Modeling of Strain Rate Effects in Automotive Impact

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Outline

- Strain rate effects in steels
  - Rationale for modeling
  - Consequences of modeling approaches on simulations
- Strain rates in symmetric crush
  - Modeling effects on strain rate history
- Strain rates in un-symmetric crush
  - Modeling effects on strain rate history
- Recommendations for modeling

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Strain Rate Effects and FEM

- For coarse FEM mesh discretization where mesh cannot conform to physical deformation, strain rate sensitivity can be 'detrimental '
  - Models are already too stiff
  - Strain rate is coupled with heuristic modeling rules based on element size
- For geometrically detailed FEM mesh discretization, strain rate is essential
  - Models soften with increase in mesh density
  - Strain rate effect counters softening
- Calculated deformation and forces are also influenced by other modeling components
  - Element formulation
  - Strain rate model details

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Modeling of Strain Rate Sensitivity

- Experiments
  - Range of rates to test
  - Equipment
  - Interpretation of experimental data
- Modeling
  - Constitutive models to fit experimental data
  - Range of rates during crush simulation
  - Effects of modeling approaches on rate history and range

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Common Strain Rate Models

- Multiplicative forms

$$\sigma = (A + B\varepsilon^{n})(1 + C\ln\dot{\varepsilon})(1 - T^{*m})$$

  - Separate terms for strain, strain rate and temperature
  - Stress-strain curves fan out

- Additive forms

$$\sigma = C_0 + C_1\exp(-C_3T + C_4\ln\dot{\varepsilon}) + C_5\varepsilon^{n}$$

  - Separate terms for strain, strain rate and temperature
  - Stress-strain curves are parallel

- Mixed and tabulated forms
  - Coupled terms for strain, strain rate and temperature
  - Provide better fit to experimental data

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Strain Rates in Simulated Circular Tube Crush

- Axi-symmetric crush
  - Tube material stretches and bends
  - Shell element formulation is not critical
  - Process can be modeled by modeling tube segment with symmetric hoop boundary conditions
- Un-symmetric crush
  - Material stretches, bends and warps
  - Shell element formulation is critical
  - Entire tube has to be modeled

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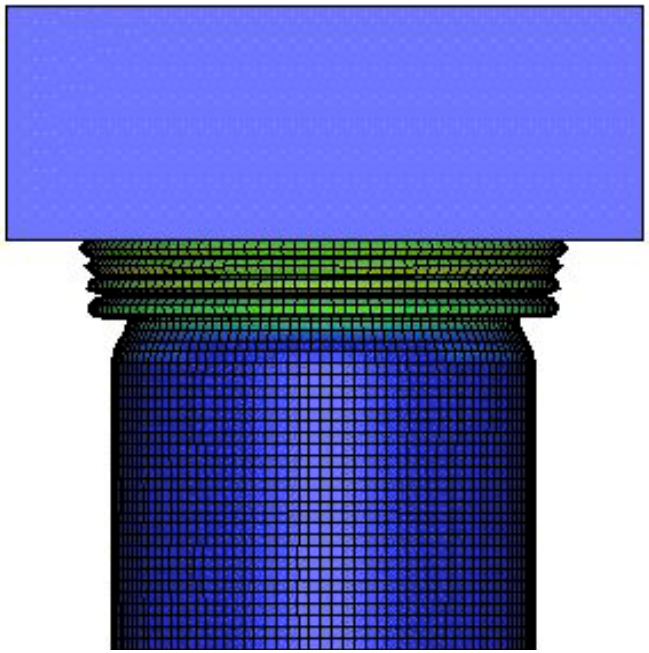
Axi-symmetric Tube Crush

- Configuration adopted from literature
  - Abramowicz, W. and Jones, N., Dynamic Axial Crushing of Circular Tubes, Int. J. of Impact Eng., vol. 2, no. 3, p. 263-281, 1984.
- DQSK steel tubes
- Results
  - Effect of strain rate on tube deformation
  - Effect of element discretization on strain rate history
  - Effect of strain rate model on strain rate history



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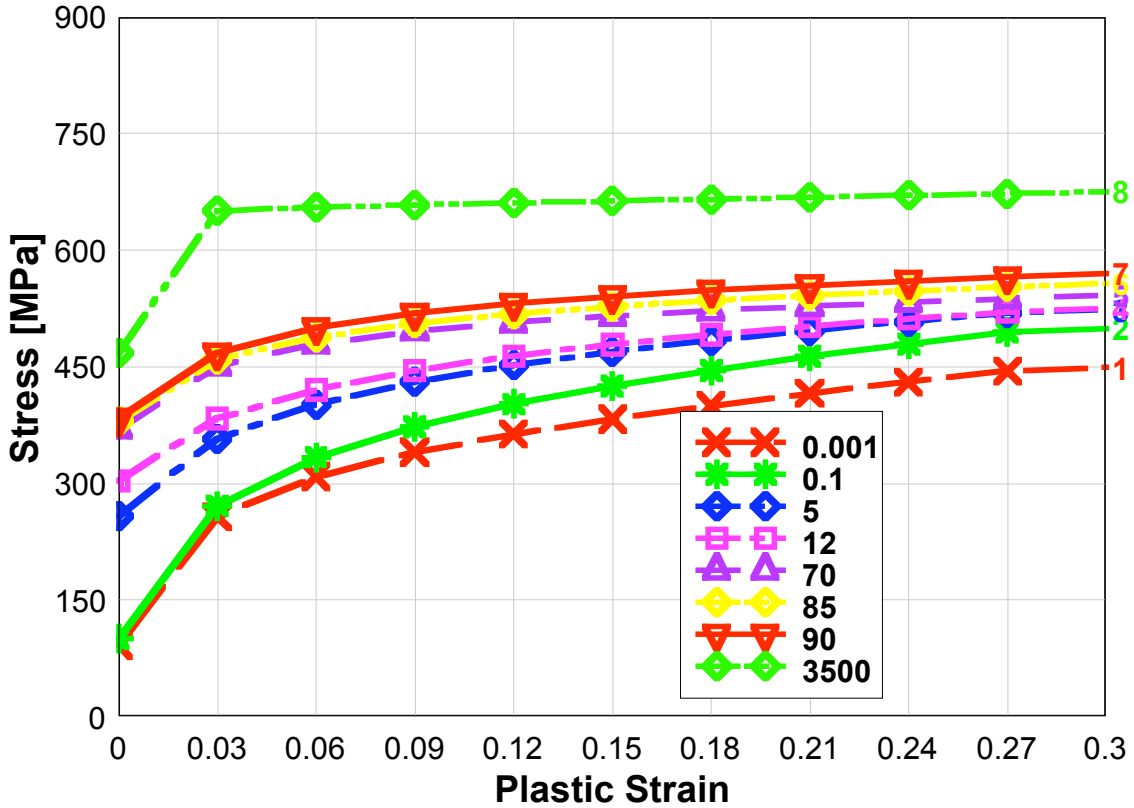
DQSK Model Data



- Data from servo-hydraulic and SHPB machines
- Material implemented as piecewise linear plasticity model in LS-DYNA3D

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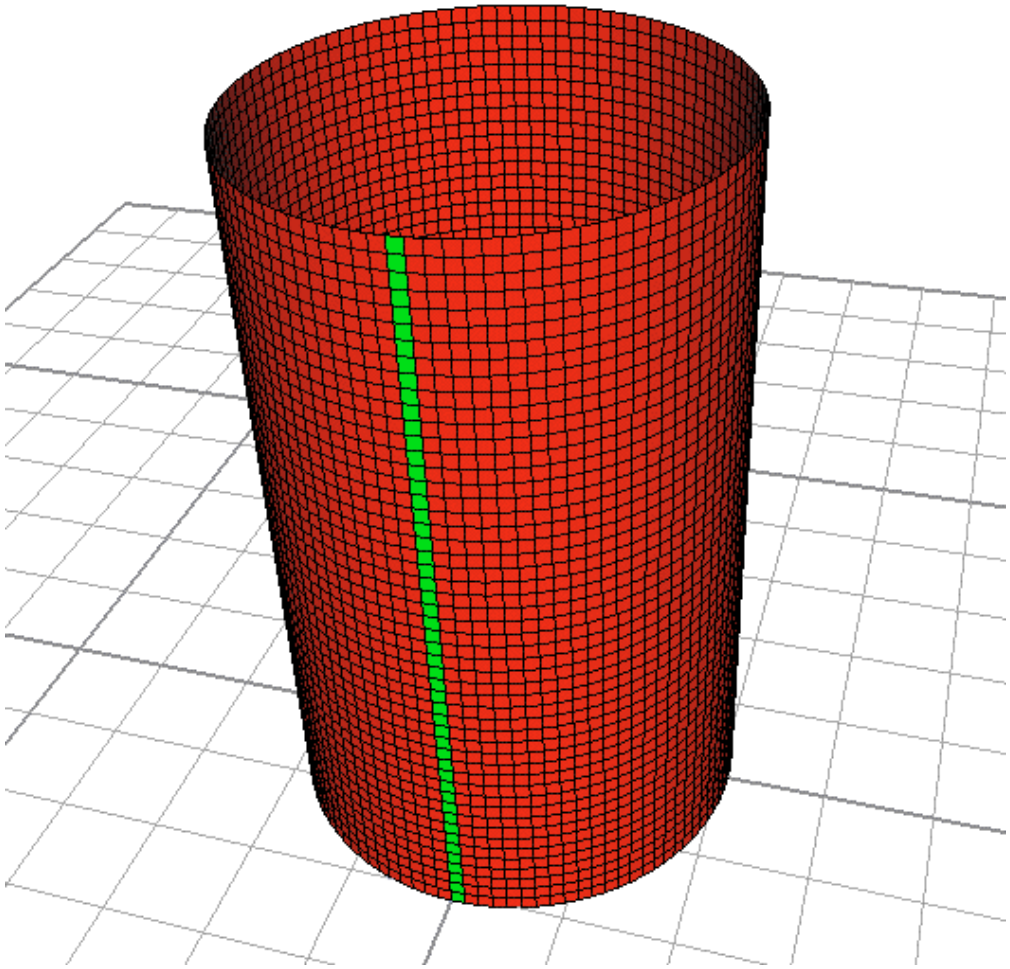
Axi-symmetric Tube Crush Model



- Green patch denotes modeled tube segment
- Boundary conditions in the hoop direction are symmetric
- For subsequent display of strain and strain rate histories, data is plotted orthogonal to the undeformed tube length

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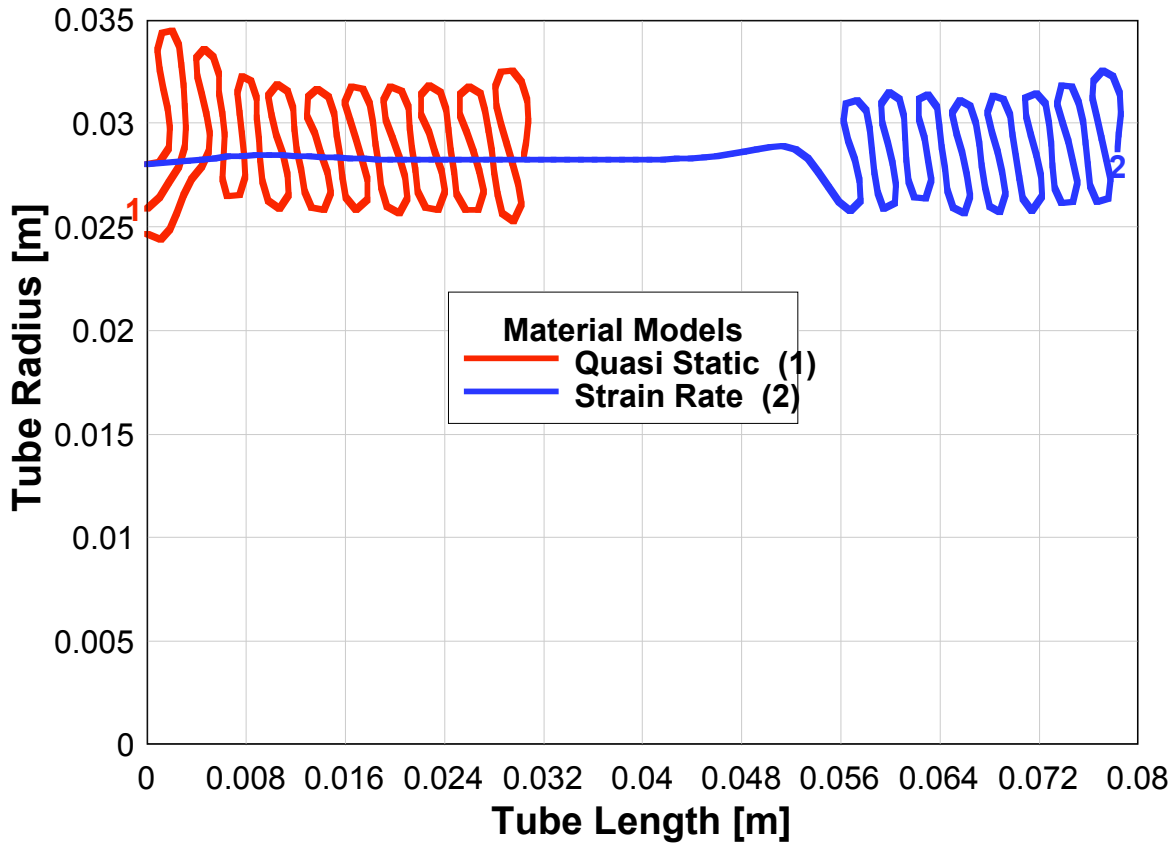
Strain Rate Sensitivity and Crush Length



- Strain rate sensitivity has strong effect on overall crush length

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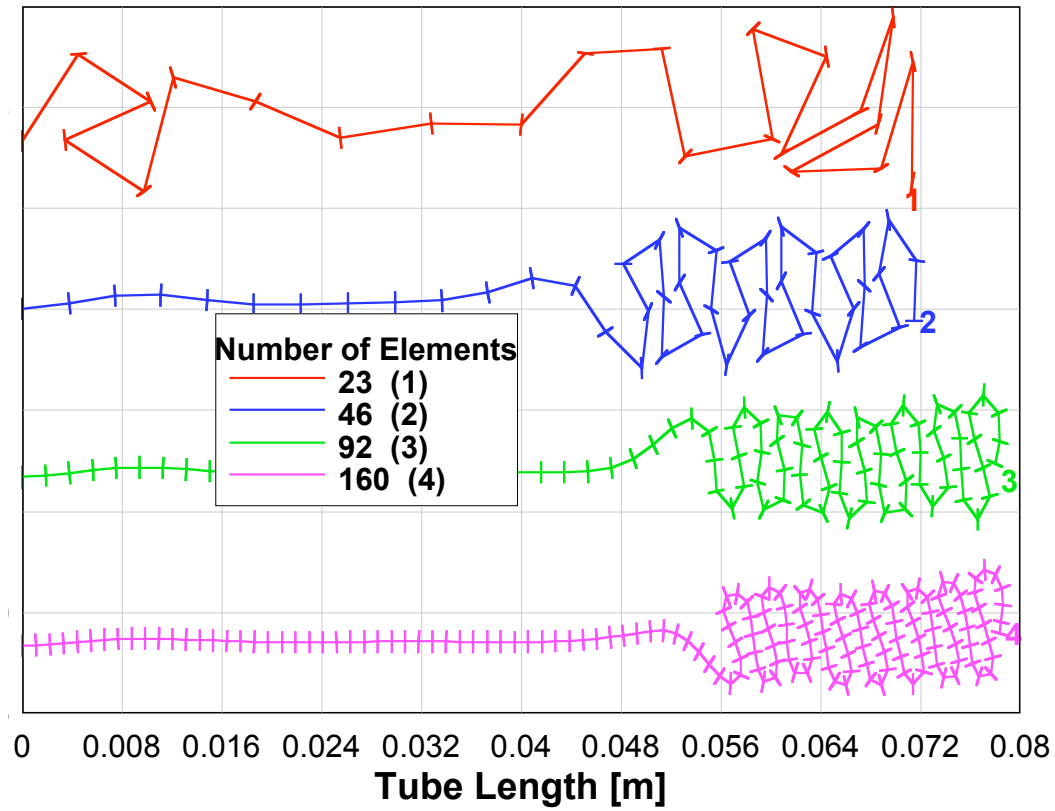
Effect of Element Discretization on Deformation



- Strain fields are interpolated from director orientations
- Continuity of shell directors indicates quality of the model

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Strain Rate History

- Constitutive model and strain rates are calculated at every computational time increment, $\mathbf{d}\boldsymbol{t}_{\mathbf{calc}}$
  - dt_{calc} is proportional to element size ~ *micro*second
- Results are saved approximately every *milli*second or more, $\mathbf{d}\boldsymbol{t}_{\mathbf{save}}$
- Strain rates in postprocessing software are calculated based on strains saved at intervals dt_{save}
- Reported strains are therefore averaged, and for buckling problems, significantly underestimated
- New program was developed to extract and analyze strain rates at dt_{calc} without saving states every dt_{calc}

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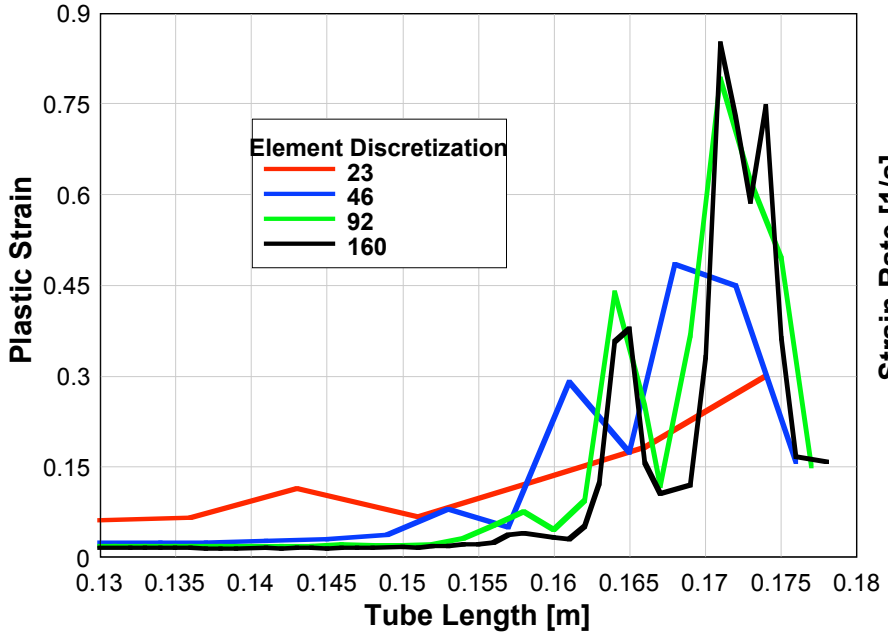
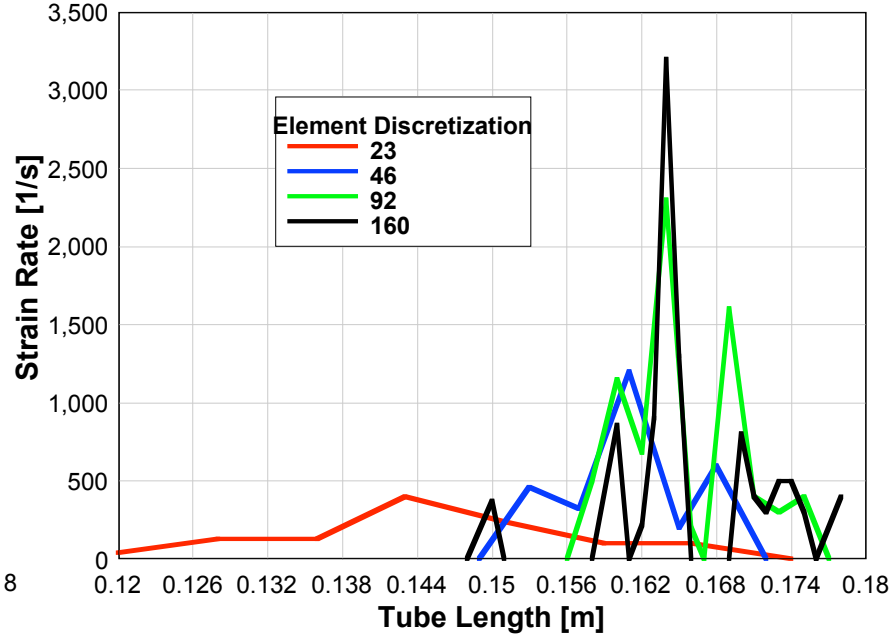
Distribution of Plastic Strains and Strain Rates





- Graphs show strain and rate distributions along the undeformed tube length at the time of formation of the second fold
- Strain rate distribution narrows with increased discretization

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Viscoplastic Option for Strain Rate Effects

- VP=0, model is based on TOTAL strain rate
- VP=1, model is based on PLASTIC strain rate
- VP is irrelevant for strain rate insensitive model

- Piecewise linear plasticity model in LS-DYNA is very sensitive on the VP switch
  - Strain rate + VP=0: Wild spatial and temporal oscillations of strain rates
  - Strain rate + VP=1: Smooth, more realistic

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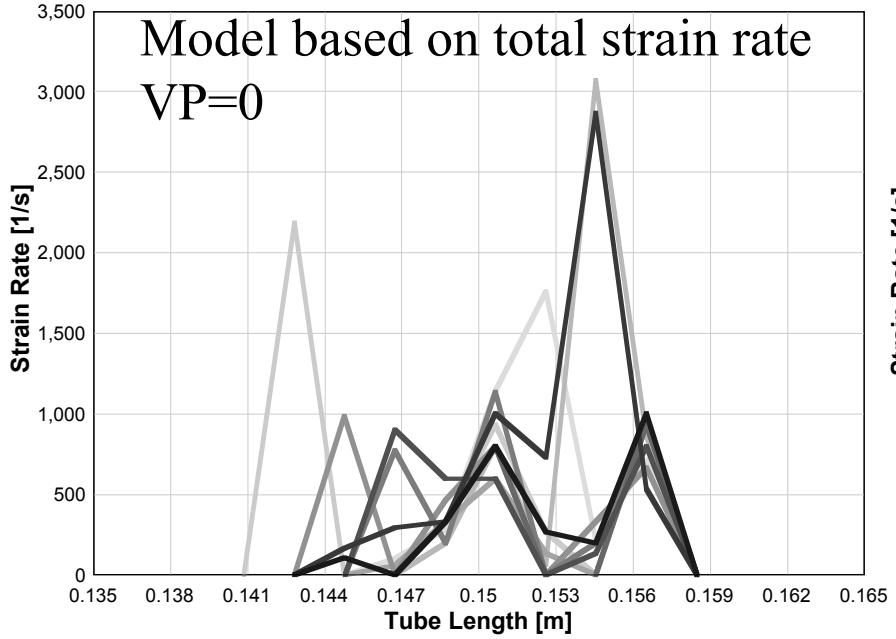
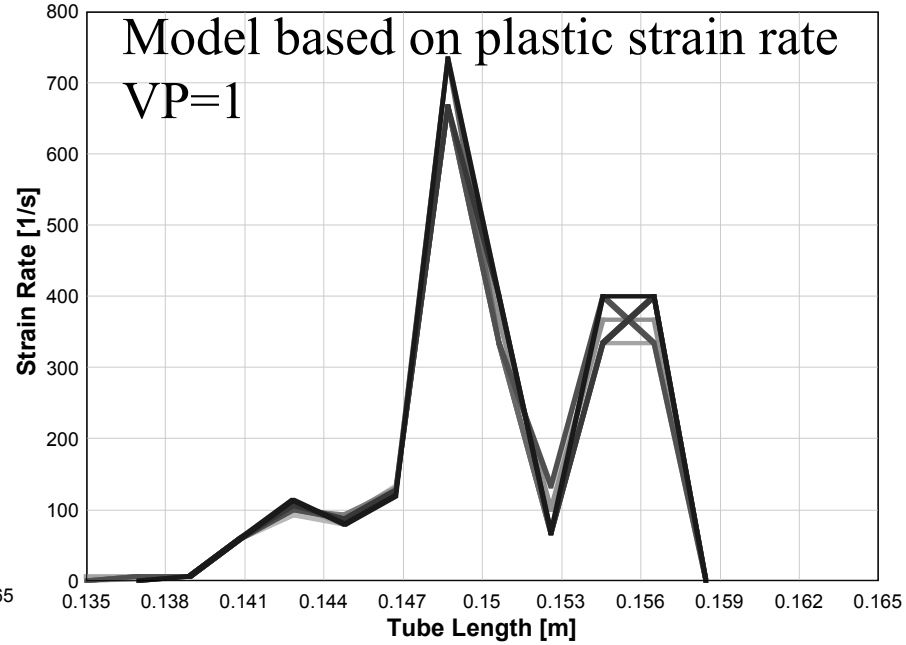
History of Strain Rates and VP Option





- Curves of strain rate distributions that are 5 computational increments apart (Shade of grey denote time sequence)
- Strain rate history for VP=1 is more realistically feasible

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Plastic Strain Rate History Animations

- Coarse mesh
- Fine mesh
- Model based on total strain rate
- Model based on plastic strain rate

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Review of Axi-symmetric Crush

- **The Effect of Mesh Resolution:**
  - Rates increase with mesh density
  - The difference is both in the increased strain peak magnitudes and in the reduced rate zone width
  - ***Implication is that the mesh resolution and the model are not independent***, i.e. the fold will form faster in finer mesh
  - Effect is more important for lower hardening material

- **The Effect of Element Formulation:**
  - No marked difference in element formulations, elements bend and stretch perpendicular to element sides
  - All common element formulations are good enough

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Un-symmetric Crush

- Prevailing deformation mode in automotive structures
- Finite elements warp, bend and stretch at angles to element sides
  - Strain fields are complex
  - Elements that can handle warping are computationally expensive and less robust than historically used element types
- What are the actually calculated strain rates in <u>un-symmetric</u> crush and how do they vary with modeling options?

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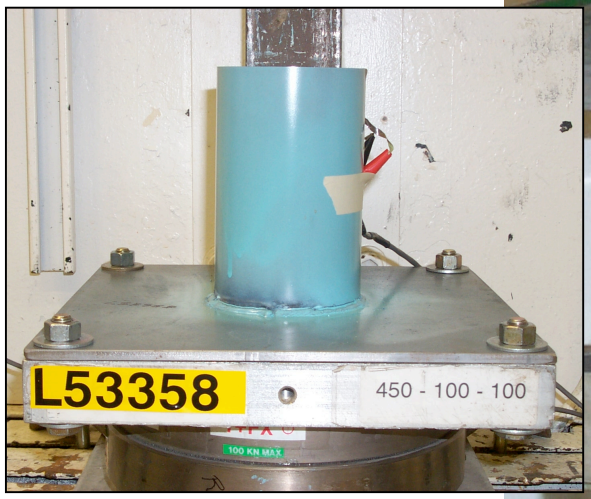
Drop Tower Test for HSLA350



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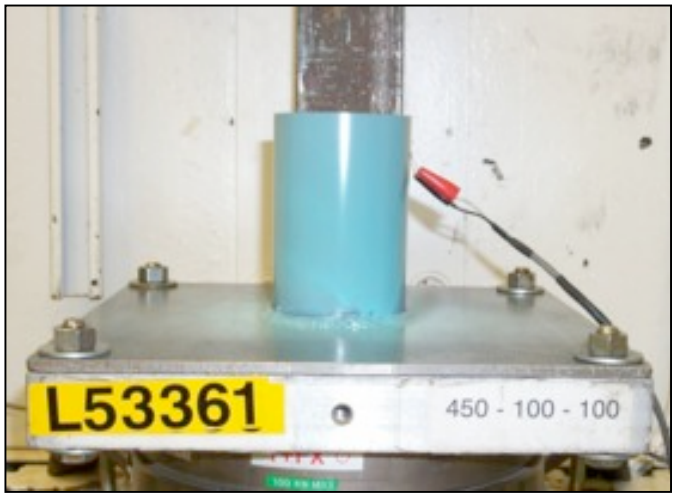
Drop Tower Test for DP600



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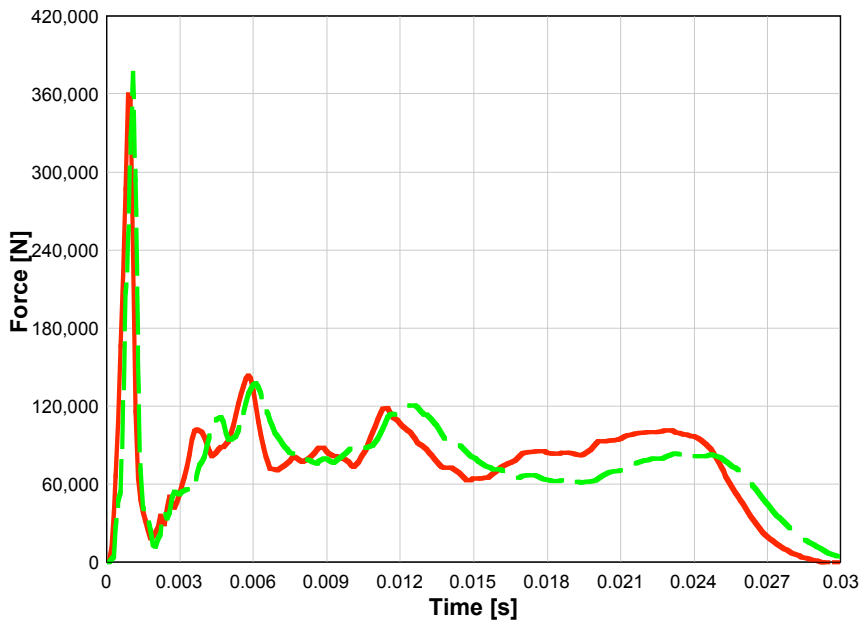
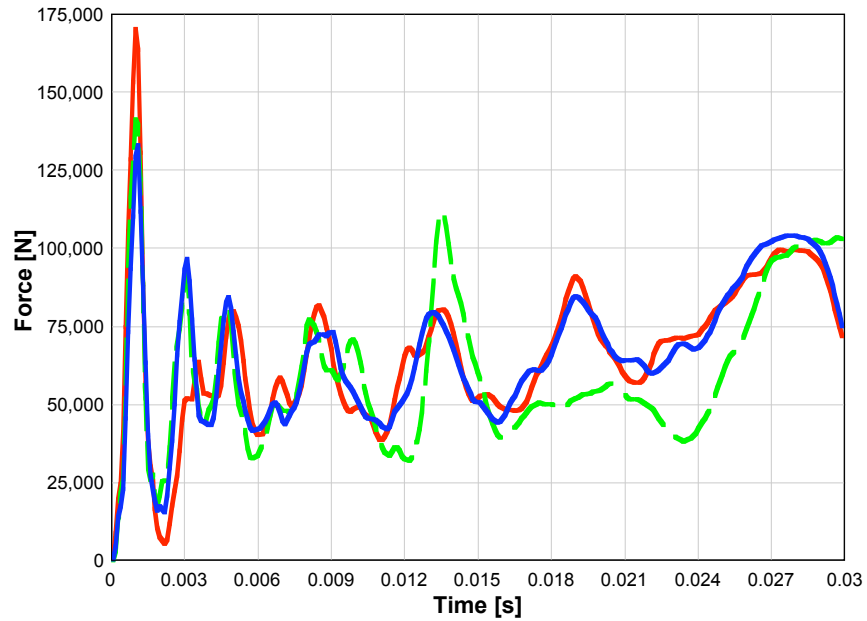
Impact Force History - Experiment

HSLA350



DP600



- HSLA350 has more pronounced first peak
- Predicted crush lengths were in very good agreement with experiments

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How to Analyze Strain Rate History?

- No symmetry to exploit
- Must use large number of elements to capture spatial variations of strain rates
  - Quarter of the HSLA tube R=50mm, L=160mm
    - 1378 elements for element Length =1.96 * Thickness
    - 4900 elements for element Length =1.00* Thickness
- Data must be saved every computational time step
  - Computational time step depends on element size
    - ~1.5E-07 s for element Length =2 * Thickness
    - ~1.0E-07 s for element Length=Thickness
- 100s of GB of data if stored directly using program options
  - Prohibitive in disk space and computer time

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Solution

- Developed programs that analyze data from LS-DYNA3D on the fly, compress and store data for post processing

- Programs can also be used for analysis of trouble spots in models to obtain detailed history of plastic strains and rates

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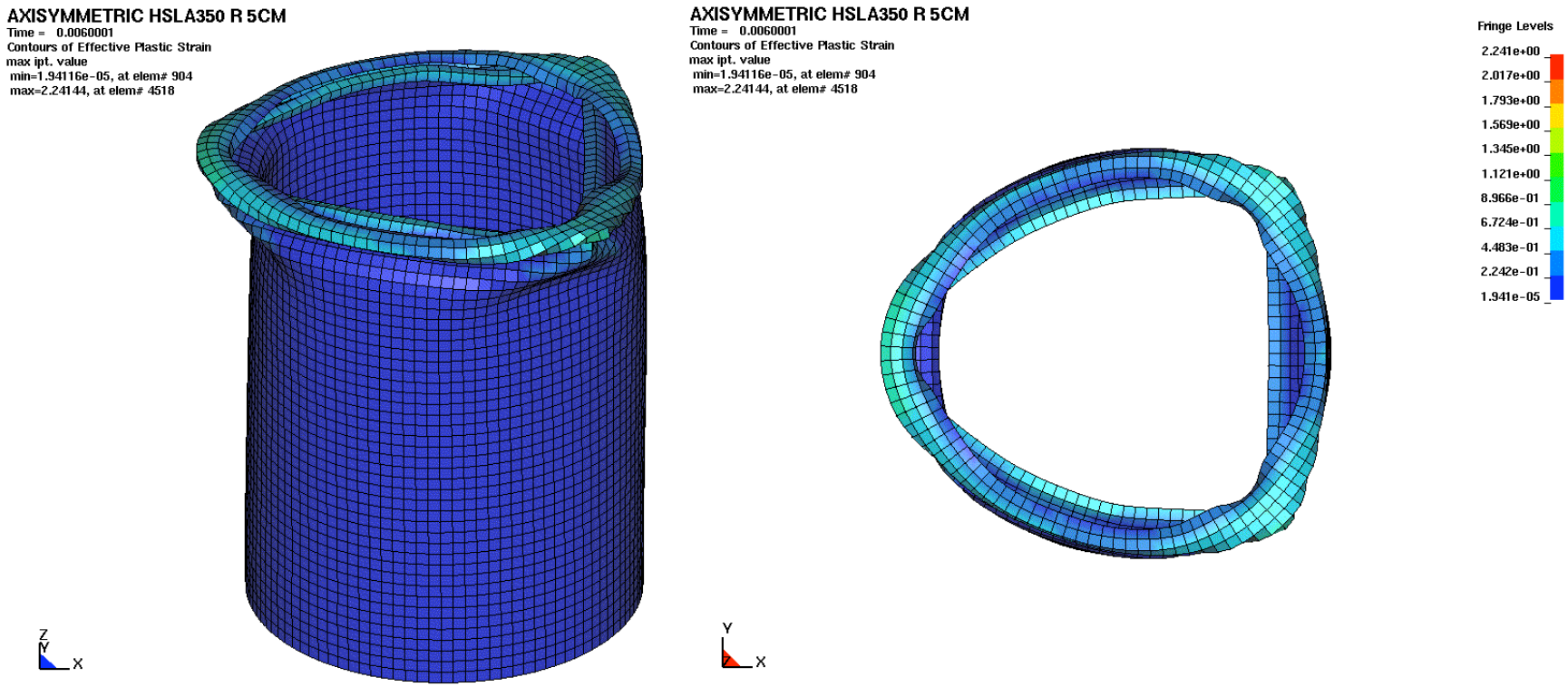
Tube Crush



- No symmetry to reduce number of elements for analysis
- Must use patch of elements large enough to cover interesting areas

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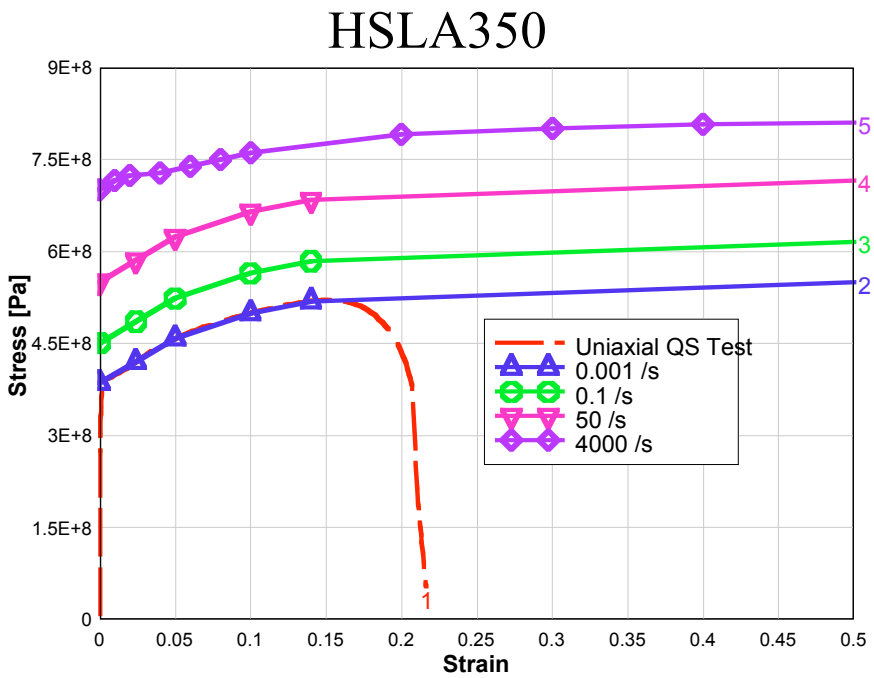
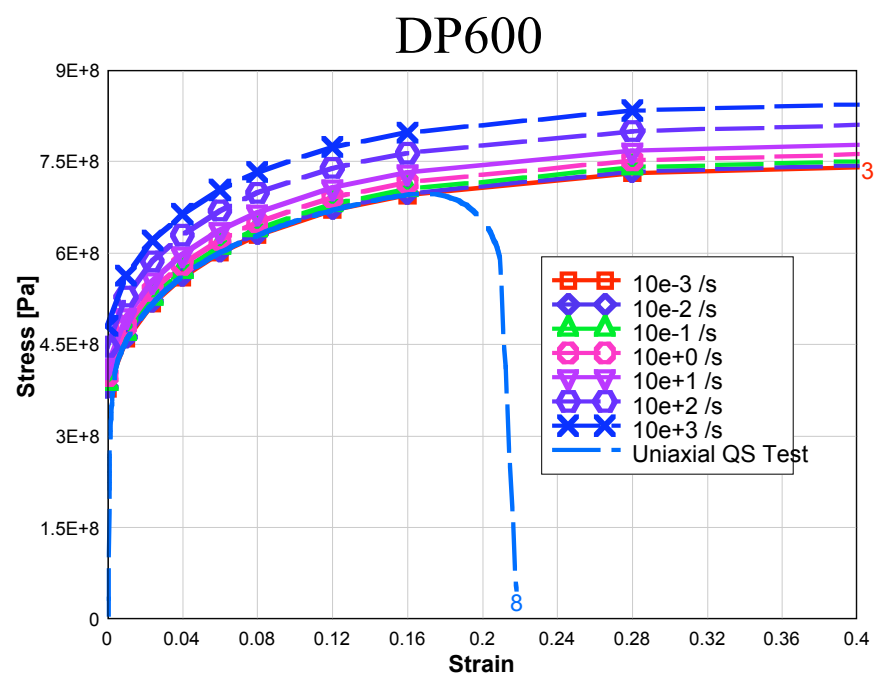
HSS Material Models





- Material data from servo-hydraulic and SHPB tests
- HSLA350 experimental data shows pronounced YPE but it has been disregarded in the material model

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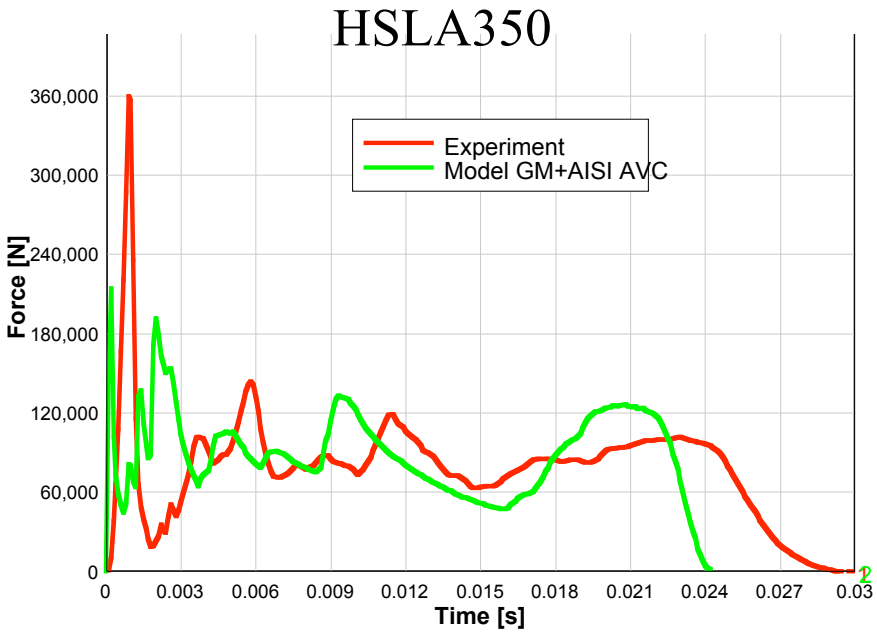
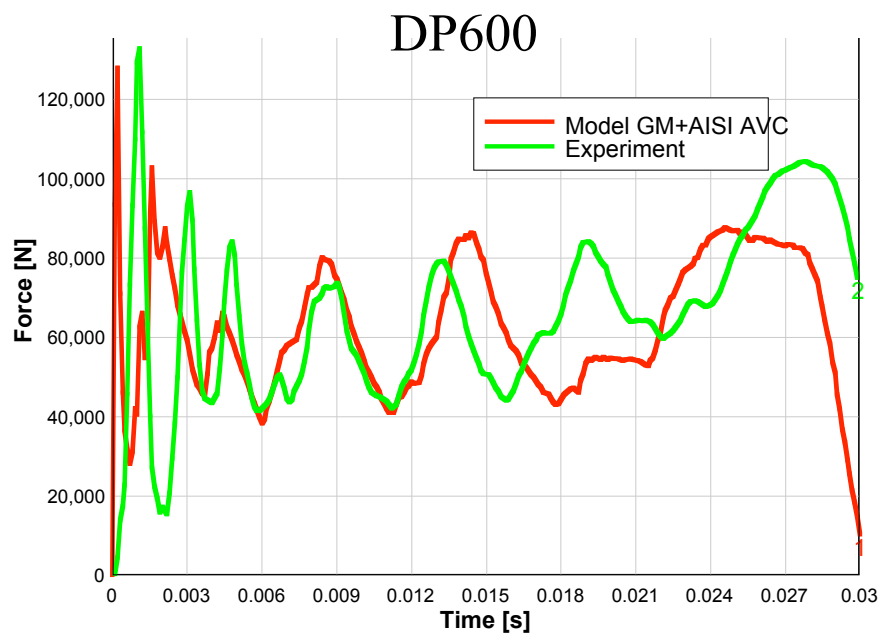
Impact Foce, Experiment vs. Model





- HSLA350 model misses the first peak
  - Adding YPE matches the peak force
- Crush lengths are in excellent agreements

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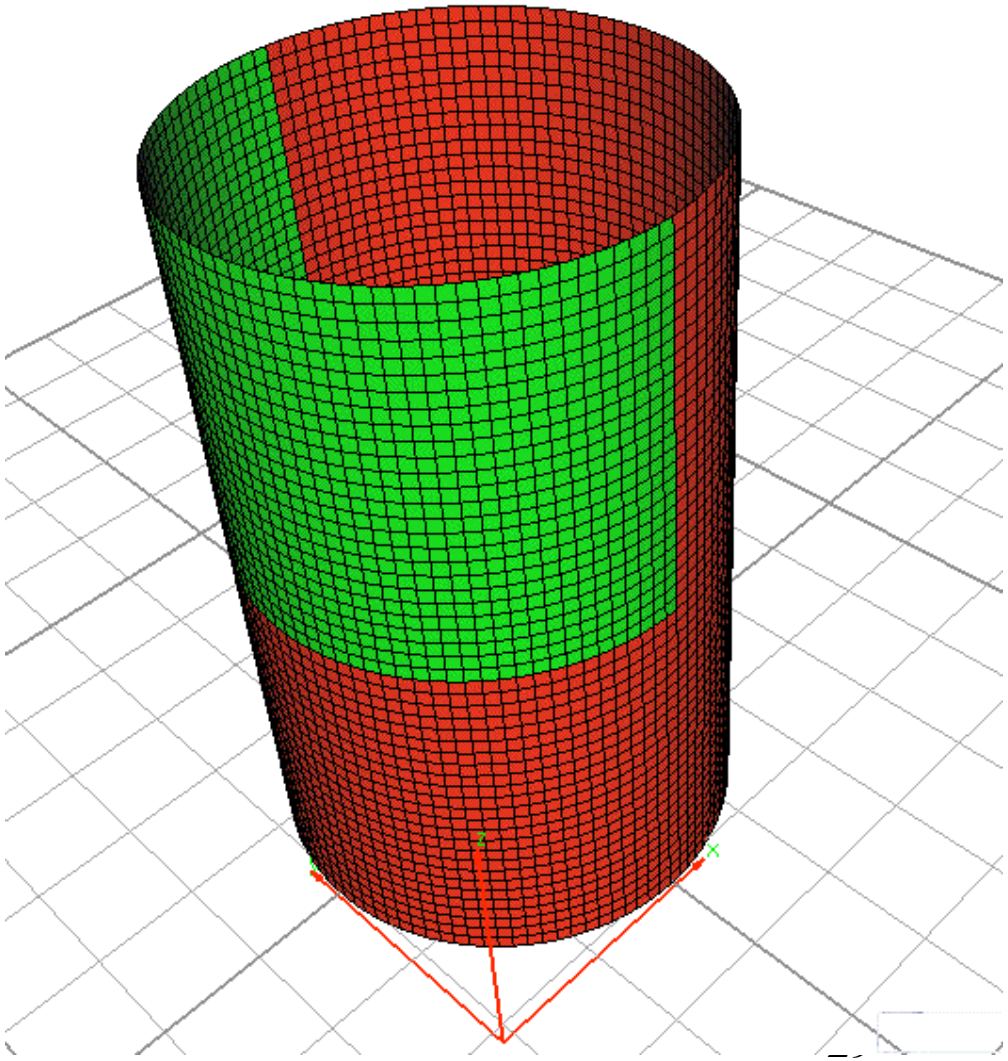
Elements Selected for Analysis



- Green patch denotes selected elements
- The mesh in the picture is for element L~2T
- Same size area is selected for finer mesh L~T
- For post processing patch is developed into plane and the results are mapped on it

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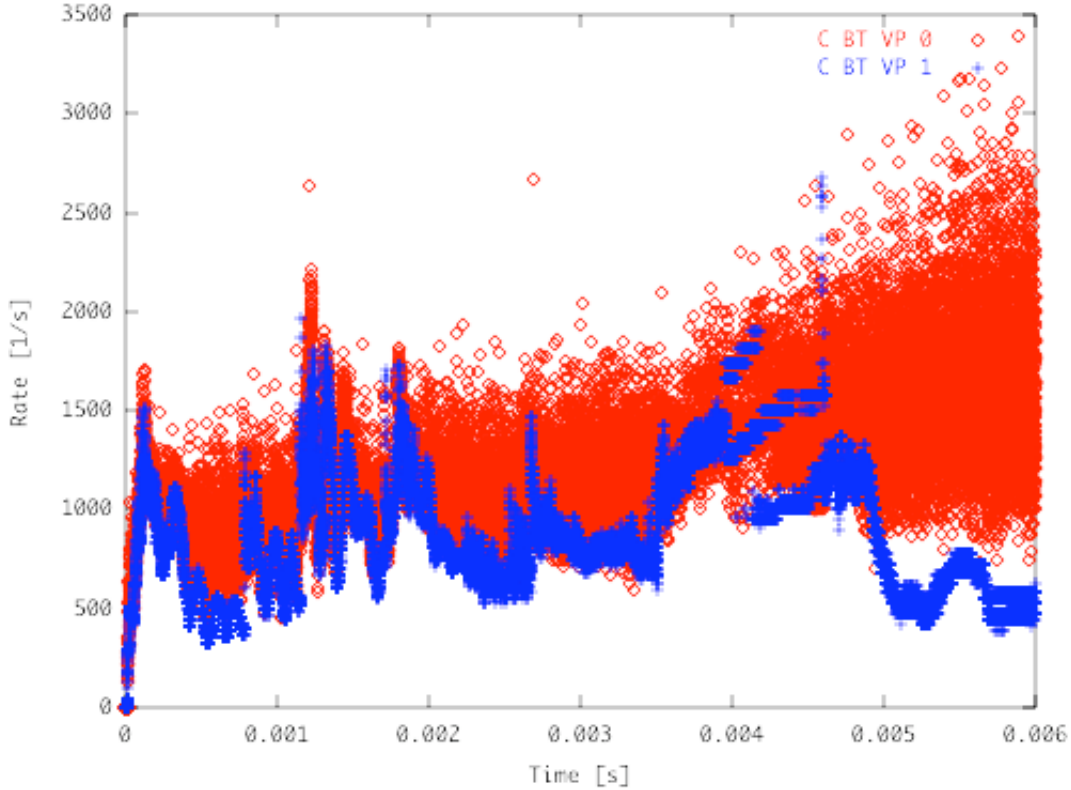
History of Maximum Rates, BT Shell



C: Coarse mesh

- L~2T

BT: Belytshko-Tsay shell

VP: VP effect

- VP=0 model based on total strain rate
- VP=1 model based on plastic strain rate

- History of MAXIMUM strain rate is significantly more noisy for VP=0
- For VP=0 elements "pop" in and out of plastic straining between steps

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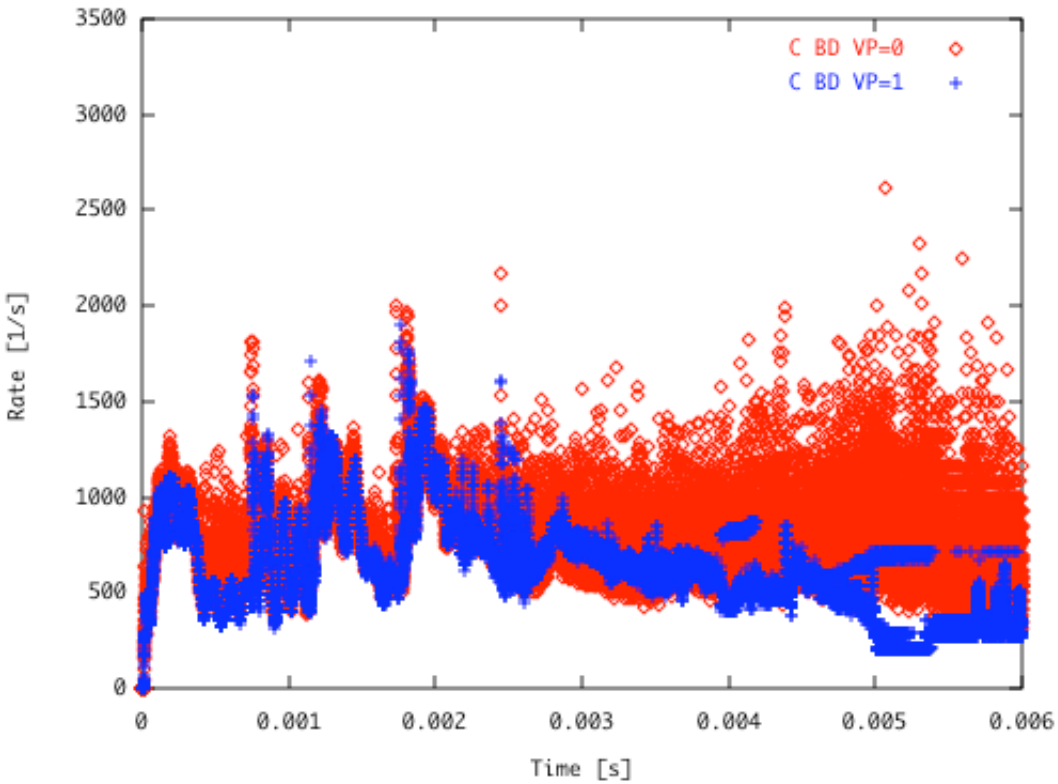
History of Maximum Rates, BD Shell



C: Coarse mesh

- L~2T

BD: Bathe-Dvorkin shell

VP: VP effect

- VP=0 (default) model based on total strain rate
- VP=1 model based on plastic strain rate

- VP effect the same as for the BT shell
- Strain rates are less noisy overall for BD shell

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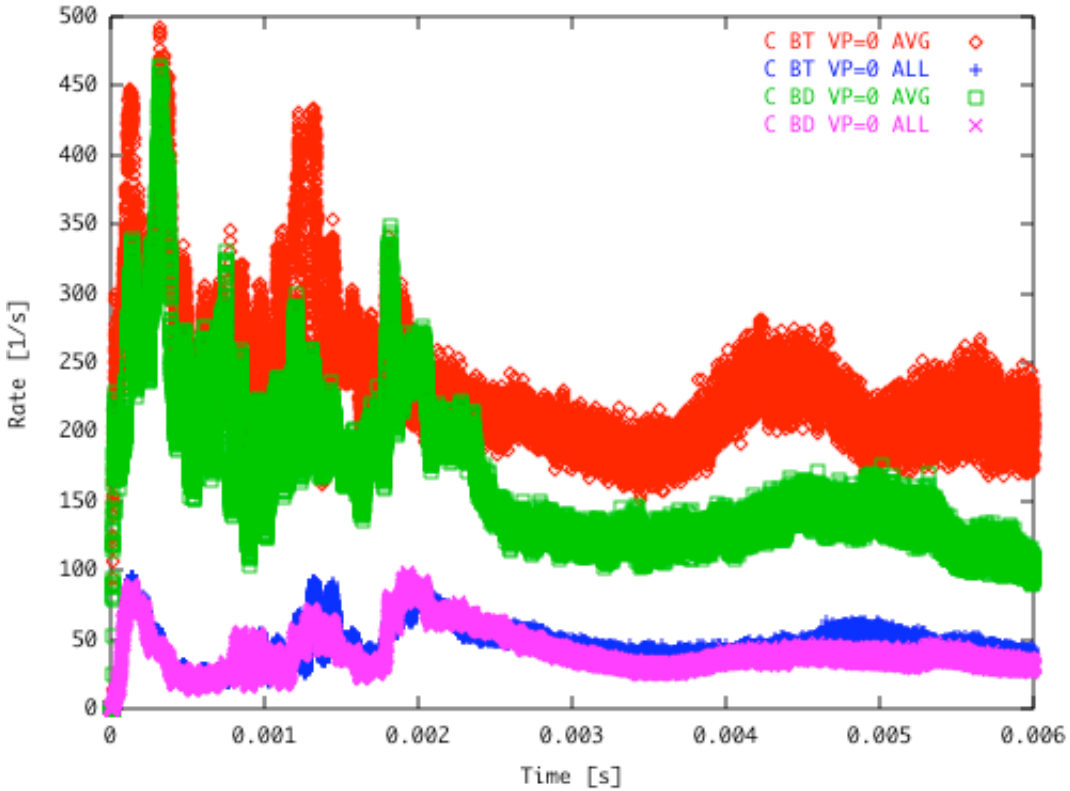
History of Average Rates, VP=0



AVG: Average over all elements for which plastic strain rate > 0

ALL: Average over all elements

VP=0: Model based on total strain rate

C: Coarse mesh

- Difference between ALL and AVG indicates spreading of plastic zones
- BD element tends to distribute strains, BT tends to localize strains
  - Important because traveling of corners during fold formation and BT tends to slow and arrest them

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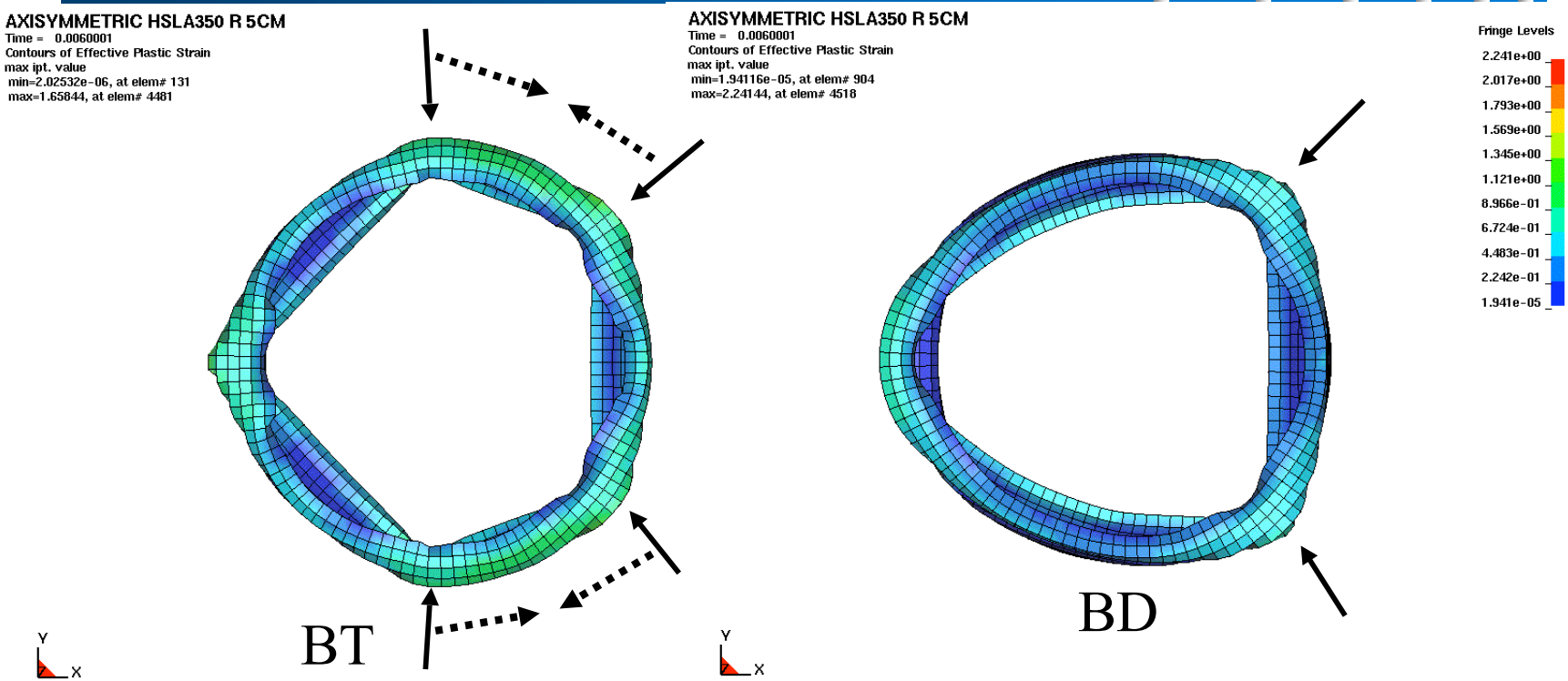
Element Formulation Effects on Deformation



- BT element formulation localizes corners and does not let them to coalesce into triangle folding shape
- Therefore, more total plastic strains in BT element

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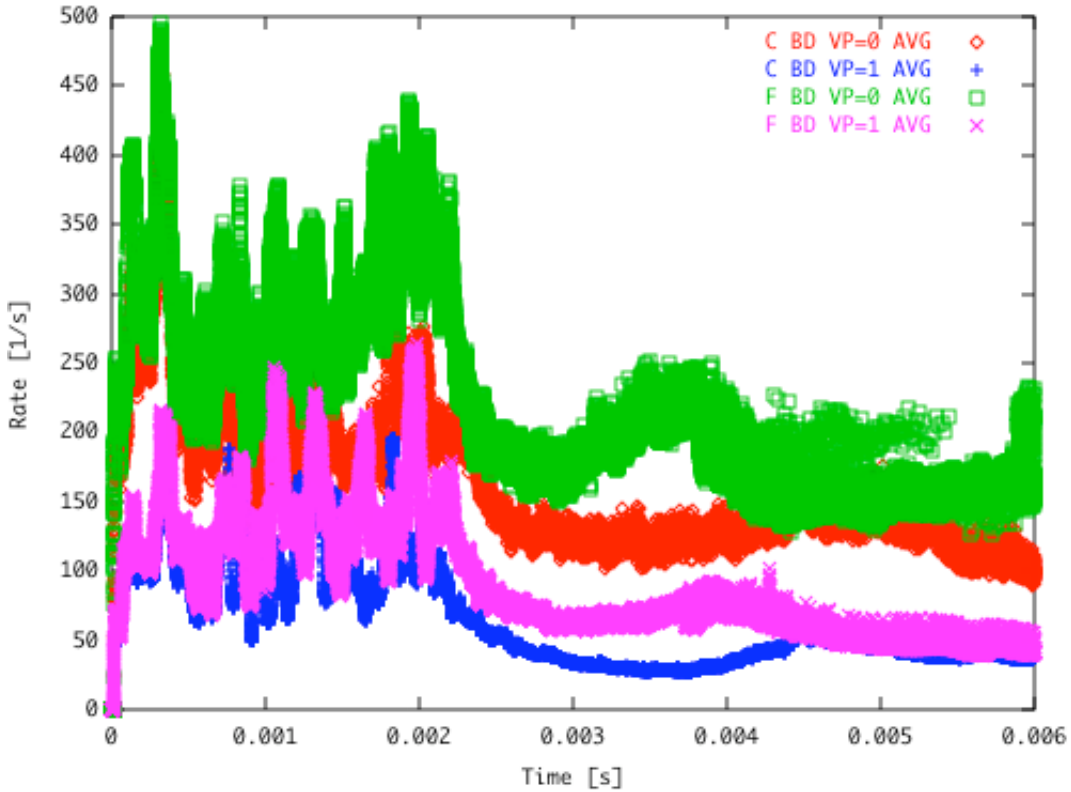
Average Rates, Element Discretization, BD Shell



C: Coarse mesh

- L~T

F: Fine mesh

- L~2*T

BD: Bathe-Dvorkin shell

VP: VP effect

- VP=0 (default) model based on total strain rate
- VP=1 model based on plastic strain rate

- Fine mesh has higher (~1.5) average strains during initial impact, difference smaller afterwards

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Plastic Strain Rate History Animations

- Coarse mesh, BD shell, VP=0
- Coarse mesh, BT shell, VP=0

- Coarse mesh, BD shell, VP=1
- Coarse mesh, BT shell, VP=1

- Fine mesh, BD shell, VP=0
- Fine mesh, BD shell, VP=1

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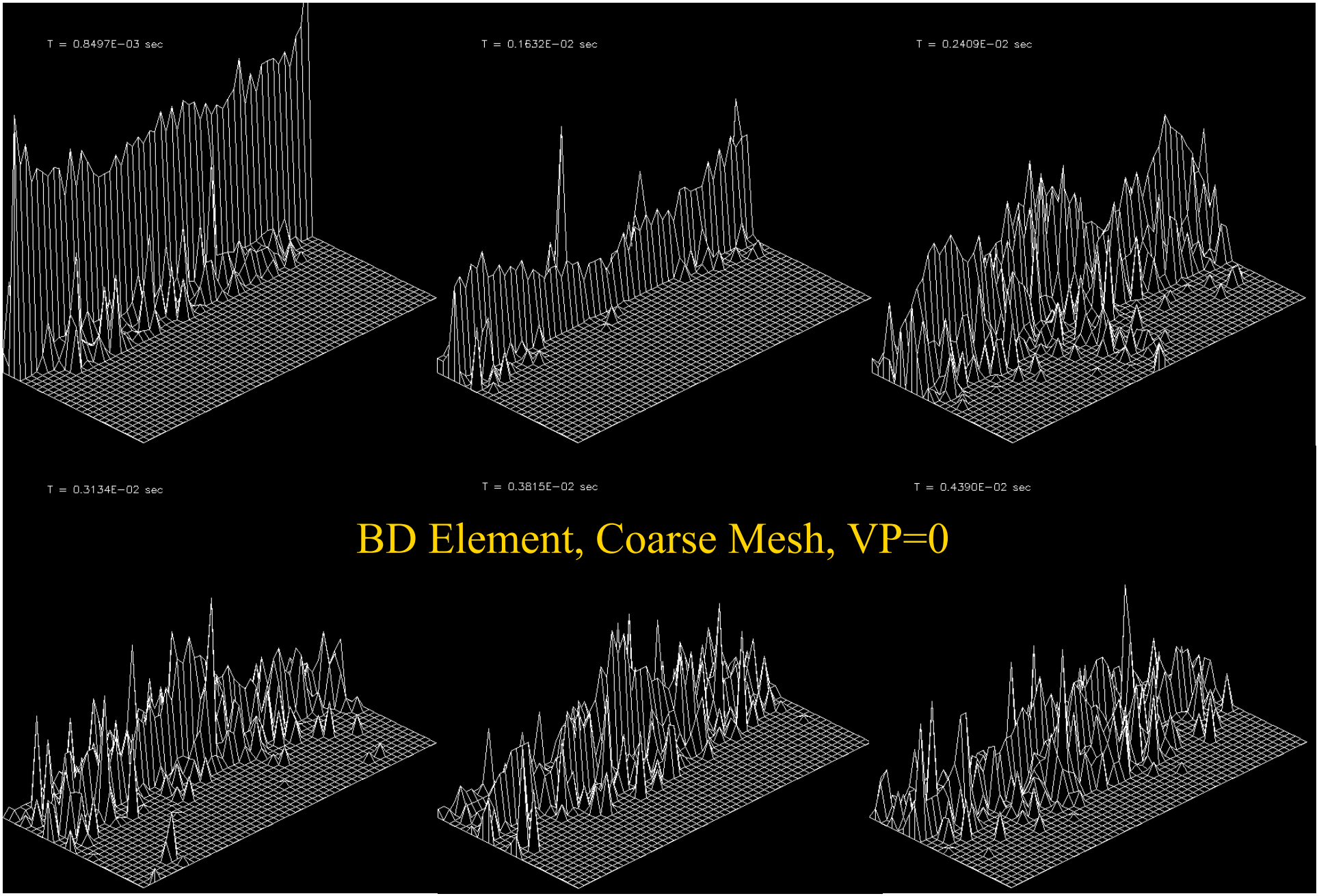
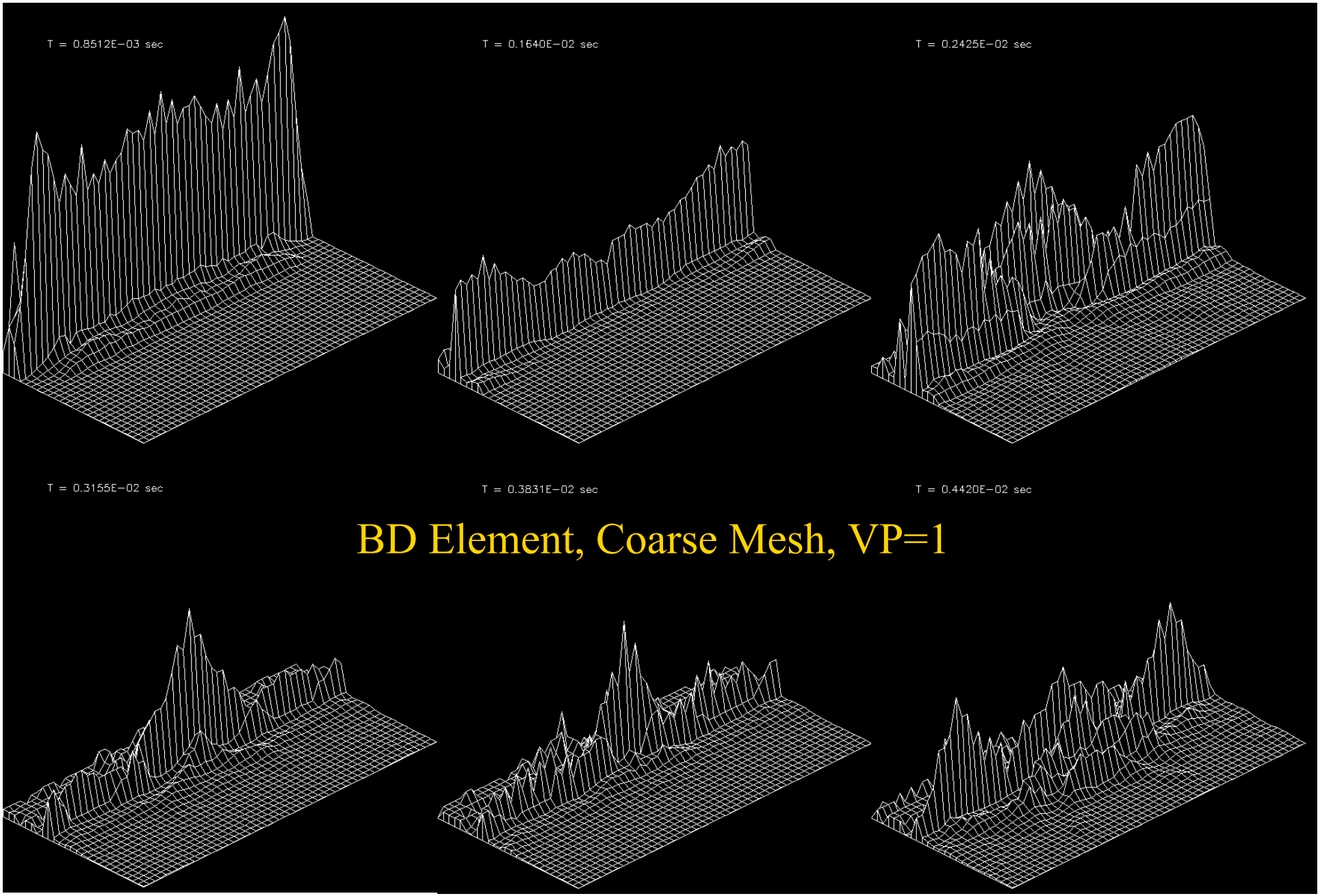


BD Element, Coarse Mesh, VP=0



BD Element, Coarse Mesh, VP=1

Conclusions

- Determined ranges of plastic strain rates for symmetric and un-symmetric crush
  - Developed deformation and rate analysis programs can be used in general crush problems
- For un-symmetric crush use BD element to allow plastic corners to travel (delocalize plastic deformation)
- Unless FE mesh resolution is sufficient to resolve deformation, effects of strain rate sensitive models are not straightforward
- Use viscoplastic models to delocalize plastic deformation
  - Continuous history of plastic strain rates
  - Lower plastic strain rates

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New Technology Needed

- Material models
  - Incorporate physical viscosity
    - Reduce FE mesh sensitivity
    - Better model effect of strain rate change
  - Incorporate yield point effects

- Element Formulation
  - Better modeling of warping
  - Modeling of localized features in larger elements

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The End

- Thank you for your attention
- Questions

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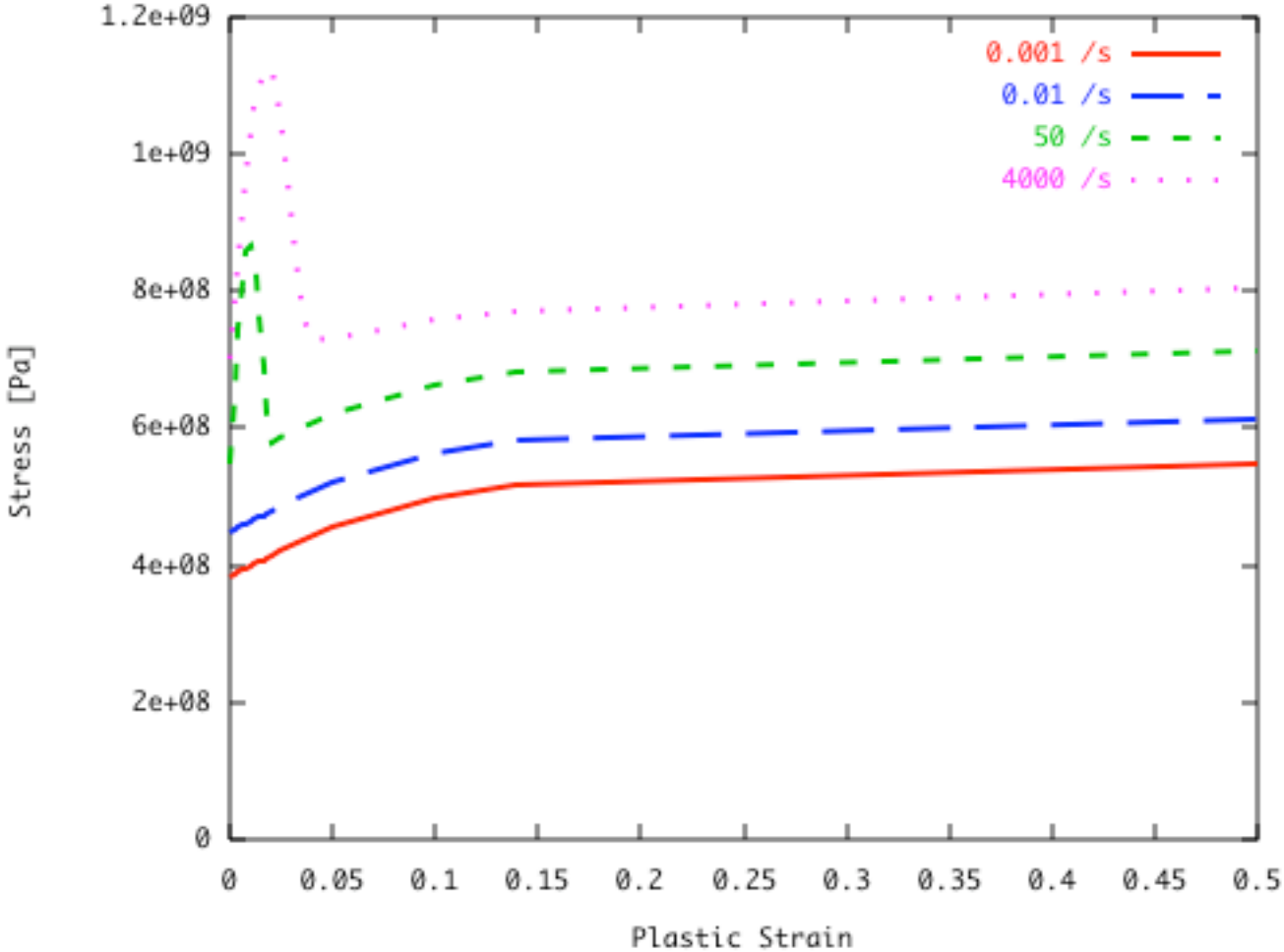
HSLA350 Simulation with YPE



Added YPE at 50 /s data set

Model data is interpolated between lower and higher strain curves

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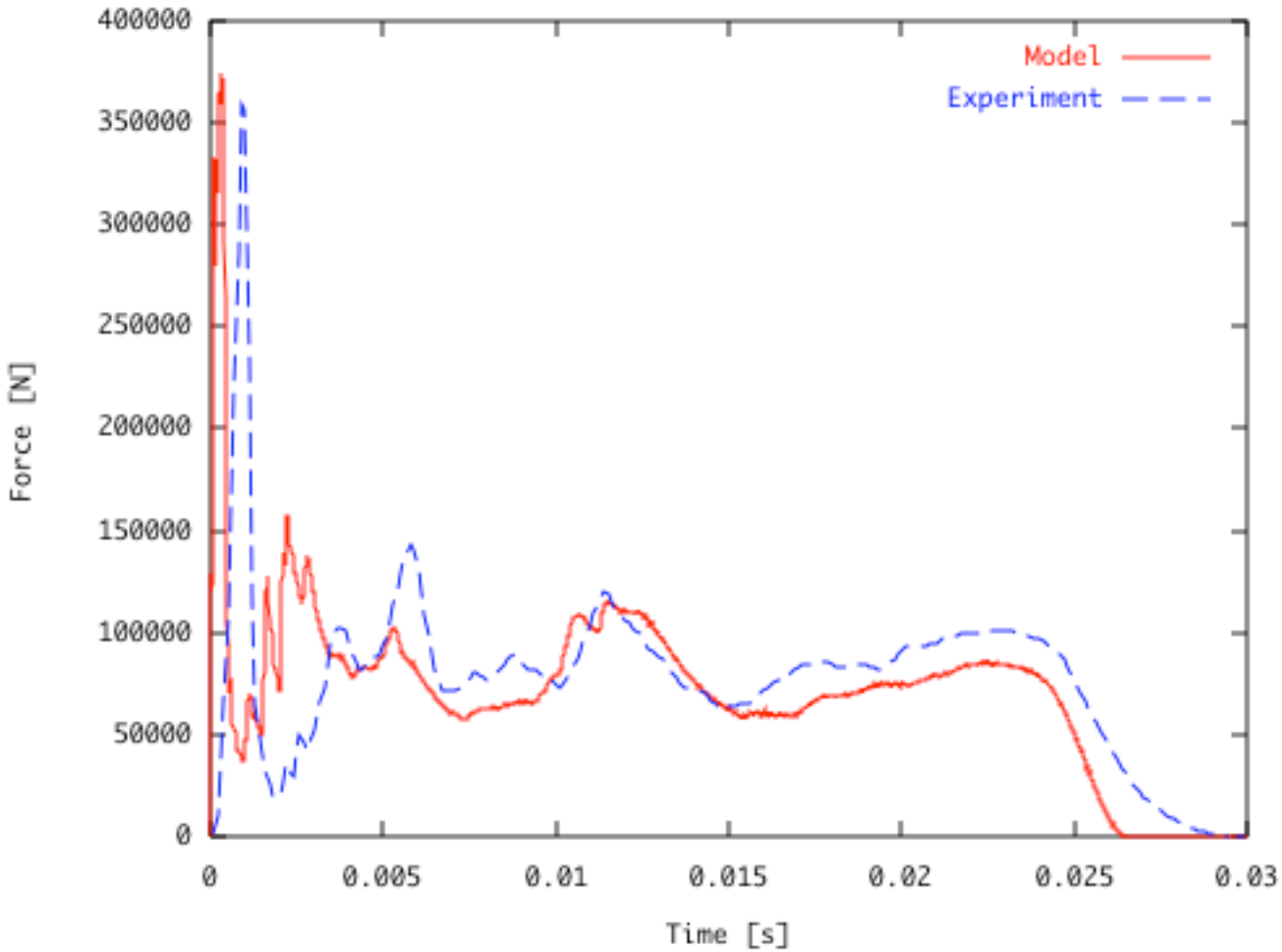
Force History with YPE for HSLA350



Force peak is in much better agreement with experiment

YPE has important effect on the initial force peak

Flexibility of impact plate in experiment accounts for initial stiffness mismatch

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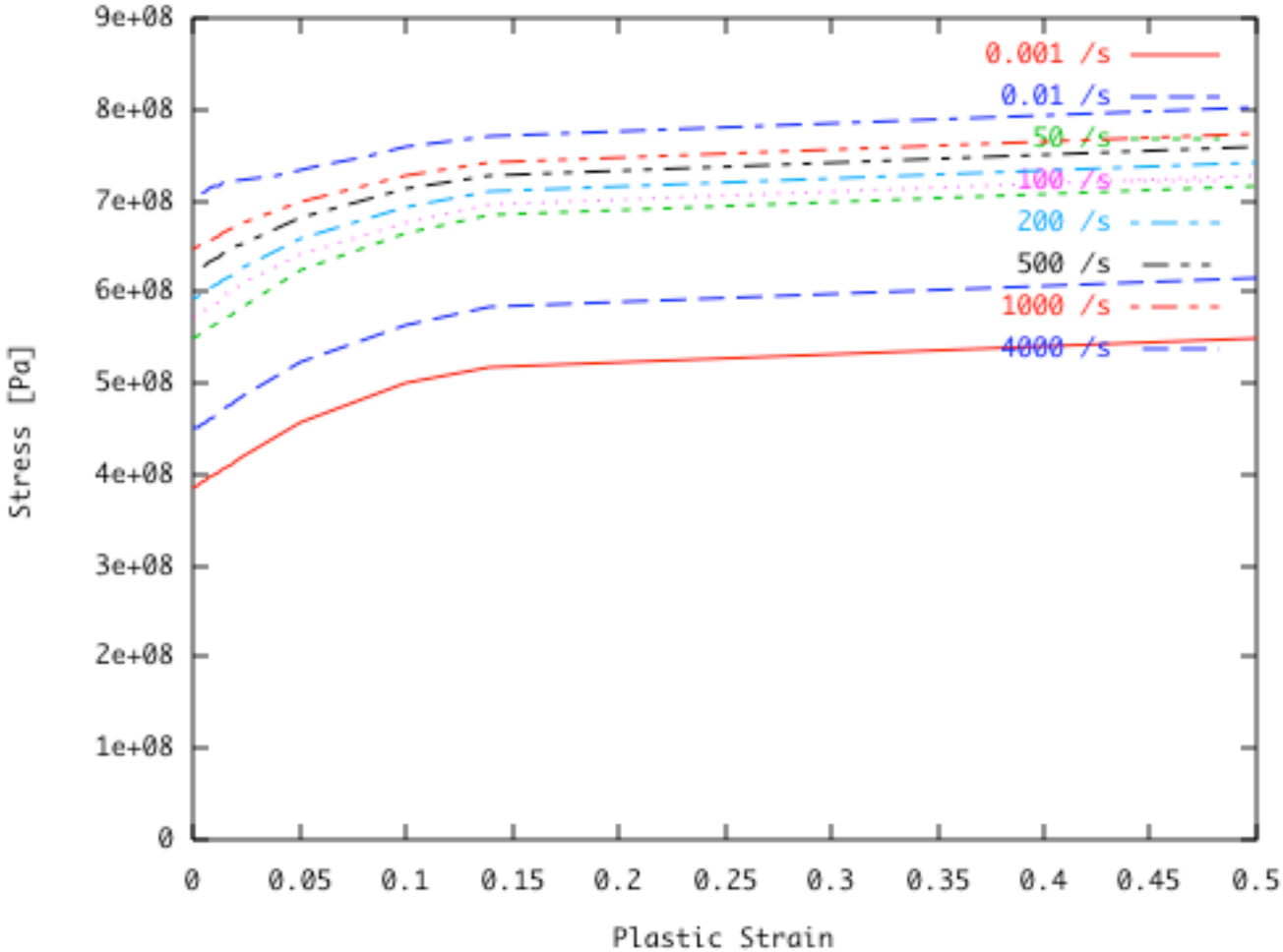
HSLA350 Rate Data Interpolation



Logarithmic interpolation for experimental data gives better overall fit than linear interpolation

Strain rate history for log-interpolated material data results in more gradual changes than linearly interpolated model

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