Evaluating Sensitivity of Beryllium Flyer Plate Simulations to Strength Parameterization

Eva Tourangeau (CCS-6)
Kyle Hickmann (XCP-8)
Jamil Gafur (XCP-8)
Michael B. Prime, ASME Fellow (E-13)
Joanne Wendelberger (CCS-6)
Material Strength

• What is “strength”?  
  – A material’s ability to withstand load without plastic deformation (permanent change)

• Los Alamos National Laboratory (LANL) is interested in material strength properties  
  – Experimentation, modeling, parameterization

Strain (m/m)  
Stress (Pa)

Elastic Region  Plastic Region

Saturation Stress  Yield Stress

Plastic strains are relatively low for flyer plate (FP) experiments
Flyer Plates (FPs) – Experiment, Simulation

- Impactor plate fired from gun at a target plate: stationary material sample, Beryllium (Be)
- Sends plane shock wave through a target material
- Free surface velocity of target measured over time

**Experiment:**

- **Target (Be)**
- **Impactor (Be, Sapphire, Quartz)**

**Simulation (1D):**

- Target
- Impactor
  - Impact Velocity
- Boundary “tracer,” simulation outputs
  - e.g. Pressure, density, velocity

**Data:**

- Time history: Target Velocity
  - Experimental
  - Simulated

VISAR Velocity Measurement

Impact Velocity
Velocity Trace: Important Areas for Strength

Wow, that fit looks pretty bad…

but we only care about part of the curve.

Reverberations past peak velocity:
- Reverse yielding and spall (damage)
- Not relevant for strength
Velocity Trace: Important Areas for Strength

- Elastic precursor
- Plastic rise
- Peak velocity

but we only care about part of the curve.

Reverberations past peak velocity:
- Reverse yielding and spall (damage)
- Not relevant for strength

Wow, that fit looks pretty bad…
Modeling Strength: Preston-Tonks-Wallace (PTW)

Conventional calibration at “lower” and “higher” strain rates:
- Hopkinson Bar (HB) (10^{-3}/sec – 10^{0}/sec)
- Quasi-Static (QS) (10^{3}/sec – 10^{4}/sec)

Strong shock theory allows us to estimate strength at strain rates 10^{9}/sec and above

Gap in calibration from 10^{5}/sec – 10^{8}/sec
FP data is sensitive to strength at ~ 10^{6}/sec

Current PTW parameter settings (calibrated using HB/QS data) provide poor fit to FP data
We extend PTW calibration to higher strain rates using FP data

UNCLASSIFIED
PTW defines strain rate transitions for yield stress

- For elastic and plastic deformation behavior, we care about yield stress: \( \hat{\tau}_y \)
- PTW uniquely emphasizes a model transition between strain rate regimes

\[
\hat{\tau}_y = \max \left\{ y_0 - (y_0 - y_{\infty}) \text{erf} \left[ k \hat{T} \ln \left( \frac{y_1}{\dot{\varepsilon}} \right) \right], \min \left[ y_1 \left( \frac{\dot{\varepsilon}}{y_1} \right)^{y_2}, S_0 \left( \frac{\dot{\varepsilon}}{\gamma \xi} \right)^{\beta} \right] \right\}
\]

- \( \dot{\varepsilon} \) is our independent variable
- We consider \( \xi \) known
- \( \gamma \) is part of \( \hat{\tau}_L \) and has been previously constrained
- **Will only perturb** \( y_1, y_2 \)

- FPs fall in the medium strain rate yield stress, \( \hat{\tau}_M = y_1 \left( \frac{\dot{\varepsilon}}{y_1} \right)^{y_2} \)

strain rate regime
Yield Stress

\[ \hat{\tau}_y = \max \{ \hat{\tau}_L, \min \{ \hat{\tau}_M, \hat{\tau}_H \} \} \]

What effects do Y1 and Y2 have on these curves?

\[ \hat{\tau}_M = y_1 \left( \frac{\dot{\varepsilon}}{y_\xi} \right)^{y_2} \]

Y1: Stretch/compress
Y2: Steepness

Shift intersection points of \( \hat{\tau}_M \) with \( \hat{\tau}_H \) and \( \hat{\tau}_L \), determining the strain rates at which \( \hat{\tau}_M \) is exercised
Sensitivity Analysis

What is it?
- Model output’s dependency on variation in parameter inputs
- Which parameters are most important for model prediction

We used this approach to assess the quality of the optimum/a we found:
- Nature of optima ("shallow" vs. "steep" on response surface)
- Local vs. global sensitivity – sensitivity landscape
Sensitivity shows large flat regions, high sensitivity regions, and a minimum curve, not point.

Simulation Global Sensitivity: RMSE as Y1, Y2 Vary (2d)

Less sensitive to Y1

More sensitive to Y2

High sensitivity

Low sensitivity
Slope and fit of simulated plastic rise initially sensitive to varying $Y_2$, then plateau

Fix $Y_1 = S_0 = 0.011498$

Note: Slope can also be affected by numerical issues, so we must be careful to have converged solution
Logarithmic relationship between Y1 & Y2

Simulation Global Sensitivity: RMSE as Y1, Y2 Vary (2d)

Y2 = 1.501 + 0.246 * log(Y1)
RMSE and Slope along Logarithmic Curve

RMSE Along Logarithmic Regression of Optimal (Y1, Y2)

\[ Y_1 = 0.6, \quad Y_2 = 1.22 \]
How good is $Y_1 = 0.6$, $Y_2 = 1.22$?

Simulation Global Sensitivity: RMSE as $Y_1$, $Y_2$ Vary
How good is $Y_1 = 0.6$, $Y_2 = 1.22$?

RMSE = 0.0032

PTW Yield Stress Curves

Time history: TargetVelocity

UNCLASSIFIED
How about $Y_1 = S_0 = 0.011498$, $Y_2 = 0.45$?

Simulation Global Sensitivity: RMSE as $Y_1$, $Y_2$ Vary
How about $Y_1 = S_0 = 0.011498$, $Y_2 = 0.45$?

RMSE $\approx 0.0034 (+ 0.0002)$
Conclusions

- Large $Y_1, Y_2$ regions of low sensitivity, local regions of high sensitivity
- Not a unique minimum

- Have $Y_1$ & $Y_2$ parameter settings that provide better overlay of flyer-plate data than do previous calibration settings
  - Because of PTW strain rate regimes, do not affect fits to lower strain rate data
Next steps

• Incorporate additional experimental data
• Examine local sensitivity around optimal \((Y1,Y2)\) pairs
  – Include additional PTW parameters
• Further comparison of defensible optima
Thank you!

References:


FLAG Simulation – Material vs. Strength Modeling

- FLAG: Lagrangian Multi-physics code from LANL
  - LANL wants standardized material models (Equation of State (EOS), Damage, Strength)
  - For a given material, FLAG allows choices for each piece

- Material model for Beryllium (Be)
  - **EOS**: Well understood (for us, fixed)
  - **Damage**: Damage modelling is the subject of separate research
  - **Strength**: Calibrate parameters in Be’s strength model to fit FP data, extending calibration to higher strain rate regime