Rate Dependency Plastic Modeling

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Considerations before testing or modeling

- What strain rates will your part see?
  - Remember strain rate is not the same as speed
  - Strain rates may not be uniform
- What is the environment?
  - Temperature
  - Exposure
  - Etc.
- What is the material?
  - Brittle/ductile
  - Rate sensitive or not (glass vs. plastic)
- What event are you trying to simulate
  - Energy absorption
  - Drop
  - Crash

Considerations before testing or modeling

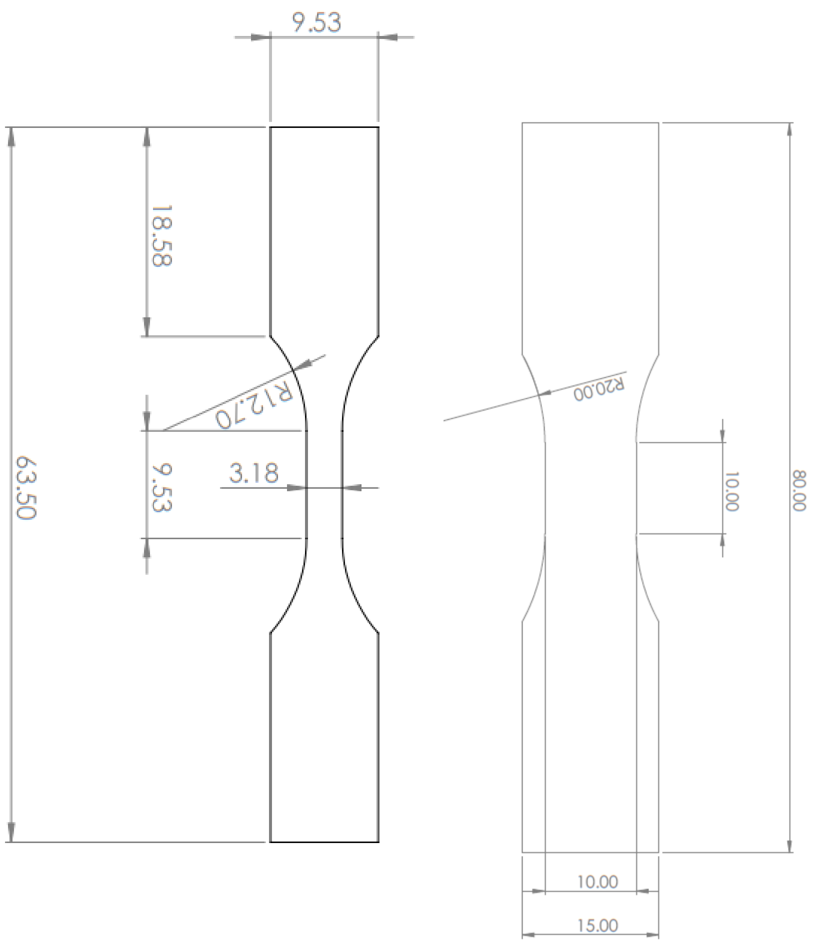
- Material model selection
  - Can the model handle rate dependency?
  - Can the model handle failure?
  - Can the model handle the material (plastic, metal, foam, etc.)
- Can coupons be taken from the part?
  - If not, can a similar process be used to make coupons?
  - Worst case use molded specimens

Strain rate

- Strain rate is not uniform
    - Point of contact
    - Deformation causes reduction
    - Interaction of multiple parts may make it hard to calculate
- If possible do a pre-simulation with substitute material
- SR=(dL/L)/dt or V/L
- Very short time events

Test specimens

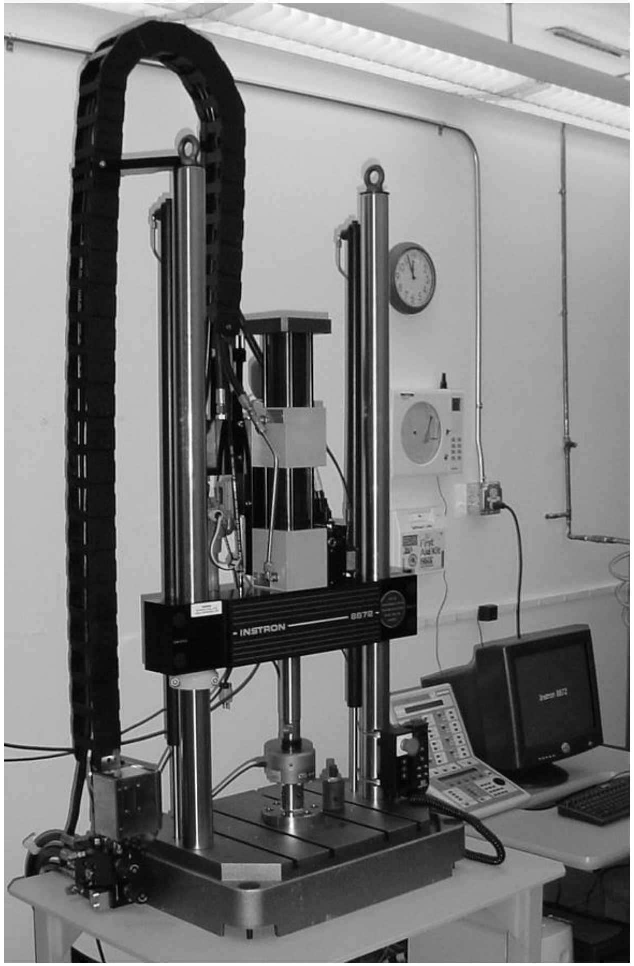
- ASTM D638Type V
  - Unfilled only
  - When space is limited
  - Short gauge length
- ISO 8256 Type 3
  - Filled or unfilled
  - Somewhat more space
  - Short gauge length
- Preparation
  - CNC from plaque
  - CNC from part
  - Molded
- Variability
  - processing
  - orientation
  - thickness



ASTM Type V   ISO Type 3

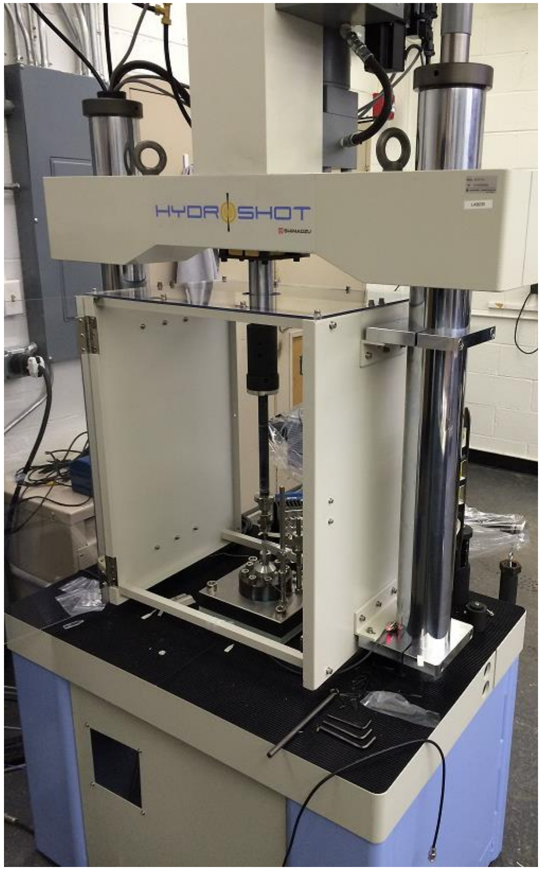
Material testing

- Moderate strain rates
  - Instron servo-hydraulic UTM
  - Contact extensometer (0.01-10 /s)
  - Dynamic load cell
  - -40C-150C
- Strain rate sensitivity is logarithmic
  - 0.01, 0.1, 1, 10, 10 /s



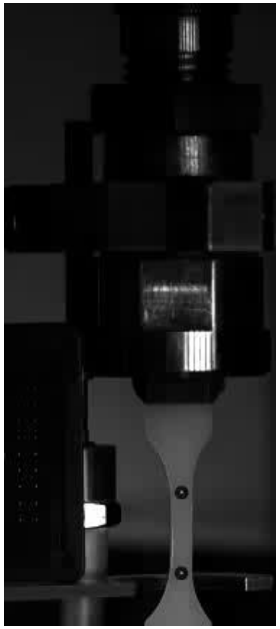
Material testing

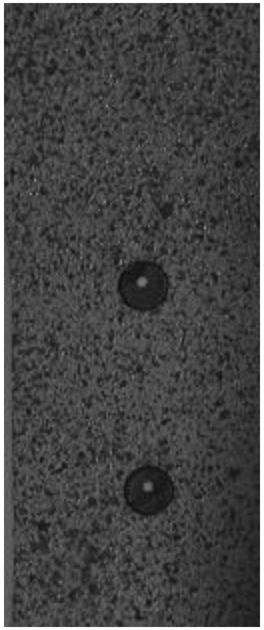
- High strain rates
    - Shimadzu HITS-T10
    - Up to 100- 2000 /s
    - Photron SA5 1M fps
    - Dynamic load cell
    - 1 μsec acquisition
    - Acceleration arm allows for speed attainment prior to engaging the specimen (no ramp up)
    - Only one in the US

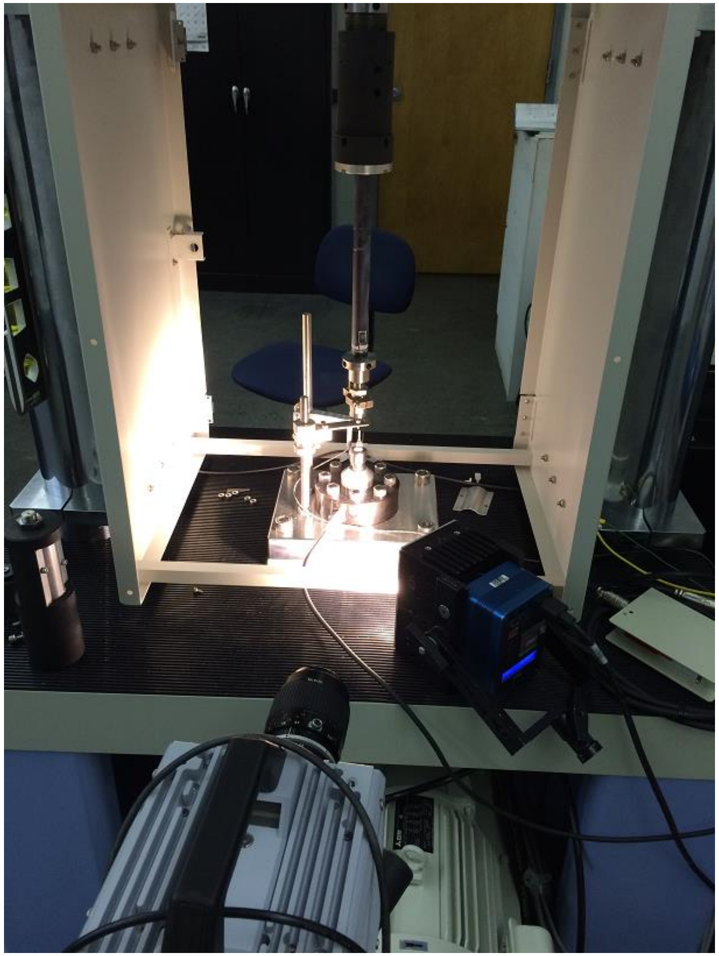


Strain measurements

- Low strain rates:
  - contact
- High strain rates >10/s
  - Photron SA5 video camera (up to 1M fps)
  - Correlated solution DIC measurements

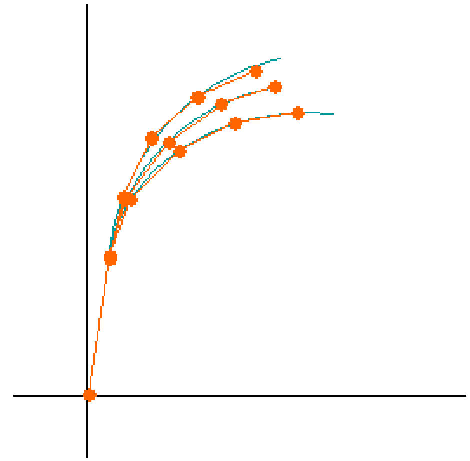


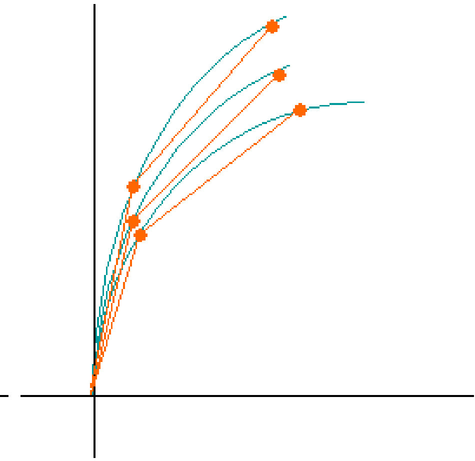




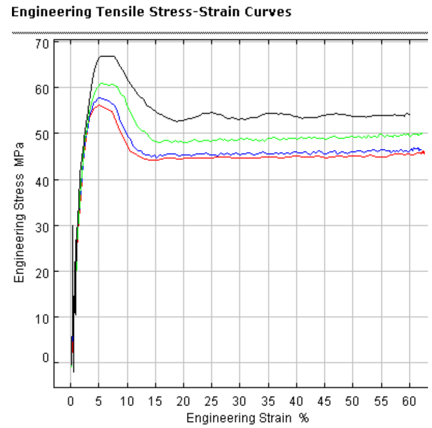
Plastics rate effects

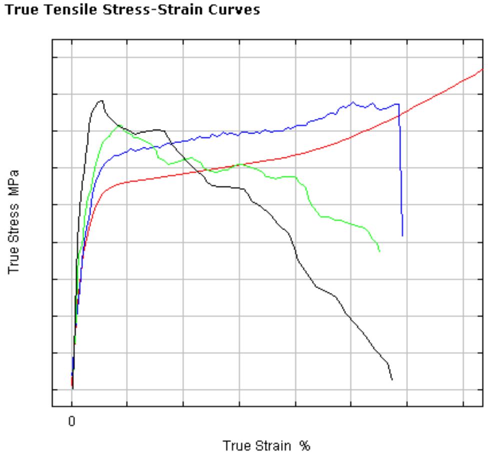
- Modulus may be rate dependent
  - Few models can account for this behavior
  - Default use the stiffest modulus





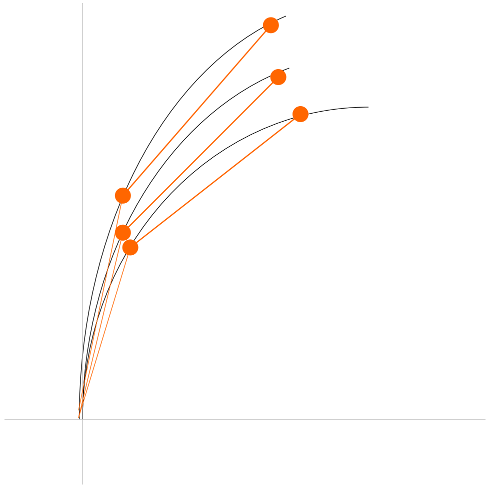
- Failure may be rate dependent
  - Only a few material models can capture rate dependent failure
  - Compromise to lowest strain





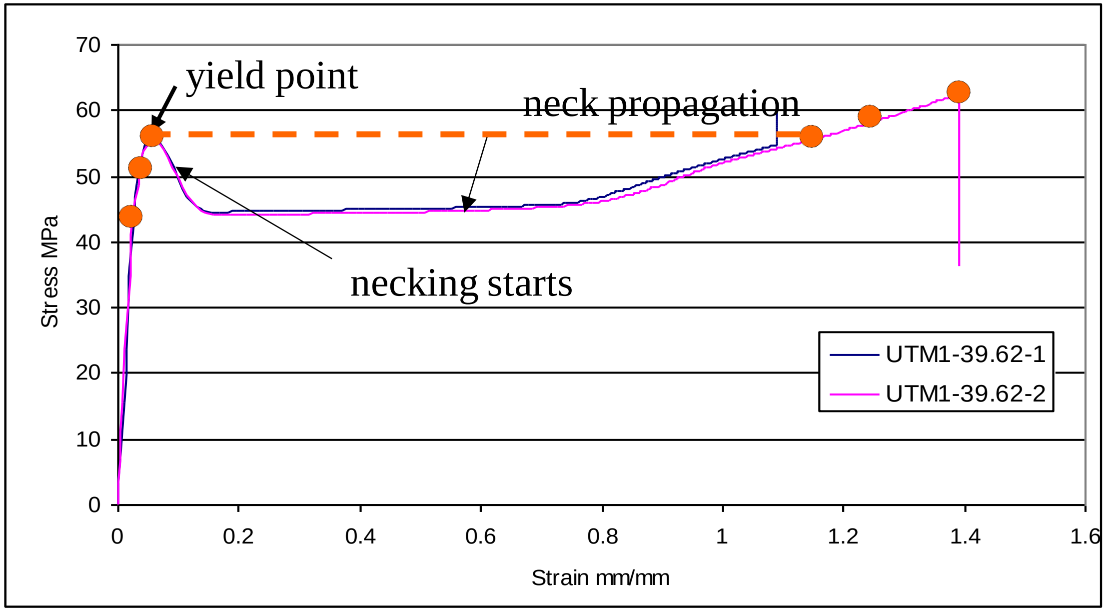
Plastics rate effects

- Fiber fillers
  - Higher modulus
  - Small strain to failure
  - Brittle failure
  - No post-yield behavior
  - Anisotropy
  - May require third party software
- Temperature
  - Shortened post-yield region
  - Change the rate dependency



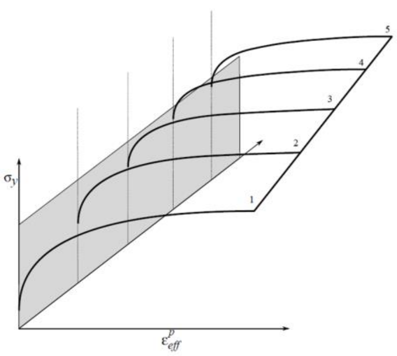
Breaking down the stress-strain curve

- Understand the stress-strain curve to better select a material model
  - Pre-yield
    - Modulus
    - Poisson's ratio
    - Proportional limit
  - Yield
    - Zero slope
    - Begin unravelling
  - Post-Yield
    - Material flow
    - Neck propagates
  - Break
    - Polymer chains break
  - Simplest material models can be made with little data
    - Modulus/Poisson's ratio
    - Yield
    - Slope or hardening parameters of post-yield
    - Break or fail



Rate dependent material models

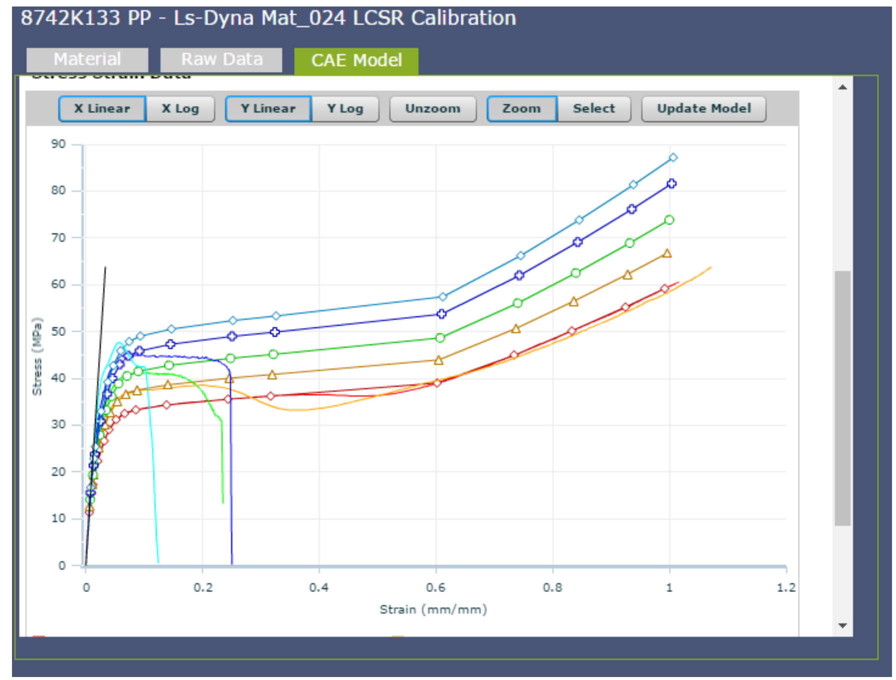
- Types of rate dependent models
  - Input stress strain at all strain rates
    - A family curves is provided that include either total or plastic true strain versus stress
    - Usually a single modulus and single Poisson's ratio
  - MAT024 LCSS (load curve stress-strain)
    - SS curve changes shape
    - Stress remains flat after end
    - More complex to make
    - More unstable
    - True stress vs. plastic strain



Rate dependent material models

- Scale up the quasi-static stress strain curve
  - Only a single stress strain curve is provided
  - Rate dependency ratio
  - Scale ratios based on quasi-static yield stress
- MAT024 LCSR (load curve strain rate)
  - Simple data preparation
  - Stable simulation
  - Fidelity to curves depends on QS
  - Table of yield stress with respect to QS yield stress versus strain rate
  - Commonly used formulation in many software (easy to translate)

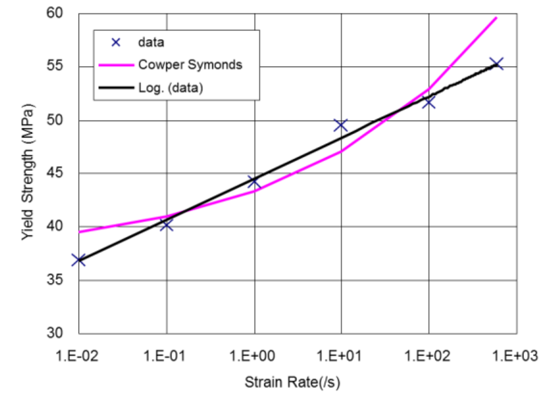
RATE	
0.0100	1.000
0.100	1.128
1.00	1.221
10	1.295
100	1.384

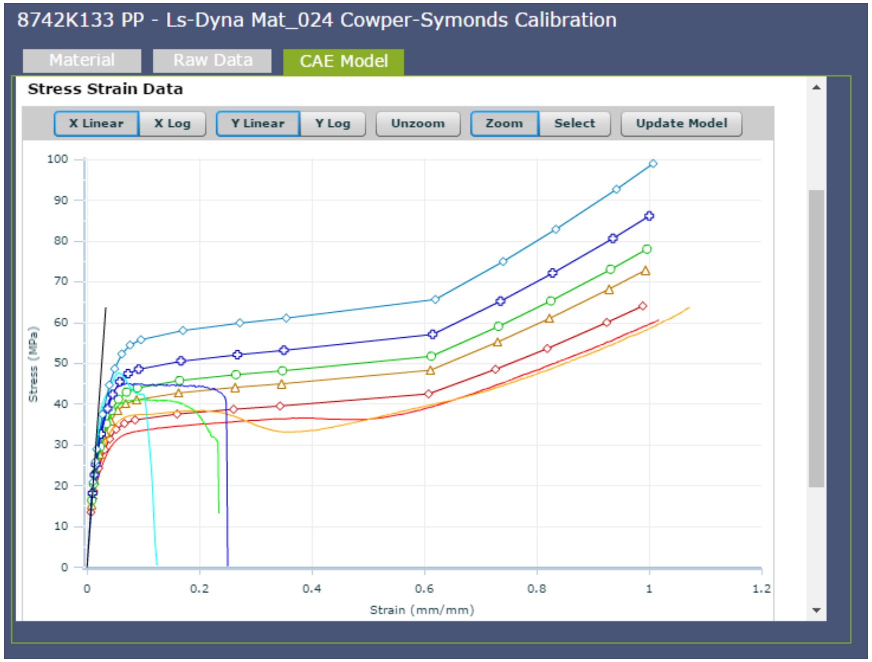


Rate dependent material models

- Scale up the quasi-static stress strain curve
  - Only a single stress strain curve is provided
  - Rate dependency ratio
  - Scale ratios based on quasi-static yield stress
- MAT024 C & P (Cowper-Symonds)
  - Equation used to scale SR
  - Stable simulation
  - Fidelity to curves depends on QS
  - C & P may not accurately depict actual strain rate sensitivity
  - Allows for simulations beyond tested strain rates
  - Commonly used formulation in many software (easy to translate)

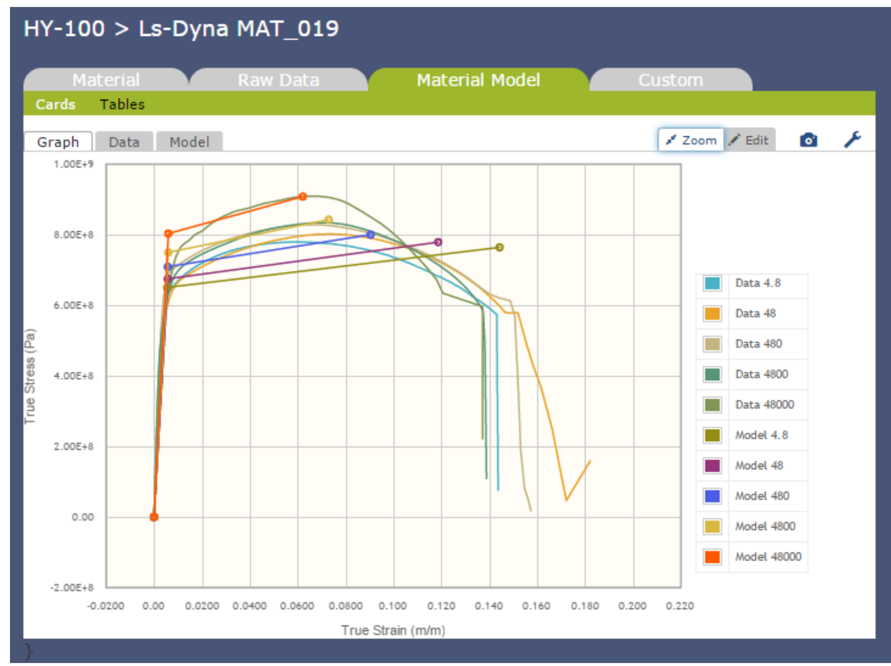
$$1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}$$





Rate dependent material models

- Simplified parameter model
  - Two domain slope formulation
  - Slope + hardening
- MAT019 (bilinear approach)
  - Useful for brittle materials (low plasticity)
  - Rate dependent modulus
  - Rate dependent failure
  - Not perfect match to curve shape



Considerations in model selection

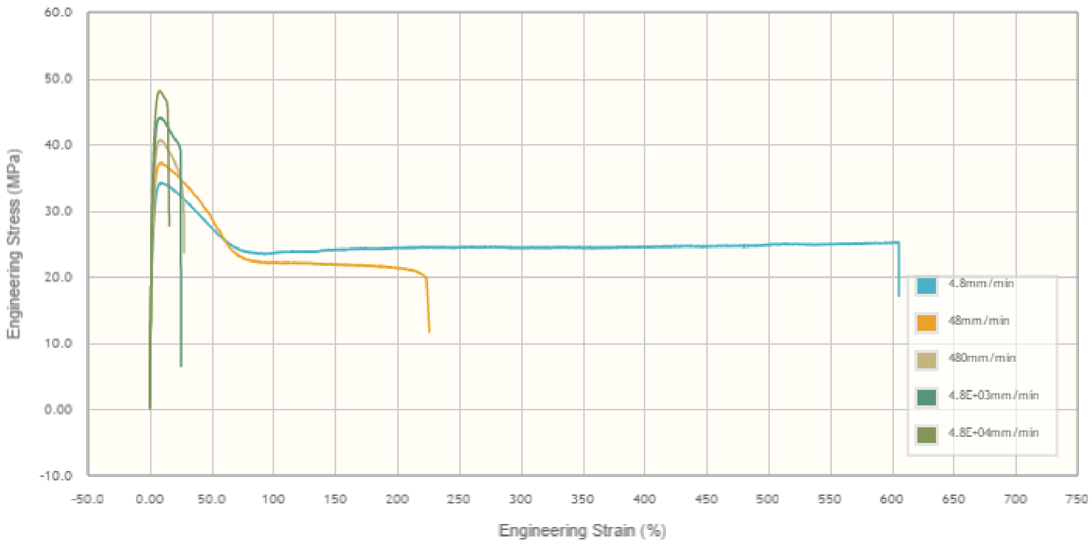
- Highly ductile materials
  - Elements may become highly distorted
  - Post-yield stress strain curves tend to go negative slope
  - High rate dependent failure (ductile/brittle transition)
  - Maybe non-Von Mises yield surface
  - PP, PE, PC, TPE, PA, Unfilled
  - MAT24, MAT89, MAT187, *RATE DEPENDENT, Johnson-Cook, etc.
- Brittle materials
  - Little rate dependent failure
  - More scattered data
  - No necking
  - Modulus tends to be rate dependent as well
  - MAT19, Johnson-Cook, bilinear models

Verification & validation

- Unit element test (easy)
  - Can be performed by analyst
  - Simple check on whether the model is sensible
- Closed loop validation (moderately difficult)
  - Check if FEA returns the original material data
- Open loop validation (difficult)
  - Comparison to alternate or multi-mode experiment

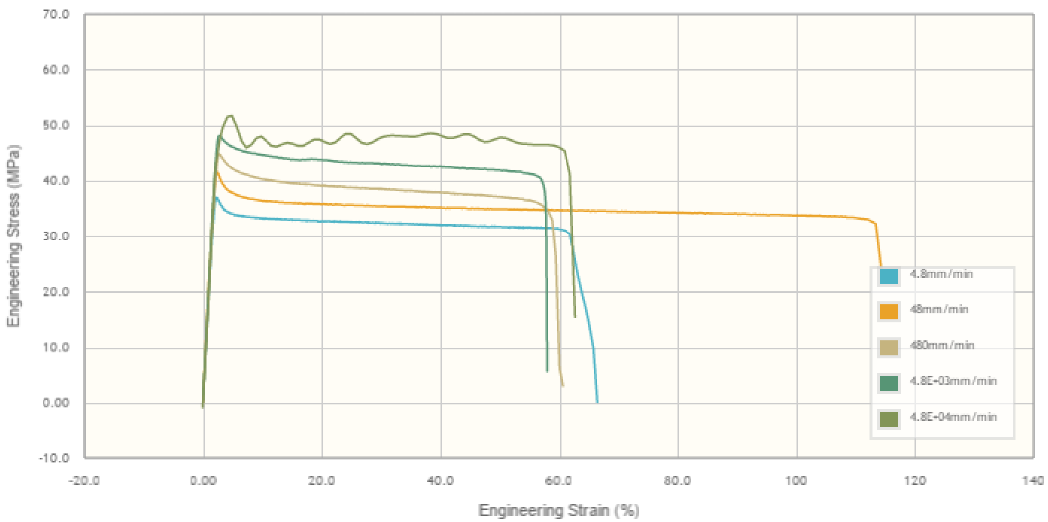
Material testing PP

- Polypropylene
- 5 strain rates tensile (0.01-100 /s)
- Modulus and Poisson's ratio at QS
- ISO type 3 tensile bar cut from sheet
- High ductile/brittle transition



Material testing ABS

- ABS
- 5 strain rates 0.01-100 /s
- Modulus and Poisson's ratio at QS
- ISO type 3 tensile bar cut from sheet
- Very little rate dependent strain to failure

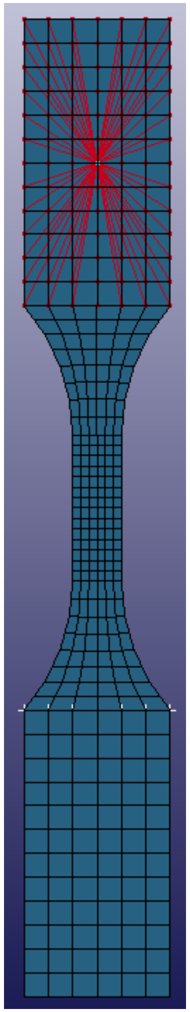


Material model

- MAT024: piecewise linear plasticity
  - Rate dependent elasto-plastic model
  - Three options for rate dependency (LCSS, CP, LCSR)
  - Singular value of failure strain; independent of strain rate
  - Visco-plasticity setting

Closed loop validation

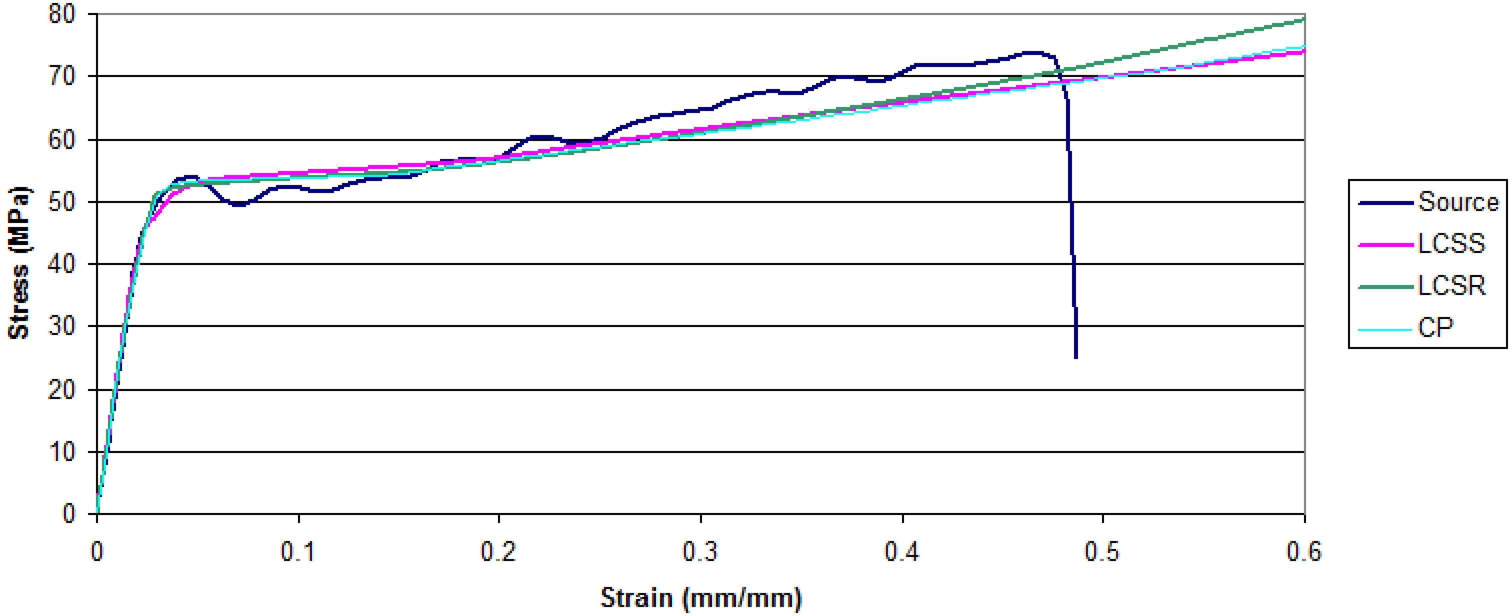
- Reproduce original stress-strain data
- Settings
  - B.C.s:
    - Fixed bottom grip area
  - L.C.s:
    - Top moves at constant velocity: 953mm/s
  - Element: shell (Belytschko-Tsay)
    - $0.36mm^2$
  - Hourglass setting:1



Viscoplastic formulation options

- VP setting affects what parts of the strain rate tensor is used in stress calculation
  - -1 Cowper-Symonds with deviatoric strain rate
  - 0 total strain rate tensor
  - 1 only parts relating to plastic strain

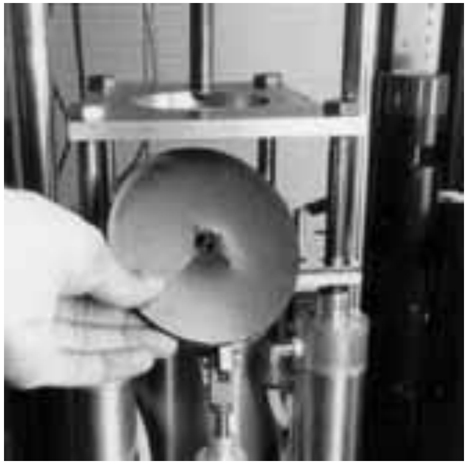
Compare rate dependency formulations (ABS)



- VP=1 (in agreement with Bala, Day)

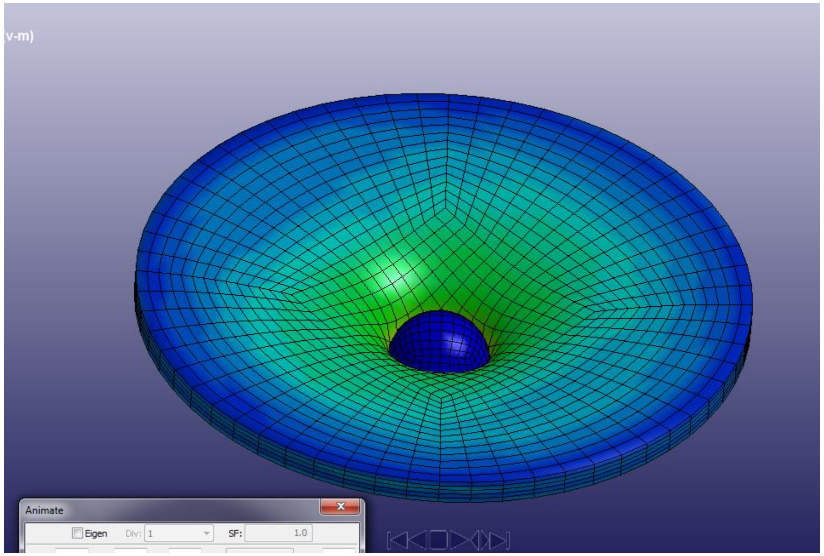
Open loop validation

- Dynamic CAETestBench™ model
- ASTM D3763 falling dart impact
- Multi-axial rate dependent loading (well-defined boundary conditions)
  - Dart
    - 12.7mm (½”) rounded tip
    - weight = 22.68 kg
    - unlubricated
  - Clamp diameter = 76 mm
  - Disk dimensions
    - Thickness = ~3 mm
  - ICs: impact velocity of 3.3m/s



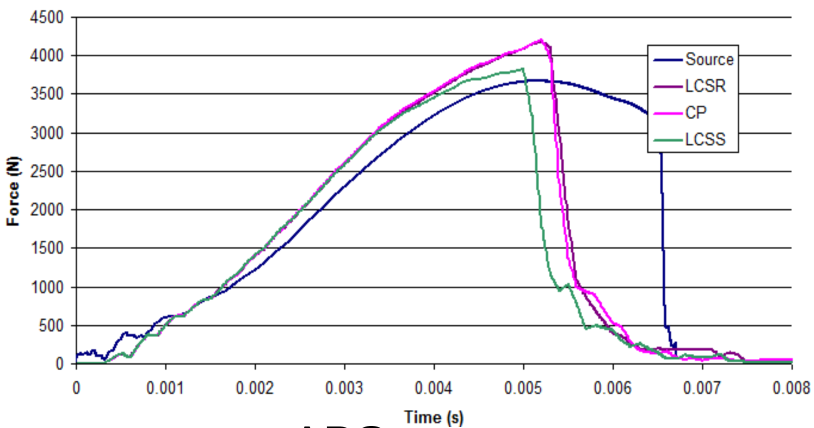
Simulation: BCs and ICs

- Set-up
  - Plate thickness: 3.175mm
  - Dart diameter:12.7 mm
  - Dart weight: 23 kg
  - BCs: fixed edge
  - Impact velocity: 3.35m/s
- Outcome
  - Force v. time. Displacement
  - Max force

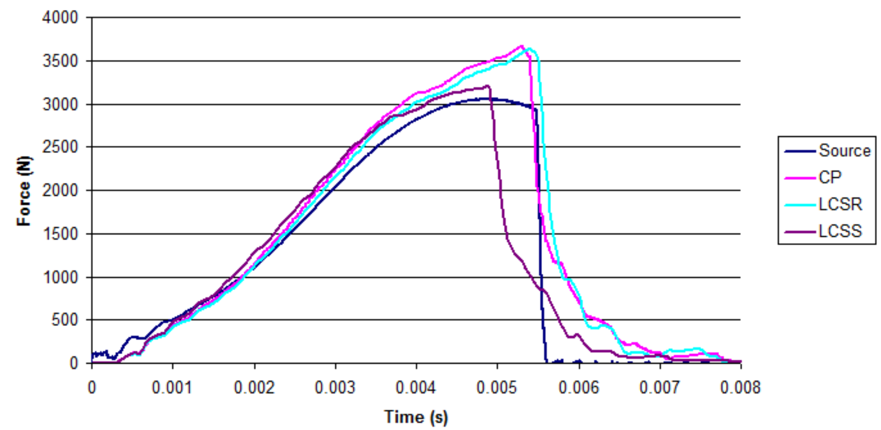


Falling dart validation results (first pass)

- LCSS performs best for each material
- ABS fails to reach correct fail time (deflection)
- PP matches quite well 4% variation
- Limitation in failure found for MAT24
  - Look at advanced material model to see if improvements can be made



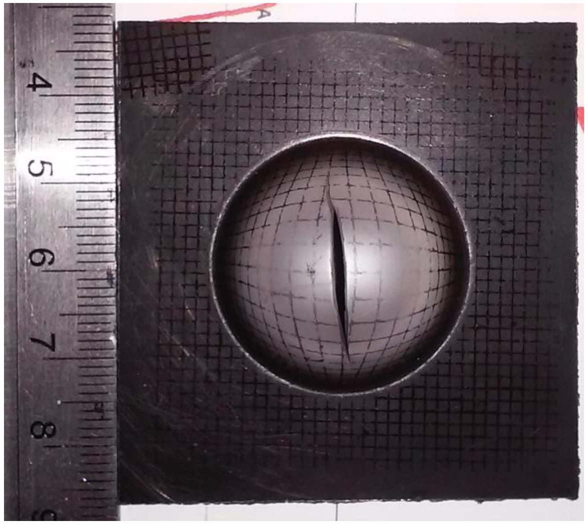
ABS



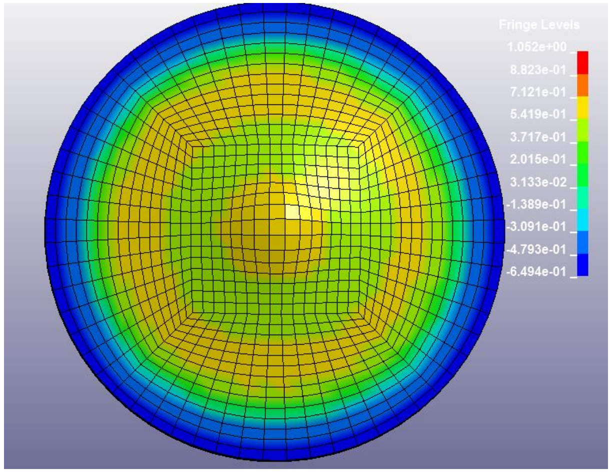
PP

Investigation of failure for ABS

- Investigate failure strains to see why they do not match
  - Tension fails at approximately 60% strain
  - Impact shows failure closer to 180%
  - Perform biaxial punch test (biaxial strain to fail =180%)
  - Simulation agrees that we see almost pure biaxial strain



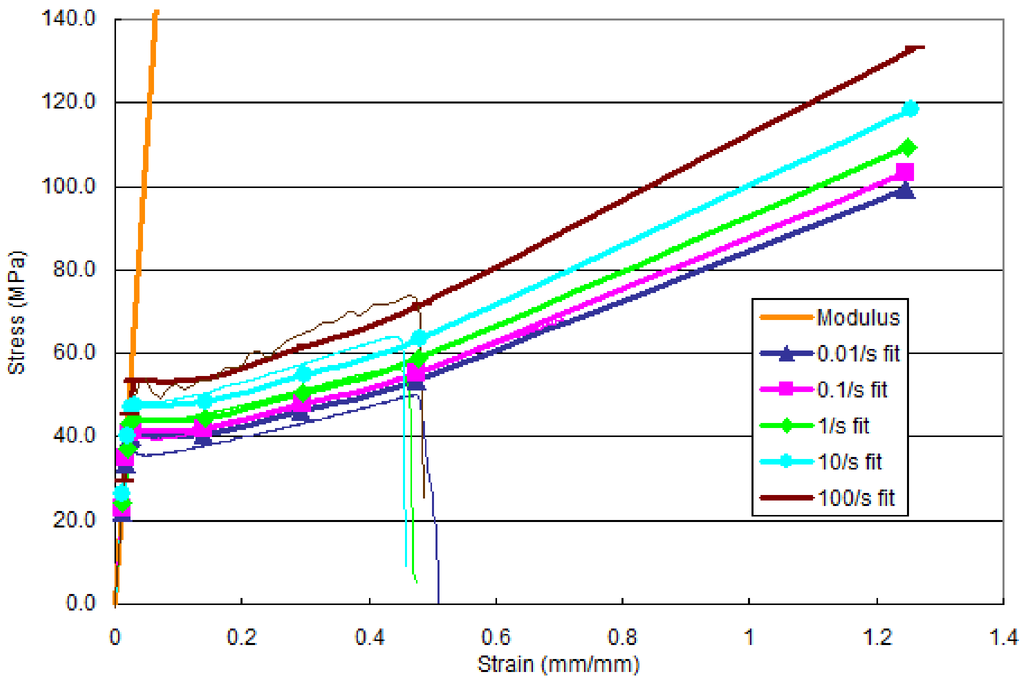
Biaxial Punch Test



Triaxiality Plot

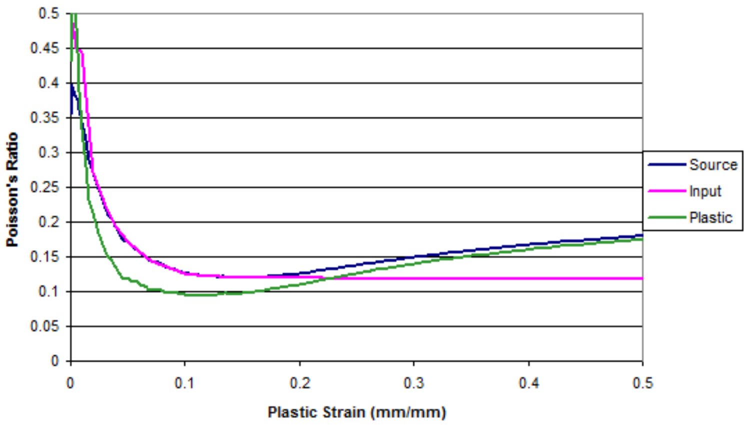
Failure strain extrapolation

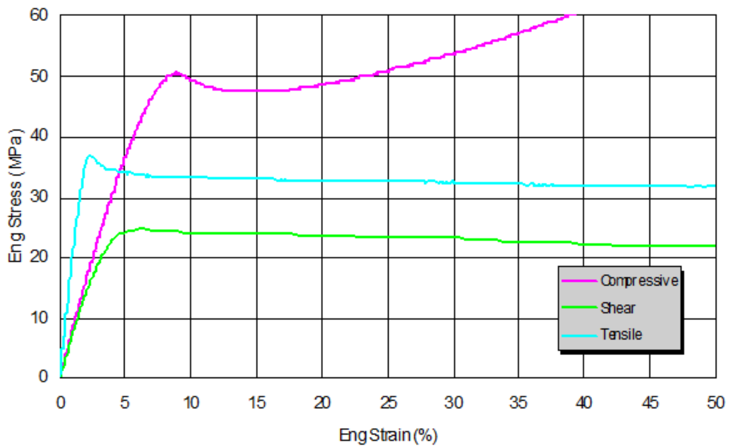
- Plasticity data extrapolated to 1.2
- Failure strain from uniaxial test is premature for multi-axial deformation



Supplemental material testing ABS

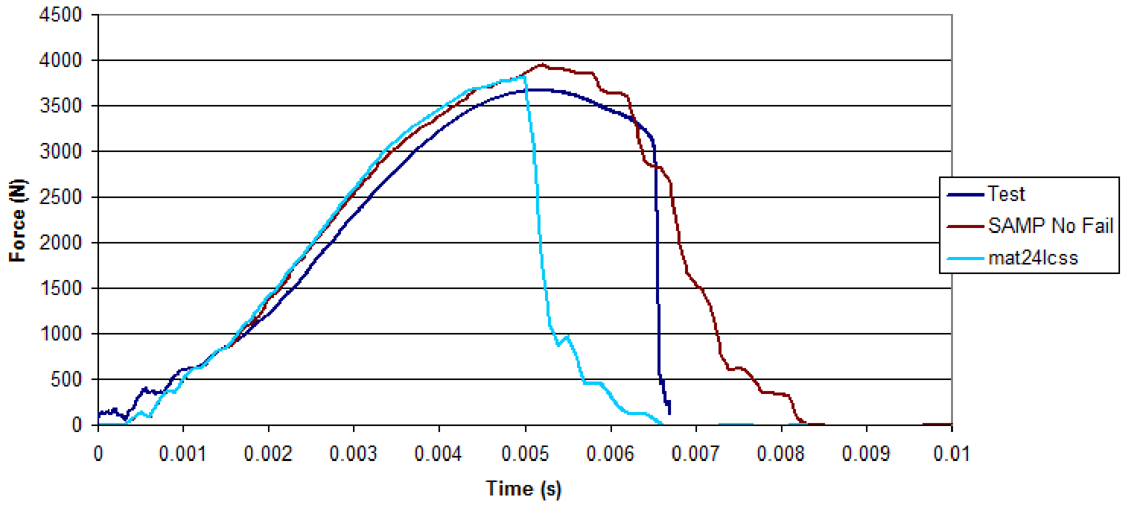
- Define non-Von Mises yield surface
  - Tension
  - Compression
  - Shear
  - Post-yield Poisson's ratio (flow rule)
    - Allows for computation of true stress in post-yield $\sigma_t = \sigma_e (1 + \varepsilon_e)^{2\nu p}$
    - Default MAT24 uses constant Vp=0.5





Improvement using advanced model

- MAT_187 for ABS using tension, compression, and shear stress-strain curves
- Did not see improvement using the plastic Poisson's ratio
- Much better agreement with failure using advanced model



Conclusions, part 1

- Rate dependent testing
  - Know strain rates of interest prior to testing
  - Collect data covering the entire span of strain rates
  - Use sophisticated techniques to acquire clean data
- Model selection
  - Never too early to think of the end results
  - Be aware there are other models out there
  - Start small
- Validation
  - Validations of the material model must be performed prior to scaling up
  - Helps point out limitation of material model
  - Helps make decision about possible improvements

Conclusions, part 2

- Falling dart impact test is a good benchmark for high strain-rate material models with ductile plastics
  - International standard for plastics
  - Multi-axial complexity
  - Easily replicated boundary conditions
- Allows you to check the validity of simulation settings
  - Element formulation and hourglass settings effect simulation accuracy (doubles error in some cases)
    - visco-plasticity option = 1 best for ductile plastics