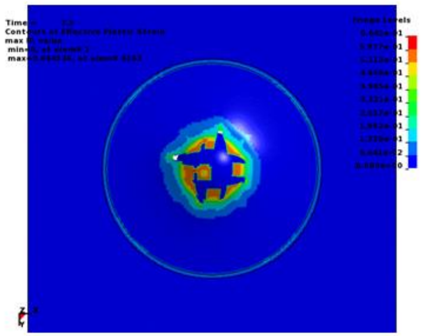


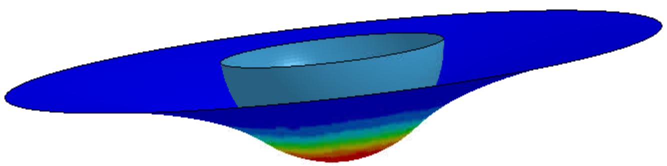
Cone Push Test with DIC conducted by Ohio State Univ (OSU)

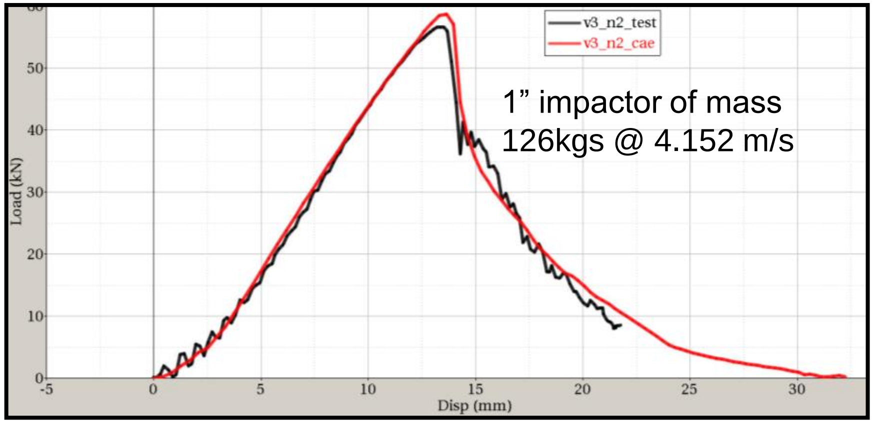


Material2 – Drop tower

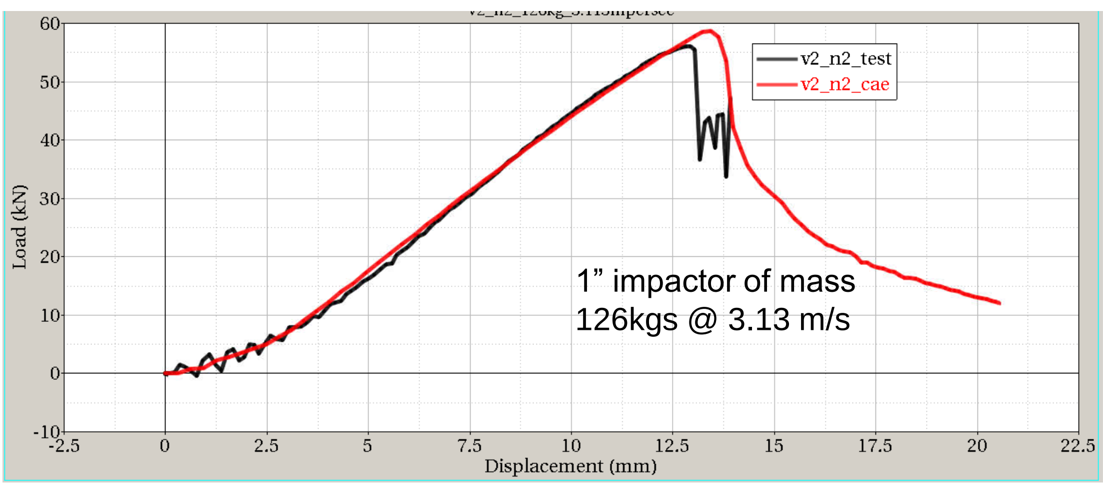




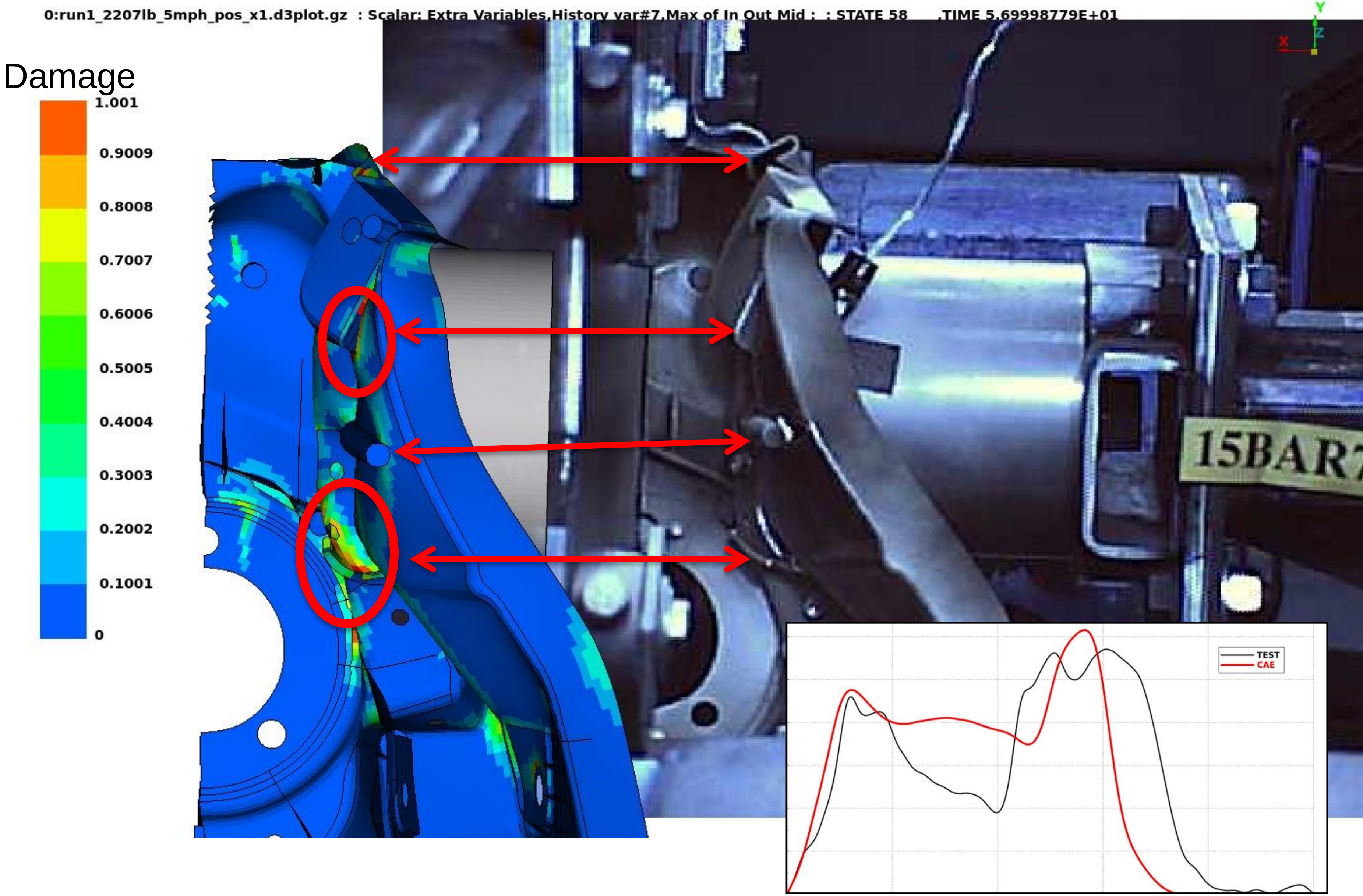




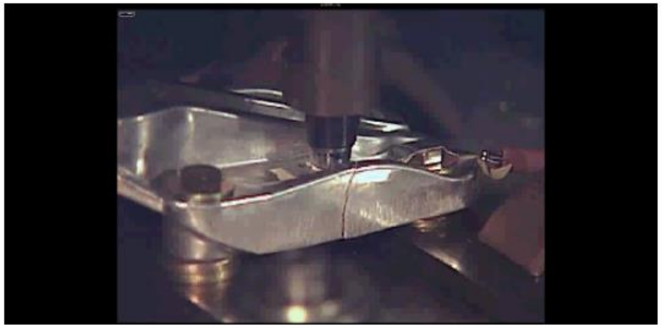
Drop tower test with DIC conducted by Ohio State Univ (OSU)

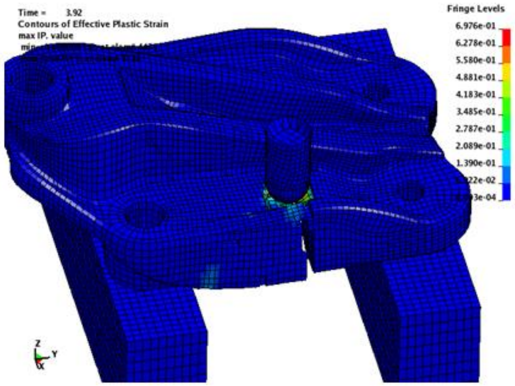


Material3 - Casting Shell model Impact

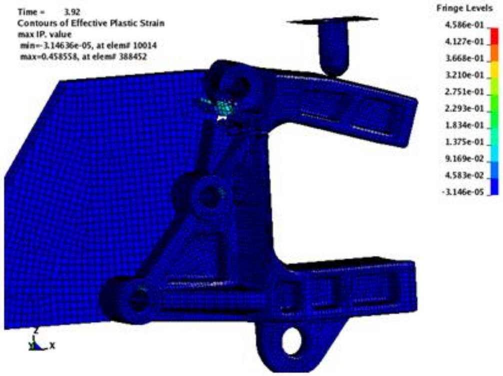


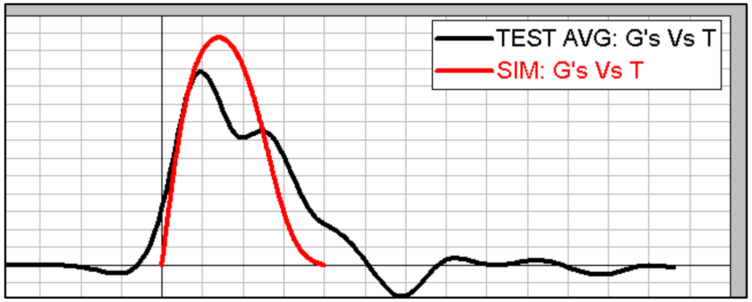
Material4 - Casting Solid Model Impact

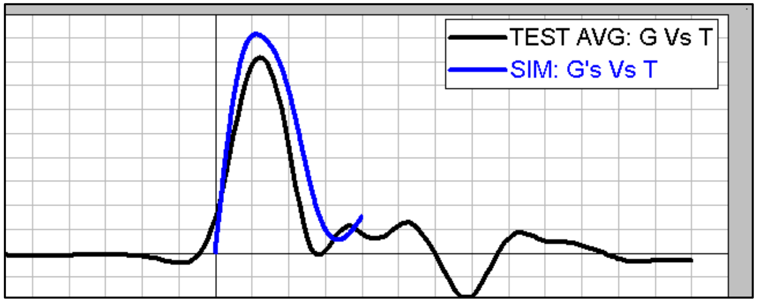




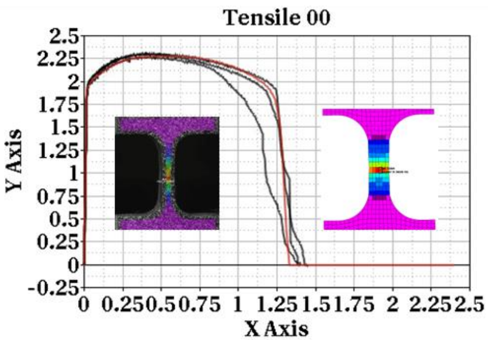
Mount Test
58.6 lbs dart dropped @ 12.78 mph

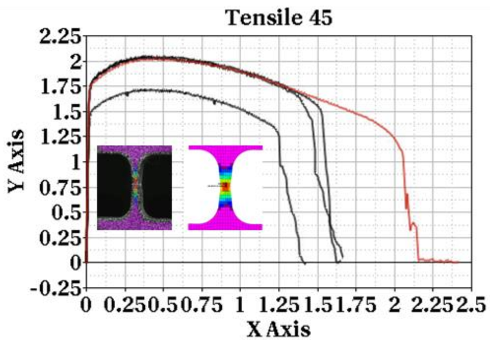


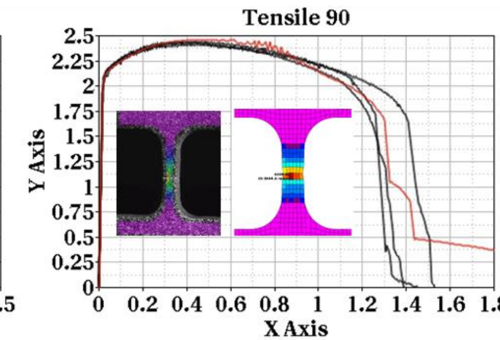


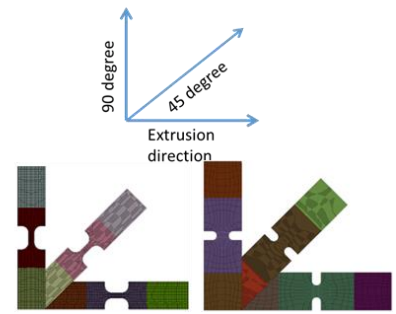


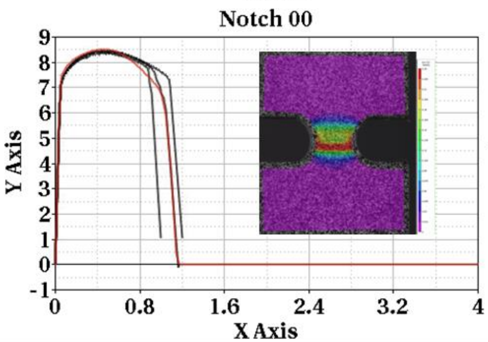
Material5 – Extrusion MAGD Development

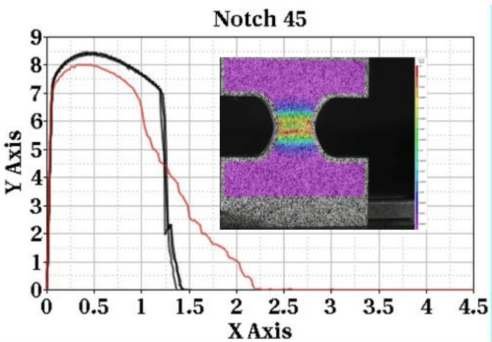


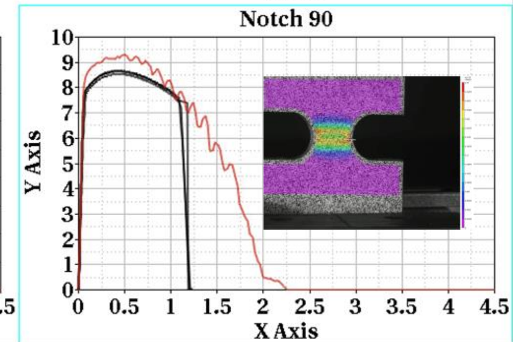


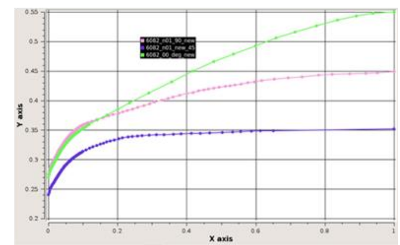


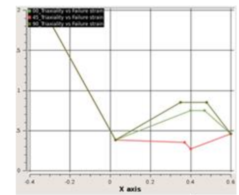


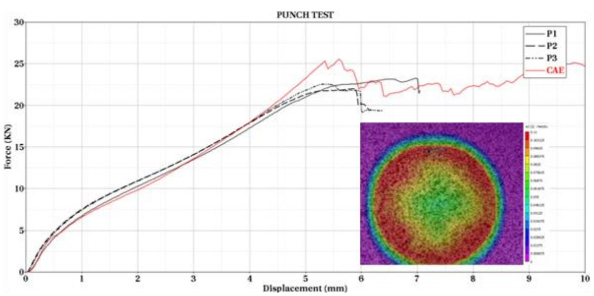


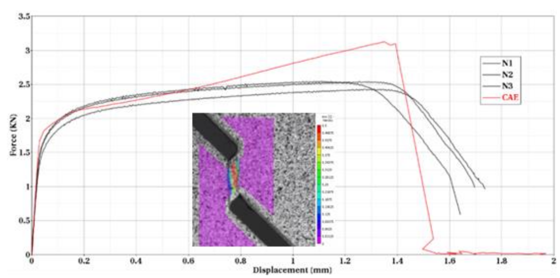


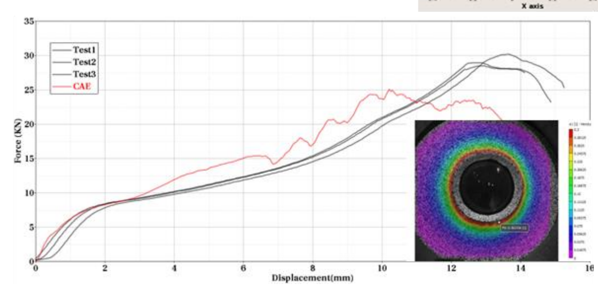








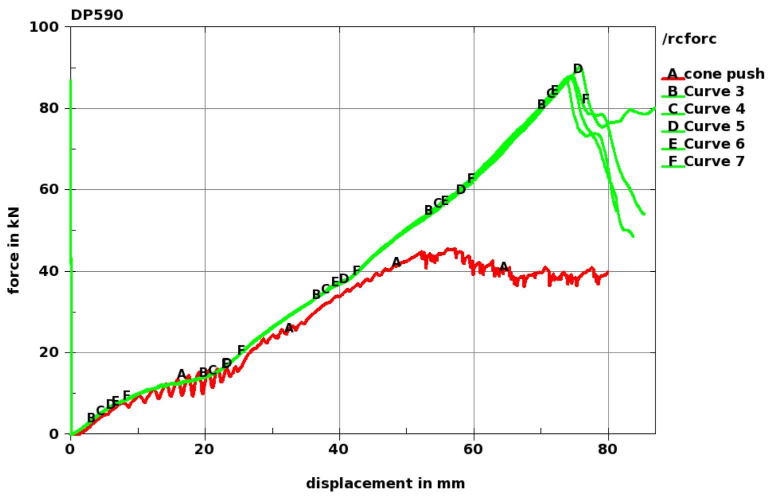


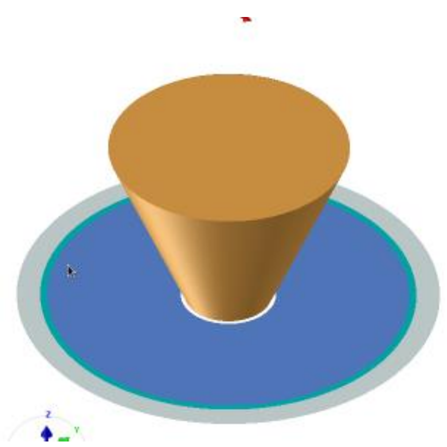


Lessons Learned

Imperfect Boundary Condition

Example of conepush test

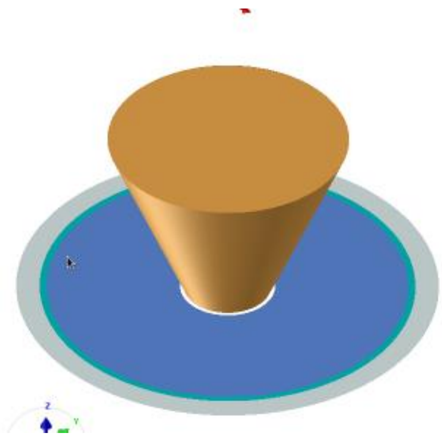


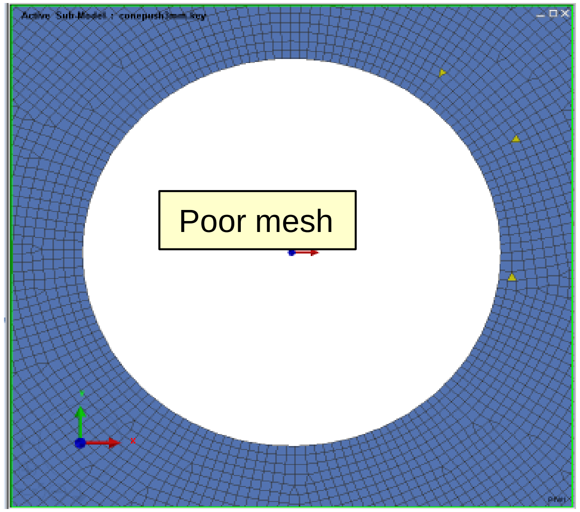


Imperfect test BC (see deformed bolt holes) can explain the early failure in the simulation where a perfect BC is assumed

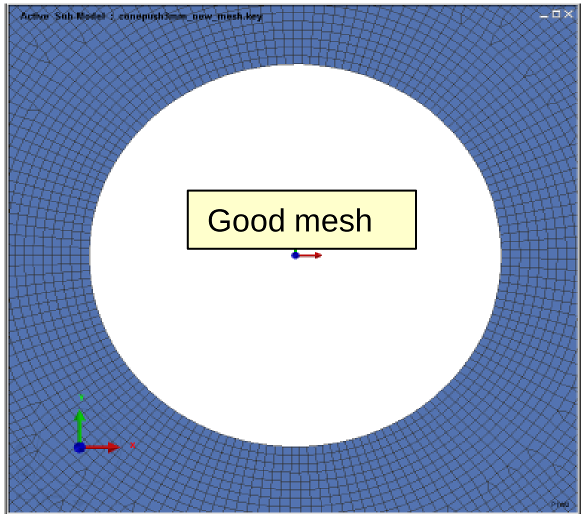
Mesh Quality

Example of cone push test



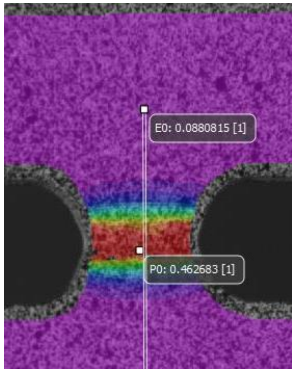


Highlighted Tria elements near edges causing early failure

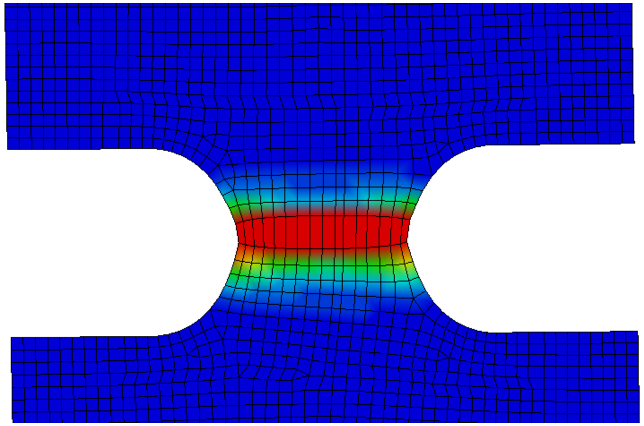


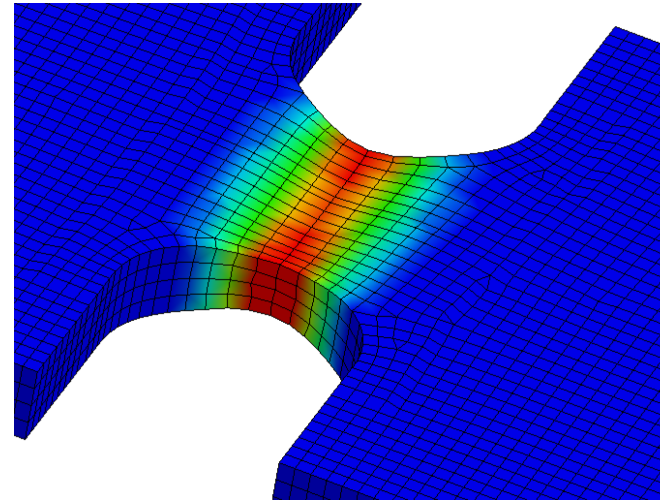
Quad elements in first seven layers from the edge

Limitation of Shell when gage is about 3mm



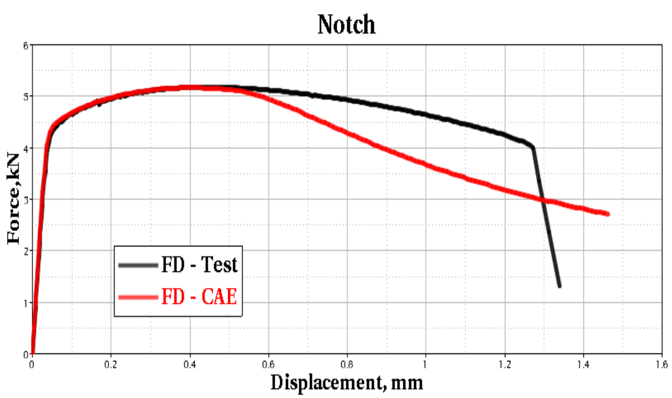
Test

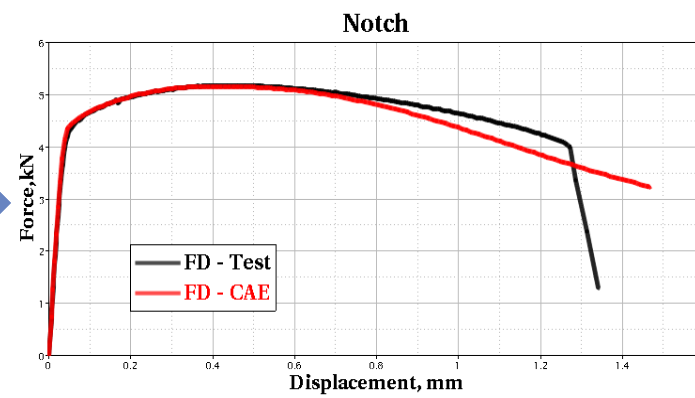




Shell

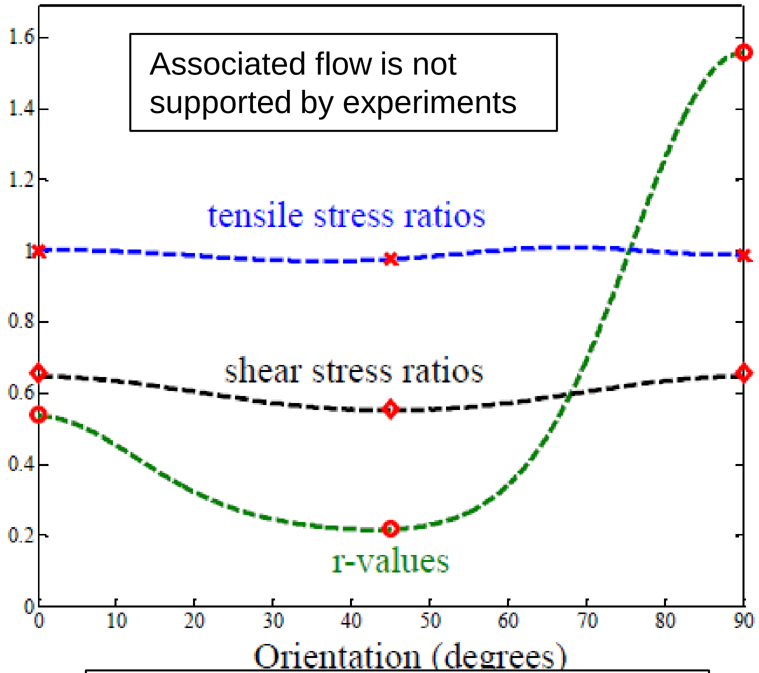
Solid

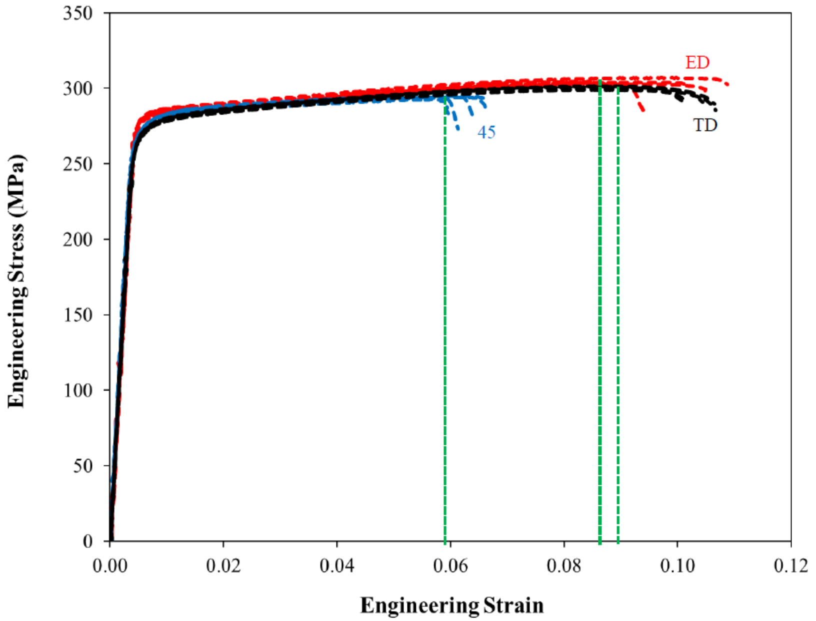




Orthotropy is not limited to tension

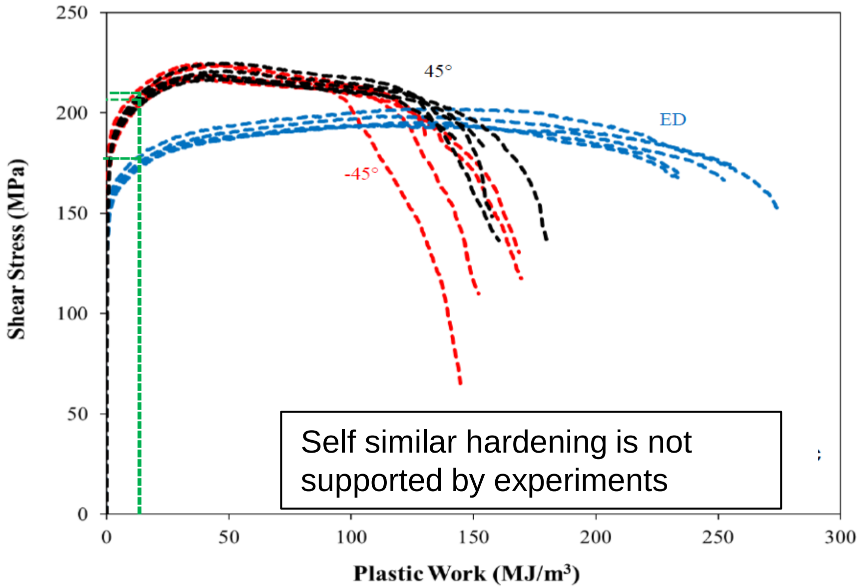
FCA
FIAT CHRYSLER AUTOMOBILES





Tests conducted at Univ of Waterloo

Stress States	Experiment	Model
Uniaxial Tension – RD (r-value)	1.0000 (0.54)	1.0000 (0.54)
Uniaxial Tension – DD (r-value)	0.9786 (0.22)	0.9760 (0.22)
Uniaxial Tension – TD (r-value)	0.9882 (1.56)	0.9880 (1.56)
Eq. Biaxial (r-value)	-	0.9990 (1.03)
Plane Strain – RD	-	1.08
Plane Strain – DD	-	1.06
Plane Strain – TD	-	1.11
Shear – DD	0.5560	0.5510
Shear – RD	0.6570	0.6470



Additional Comments

1. Every material is different and requires its own specific calibration.

2. Every structure becomes 3D when close to failure, we should be cognizant of the limits of shell elements. Sometimes it is difficult to discern between the limits of the material model and the limits of the element formulation.

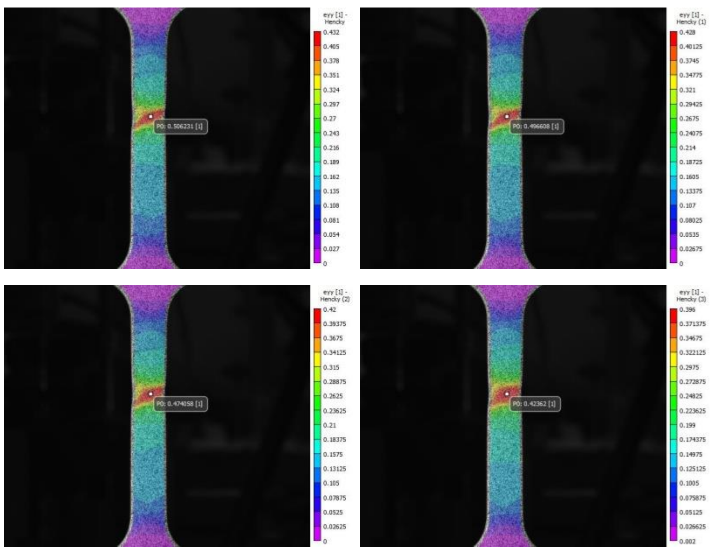
3. The value of DIC cannot be overstated, it is the most reliable part of the experimental package and no failure model is reliable without DIC data, matching the measured strain field is a minimum condition for a failure model with predictive capability.

4. Temperature effects are not limited to very high strain rates. Rate effects generally induce temperature effects. So far we have buried temperature effects in the rate effects but it is not sure that we will keep doing this in the future for all materials. The availability of measured temperature fields will help assess the real importance of temperature effects.

On-going Improvements

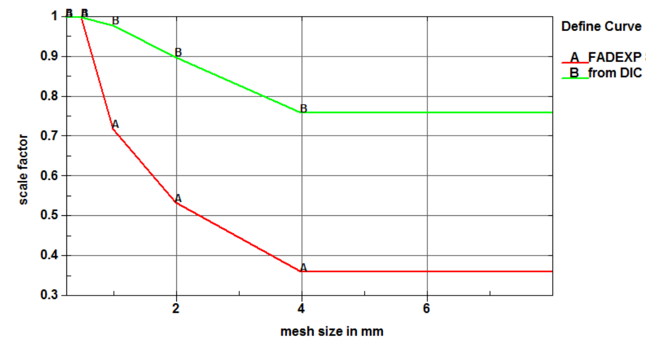
On-going Improvement : Regularization based on test data

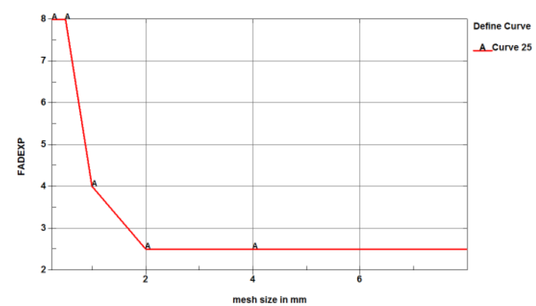
- DIC strain fields are recorded for different VSGL values covering the range between 0.5 mm and 6.0 mm. This allows to determine the LCREGD curve directly from the test data



VSGL 0.5mm
VSGL 1.0mm

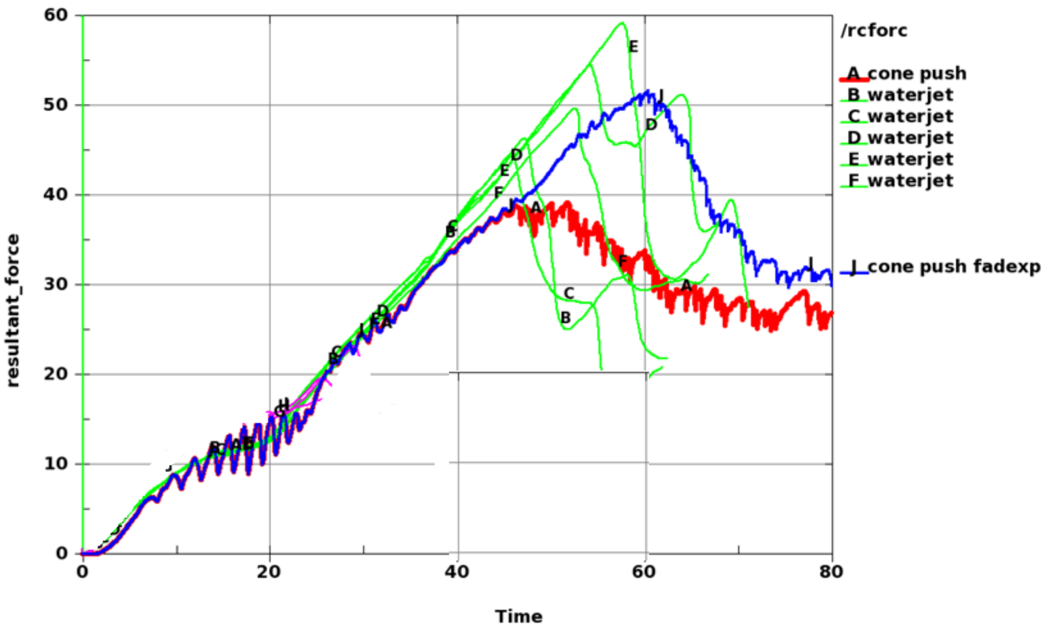
VSGL 2.0mm
VSGL 4.0mm



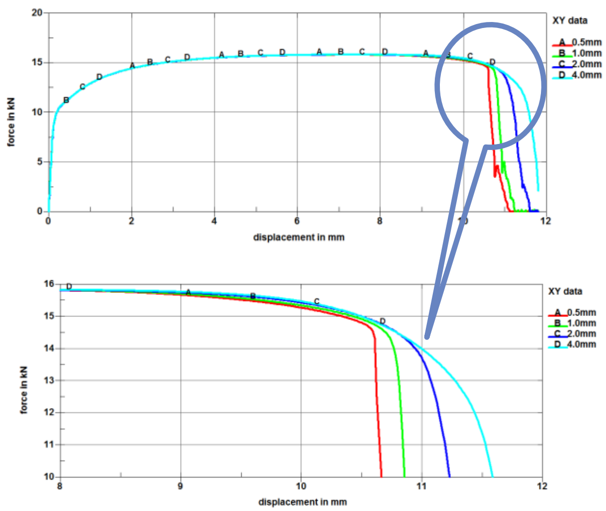


- We determine the virgin material hardening curve for a mesh size of 0.5mm with a FADEXP >=8
- We use FADEXP<0 to determine a mesh dependent fading exponent allowing to match the measured f-d curve with different mesh sizes ranging between 0.5 mm and 6.0mm

On-going Improvement : Regularization based on test data



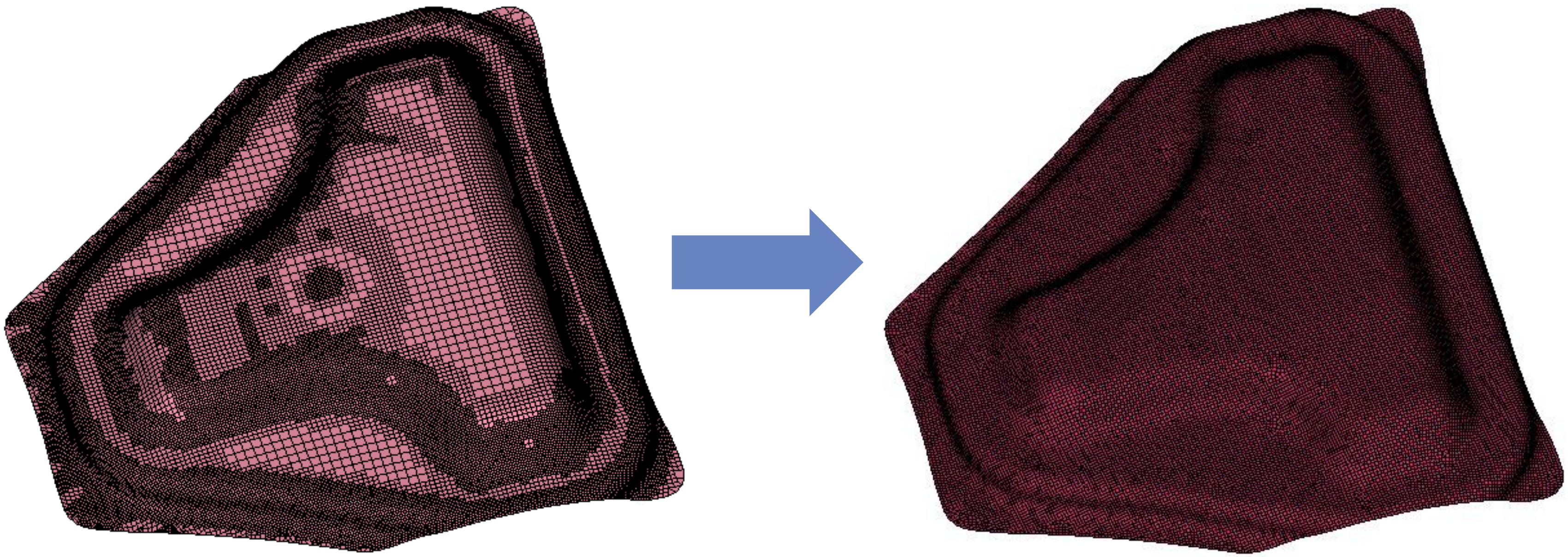
Cone push test



ASTM uniaxial tension test (Good for mesh sizes up to 3 mm)

On-going Improvement : Damage mapping

- Work at FCA US LLC was instrumental in the development of the new REFSIZ<0 option in *M_A_G_D leading to improved quality of mapping strain and damage fields between models with different mesh sizes



Future Challenges

1. 3D Parts – Solid modeling and generation of failure surfaces
2. Larger samples – how to reduce the dependency of regularization
3. Mapping Process (Stamping, Damage, Casting porosity, Extrusion core and skin properties)

The End

Thanks for your attention