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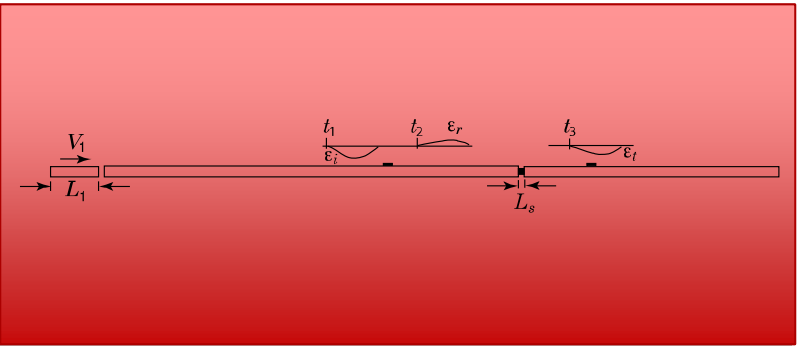

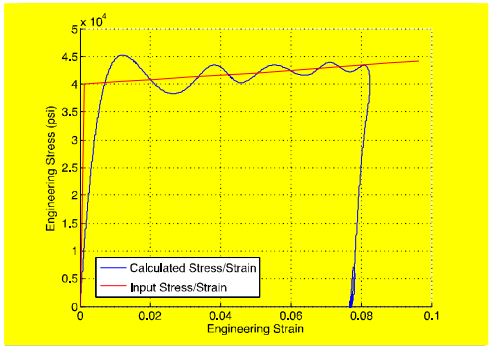

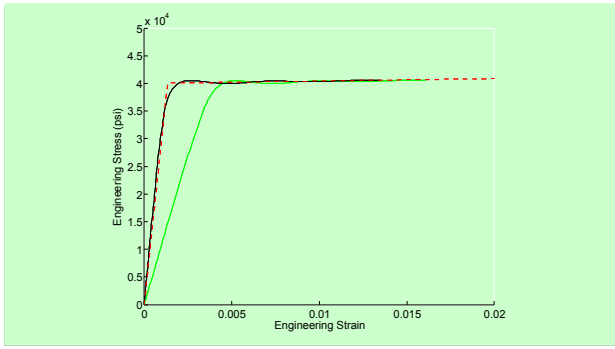

Data Reduction Uncertainties in Kolsky Bar Experiments on Metals

Erik Nishida, Edmundo Corona, Bo Song

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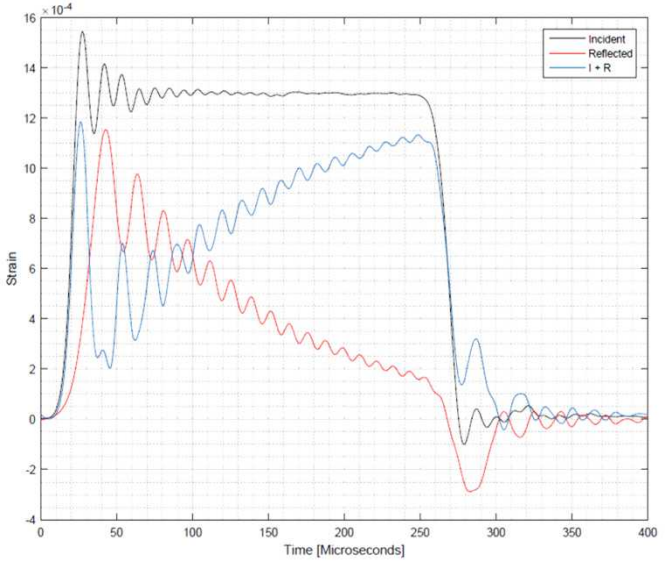
Costa Mesa, CA, June 8-11, 2015

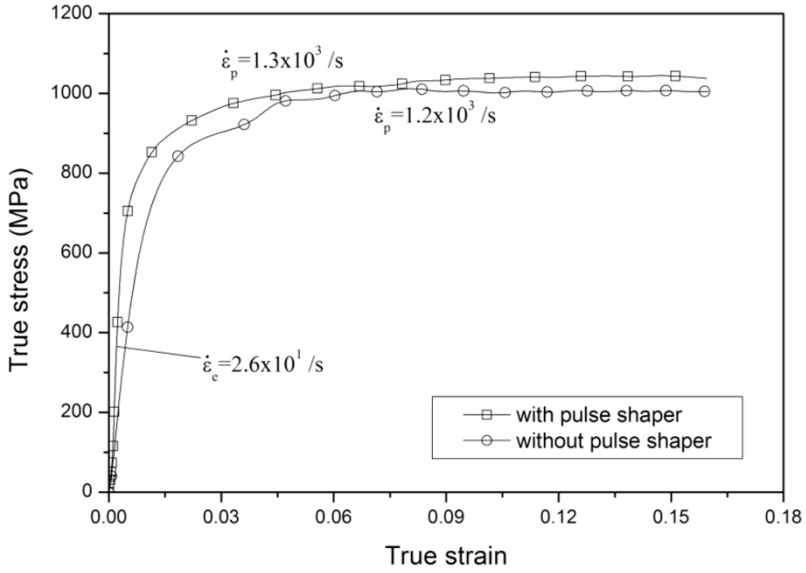
Outline

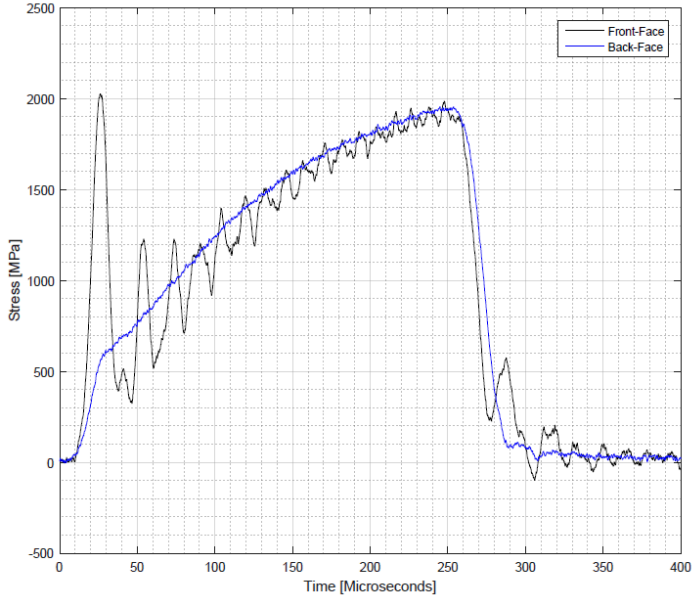
- Objective
- Numerical Simulations
- Young's Modulus Investigation
- Corrections
- Experimental Application
- Conclusions

Background

- Is small-strain measurement reliable?
  - Young's modulus for metals or brittle materials
  - Is there a dominant uncertainty?
    - System alignment
    - Wave dispersion
    - Indentation
      - Punching correction (K. Safa et. Al.)
    - Early stress equilibrium
    - Human error (data reduction methods)





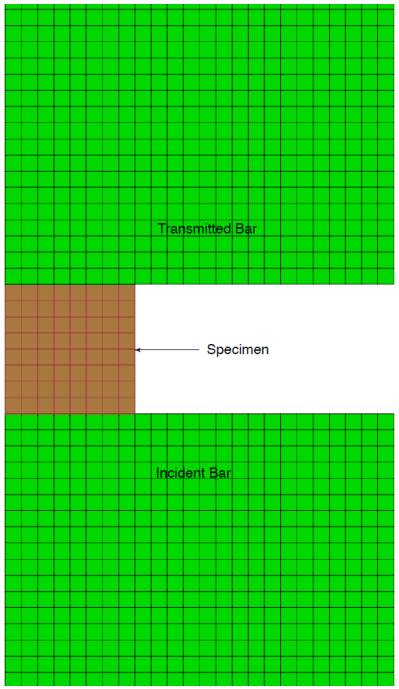


Objective

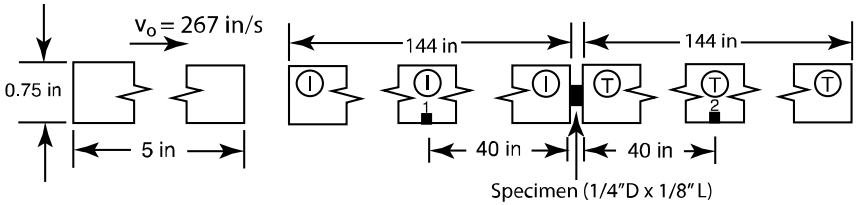
- Discuss uncertainties in the data reduction process to help explain the difficulty in measuring the Young's modulus
  - Stress wave dispersion
  - Early stress equilibrium
  - Elastic indentation
- Utilize finite element analytical models to help identify the dominant source of error
- Perform corrections on experimental data

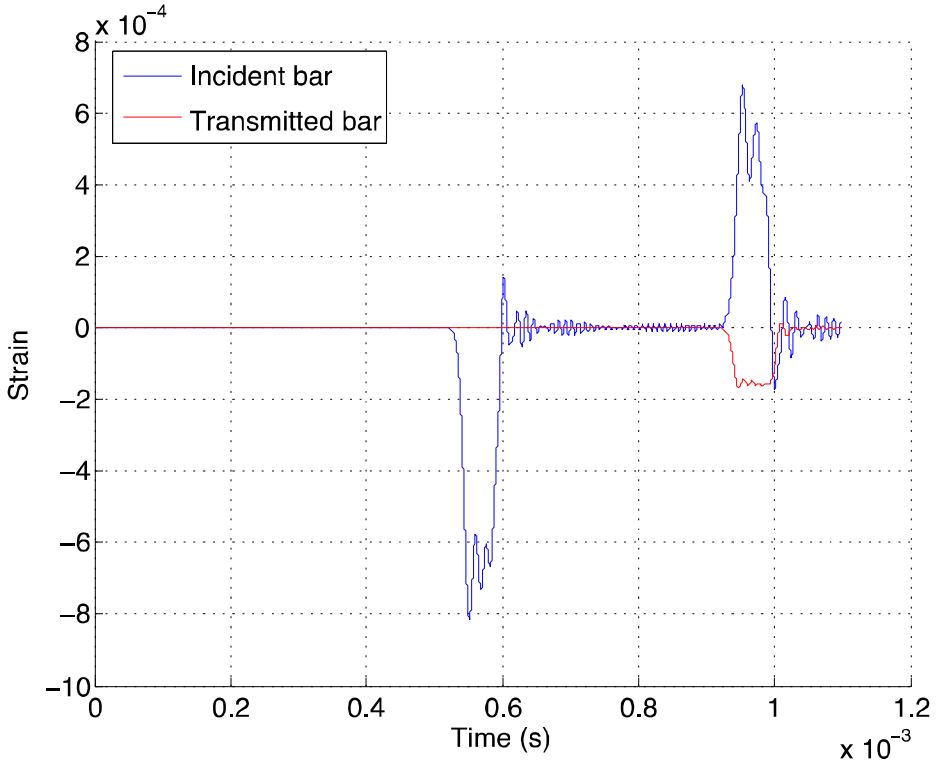
Numerical Simulations

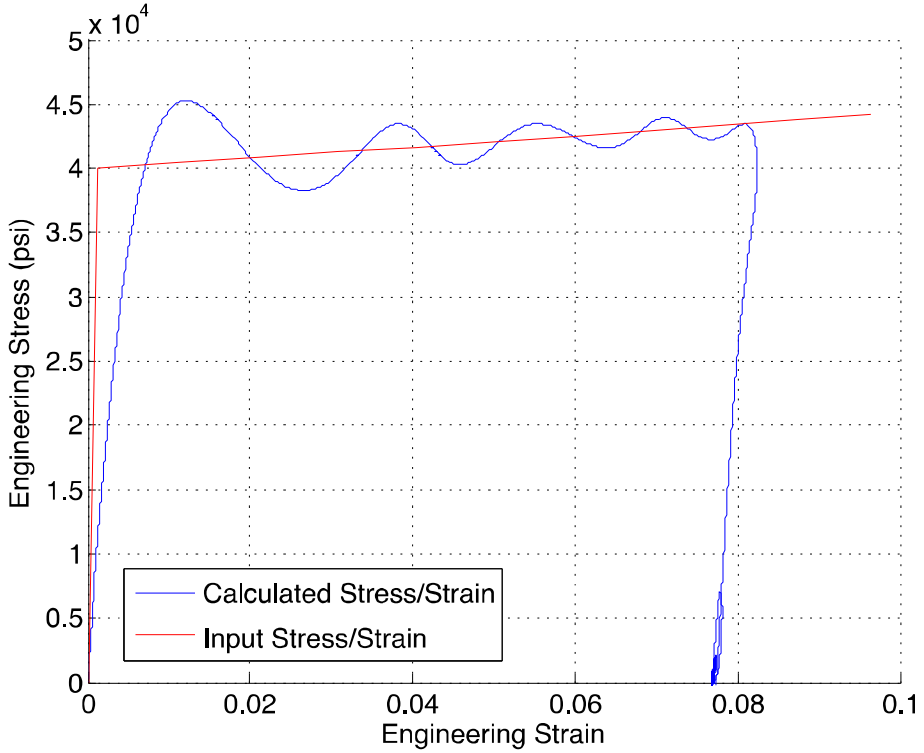
- Abaqus/Explicit
  - CAX4R elements
    - Four-node elements with reduced integration
    - Axisymmetric
    - Reduced integration with hourglass control
  - Contact
    - No friction
    - Penalty-based mechanical constraint
      - Scaled to minimize interpenetration
- Linearly elastic steel bars
- $E_{bar} = 30x10^3$ ksi
- $\nu_{bar} = 0.3$
- $c_{bar} = 200267$ in/s
- Specimen: 304L Steel
- Elastic, perfectly-plastic stress-strain response for the simulated specimen (ideal response)



No Pulse Shaper

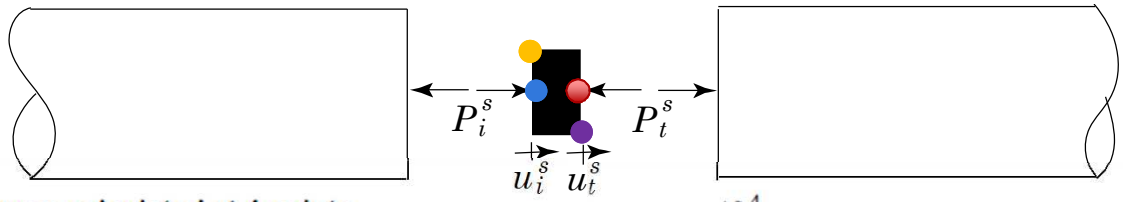


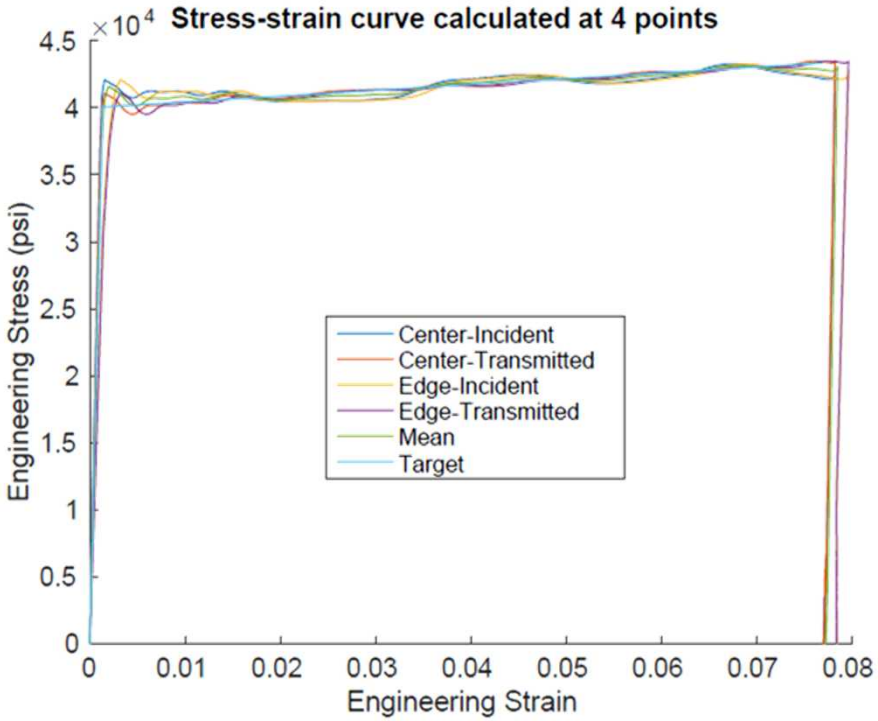


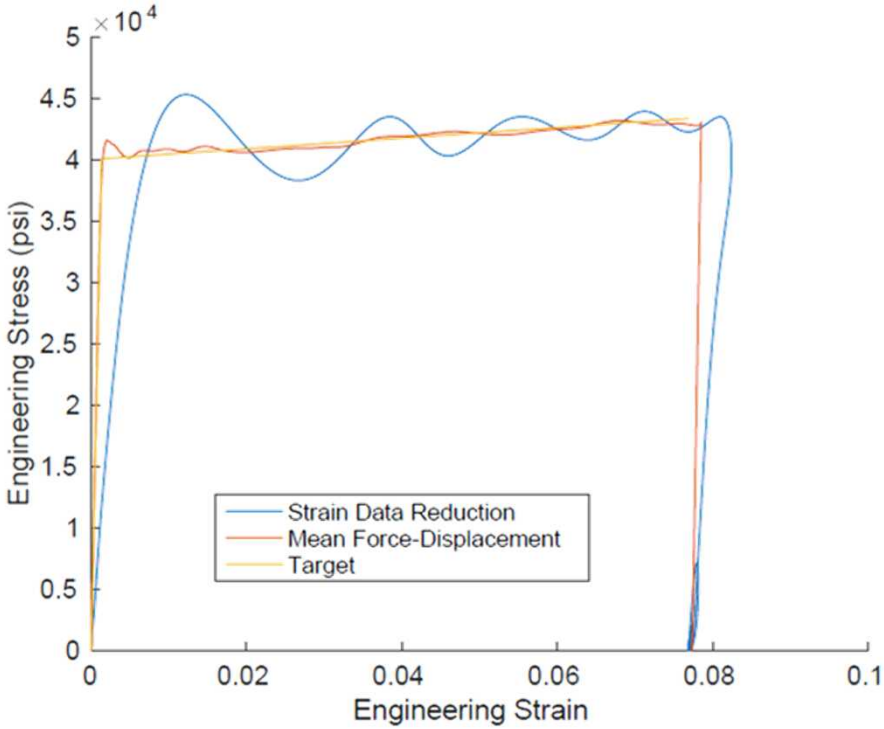


- Modulus of elasticity is significantly lower than the theoretical (Input Stress/Strain)

Young's Modulus Investigation

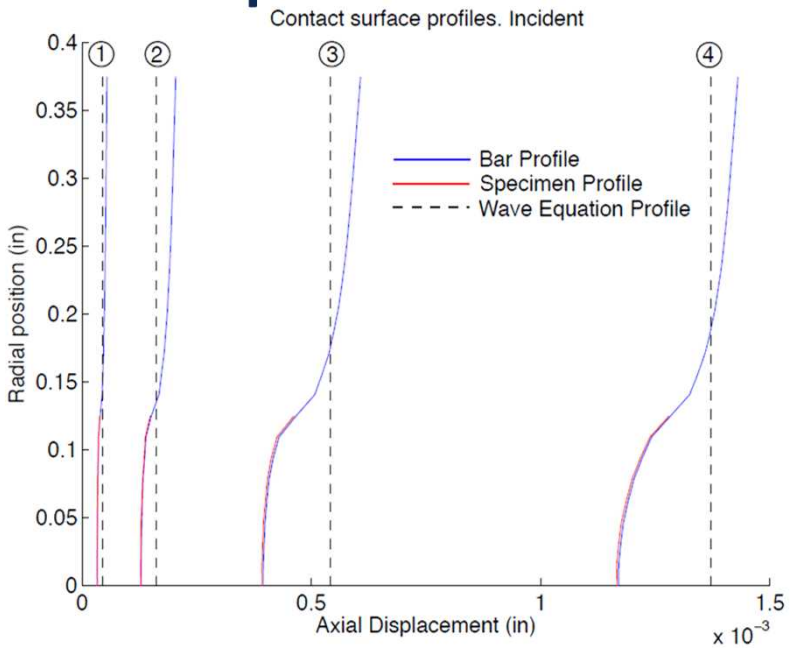


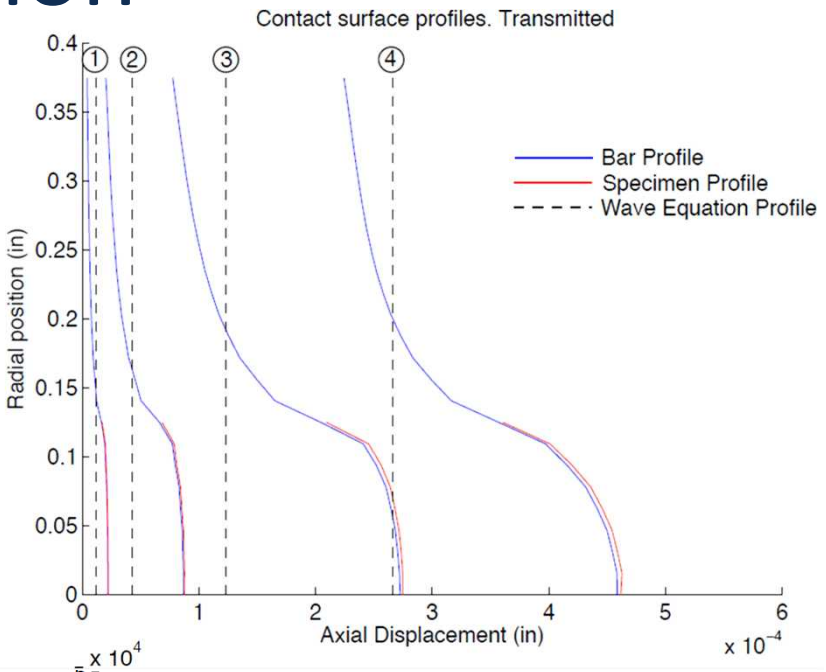




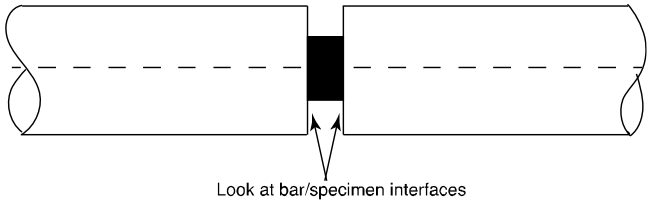
- Use contact forces between the specimen and the bars with displacements at various points on the specimen to calculate the stress-strain curves
- The mean of all four stress-strain curves match very well with the target stress-strain curve (except the oscillations) compared to the stress-strain curve developed from strain gage locations on the bar
- Meaning: There is a mechanism between the specimen/bar interface (incident and transmission side) and the strain gage location causing the error in the Young's modulus

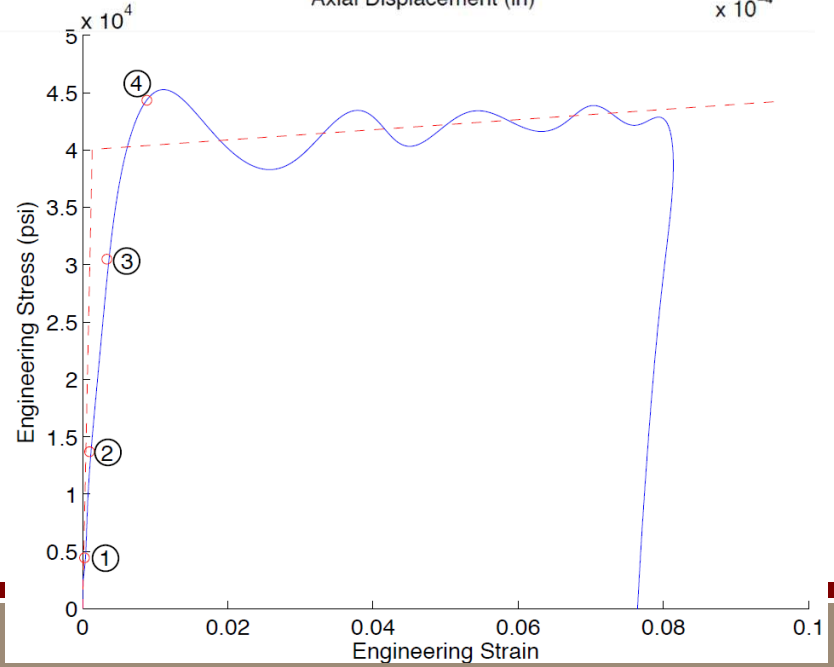
Bar-Specimen Deflection





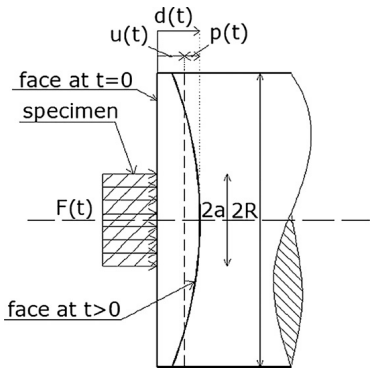
- FE simulations determined that axial displacements increase throughout the duration of the experiment (especially at early strains), introducing added strain into the conventional Kolsky bar stress-strain calculations





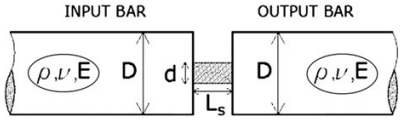
Displacement Correction

- K. Safa & G. Gary. "Displacement Correction for Punching at a Dynamically Loaded Bar End." International Journal of Impact Engineering (2010), Vol. 37, Pg. 371-384
  - Provide 3-D displacement correction for local punching due to axial loads at the end of the bar
    - Punching: axisymmetric deformation of the bar when the diameter of the specimen is smaller than that of the bar
  - First-order correction of the displacement obtained through the Kolsky bar 1-D wave analysis



Summary of main results for SHPB

We consider a classical SHPB apparatus where input and output bars are identical with diameter D and with ρ, ν and E the density, Poisson ratio and Young's modulus, respectively, of their material. The geometrical characteristics of the specimen are d, l_s and S_s corresponding to its diameter, length and cross sectional area, respectively.



At any time throughout the experiment, the strain of the sample is obtained as

$$\epsilon(t) = \epsilon_{SHPB}(t) - \epsilon_{punch.}(t)$$

where

- $\epsilon_{punch.}(t) = 2K_p \frac{\sigma_{SHPB}(t) S_s}{l_s}$
- $\epsilon_{SHPB}(t)$ and $\sigma_{SHPB}(t)$ are the strain and stress, respectively, obtained by standard SHPB formulas.
- $K_p = \frac{16}{3\pi^2} \frac{1-\nu^2}{dE} H_p(\frac{d}{D})$

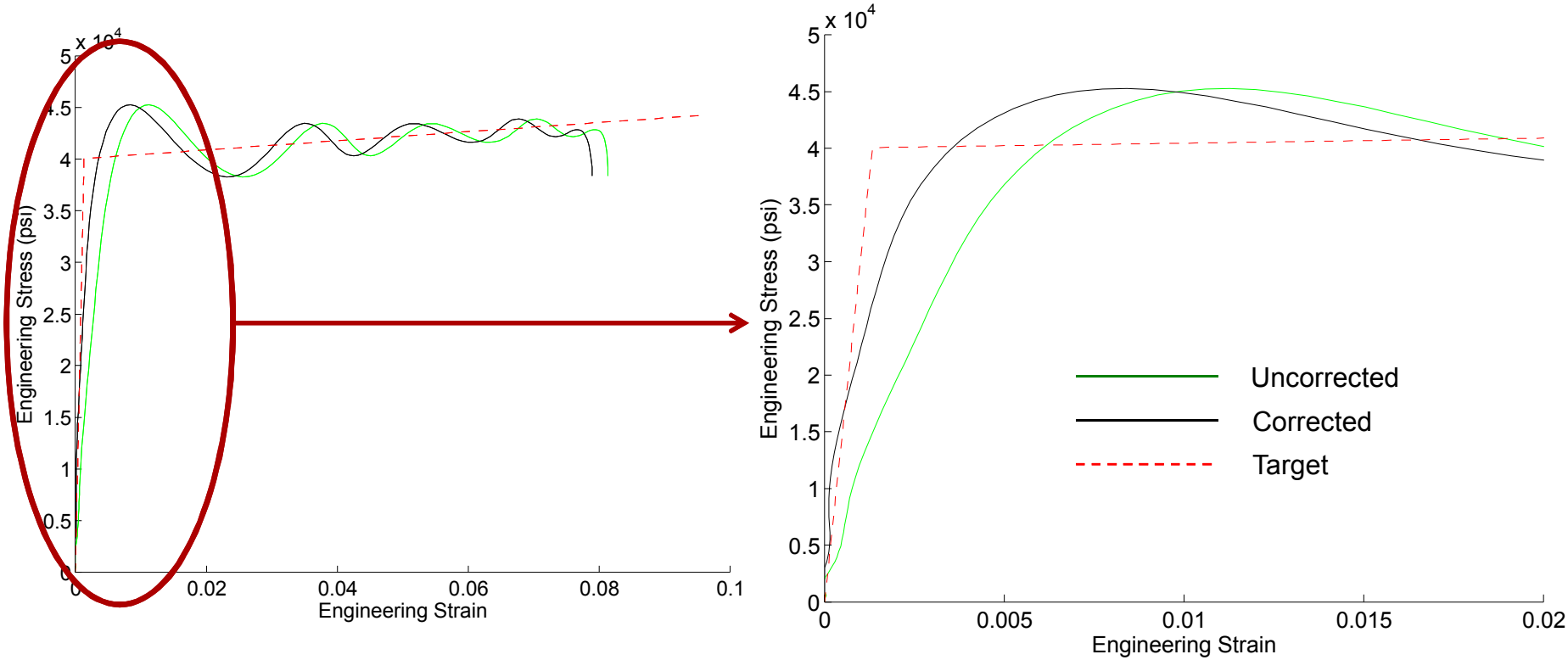
$$H_p(x) = 2 - (x + \frac{1}{x})E(x) - (x - \frac{1}{x})K(x)$$

$$E(x) = \int_0^{\frac{\pi}{2}} \sqrt{1 - x^2 \sin^2\theta}\, d\theta,\ K(x) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1 - x^2 \sin^2\theta}}$$

Tabulated results for the function $H_p(x)$ are given in the table underneath.
Values for $0.5 < x \leq 1$ are obtained by linear interpolation.

x	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.00
$H_p(x)$	1.765	1.648	1.531	1.416	1.301	1.188	1.076	0.967	0.860	0.688	0.516	0.344	0.172	0

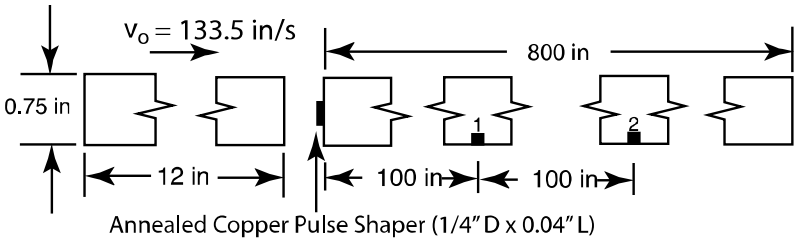
Displacement Correction Only

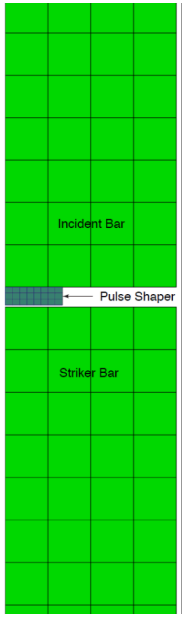


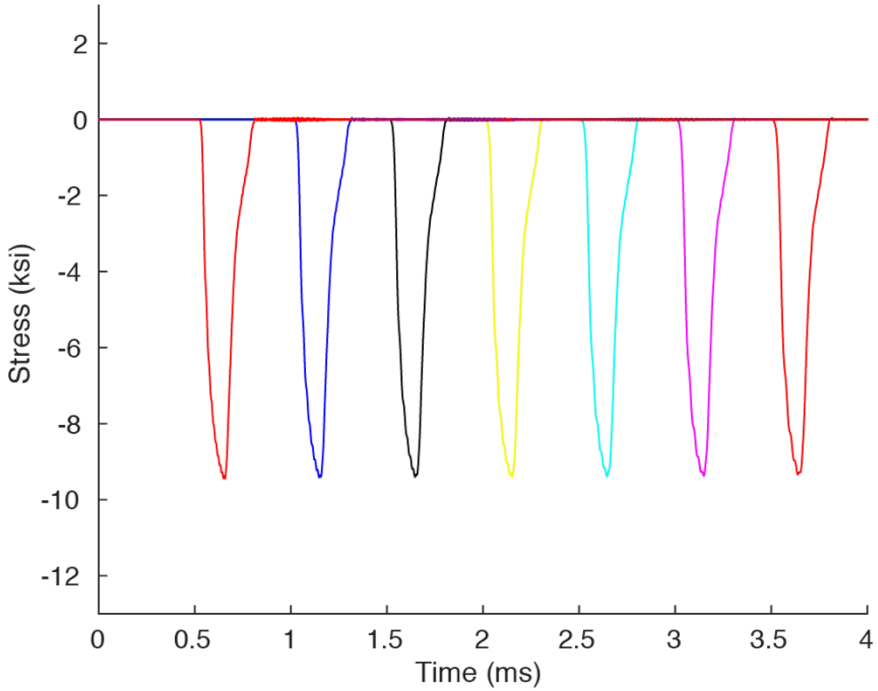
- FE simulation using the closed form displacement correction by Safa et. Al.
- Young's modulus improves a little, but does not match the target stress-strain curve

Add Pulse Shaping

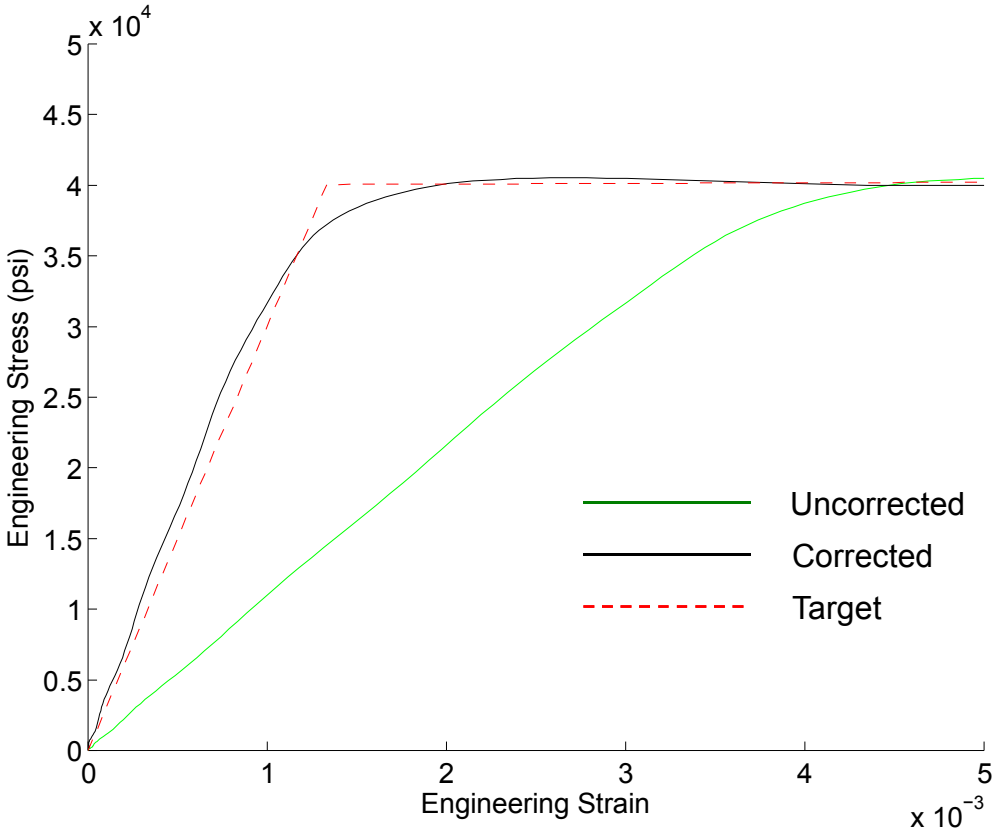
- Experimentally minimizes stress wave dispersion
- Slow rise in incident pulse enables early stress equilibrium and deform at nearly constant strain rates
- Shown to minimize oscillations in stress-strain curves





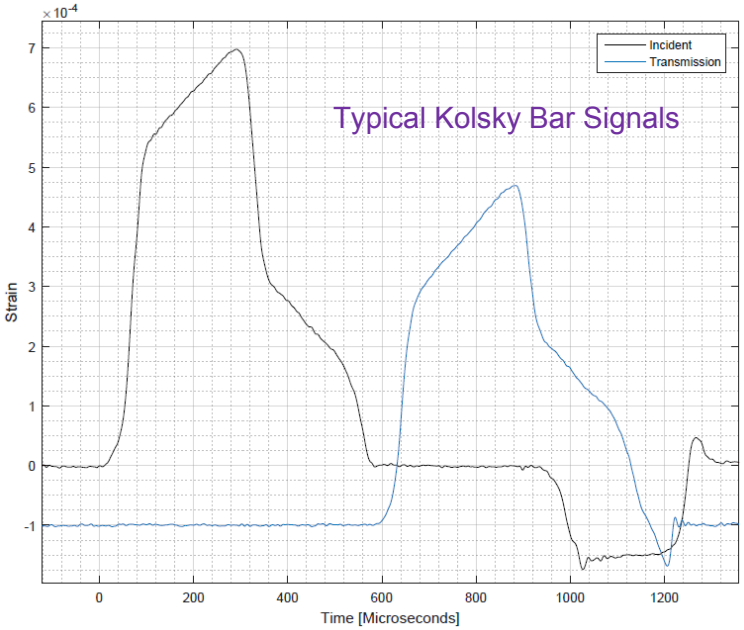


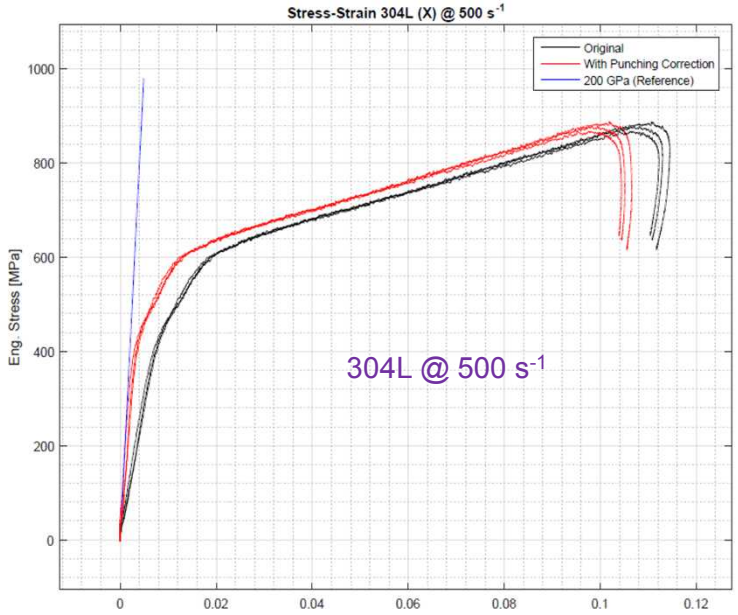
Displacement Correction + Pulse Shaping

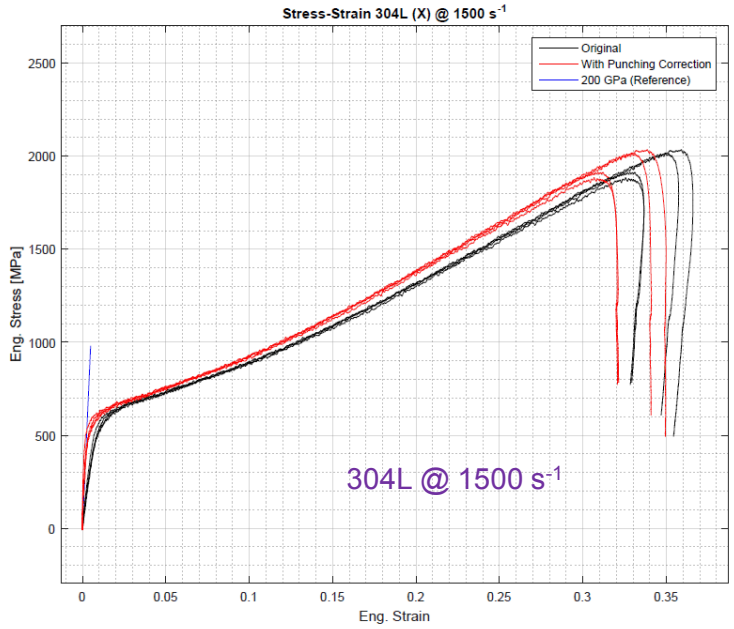


Experimental Application

- C300 steel, 0.75 in. diameter bars
  - Striker: 12 or 24 in.
  - Incident: 144 in.
  - Transmission: 72 in.
- Dual pulse shapers
  - 4140/4142 Steel
  - Copper pulse shaper
- Both pulse shaping and displacement correction assist in recovering a more reasonable Young's modulus







Conclusion/Path Forward

- Pulse shaping
  - Minimizes stress wave dispersion and enables stress equilibrium
  - Helps increase the accuracy in measuring the Young's modulus from a stress-strain curve
- Displacement correction for punching
  - Decreases the added strain due to elastic punching on the incident and transmission bar
- Correction Uses
  - Both pulse shaping and punching correction were used to determine the intrinsic mechanical behavior of 304L stainless steel Kolsky bar experiments
  - Materials: Hard vs. Soft
- Additional uncertainties
  - Filtering
  - "Starting point" for reflected pulse and transmission pulse

The End

Acknowledgements

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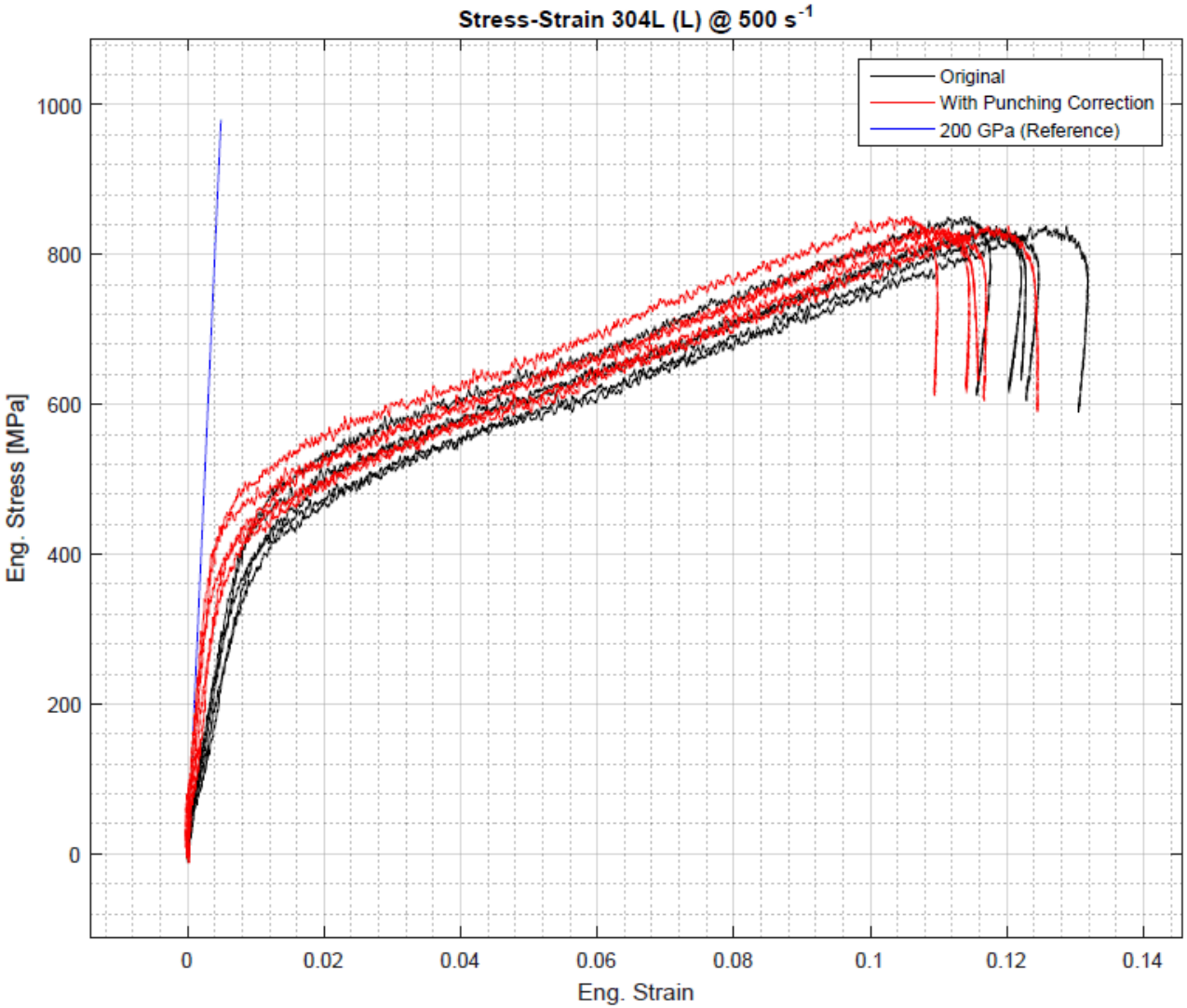

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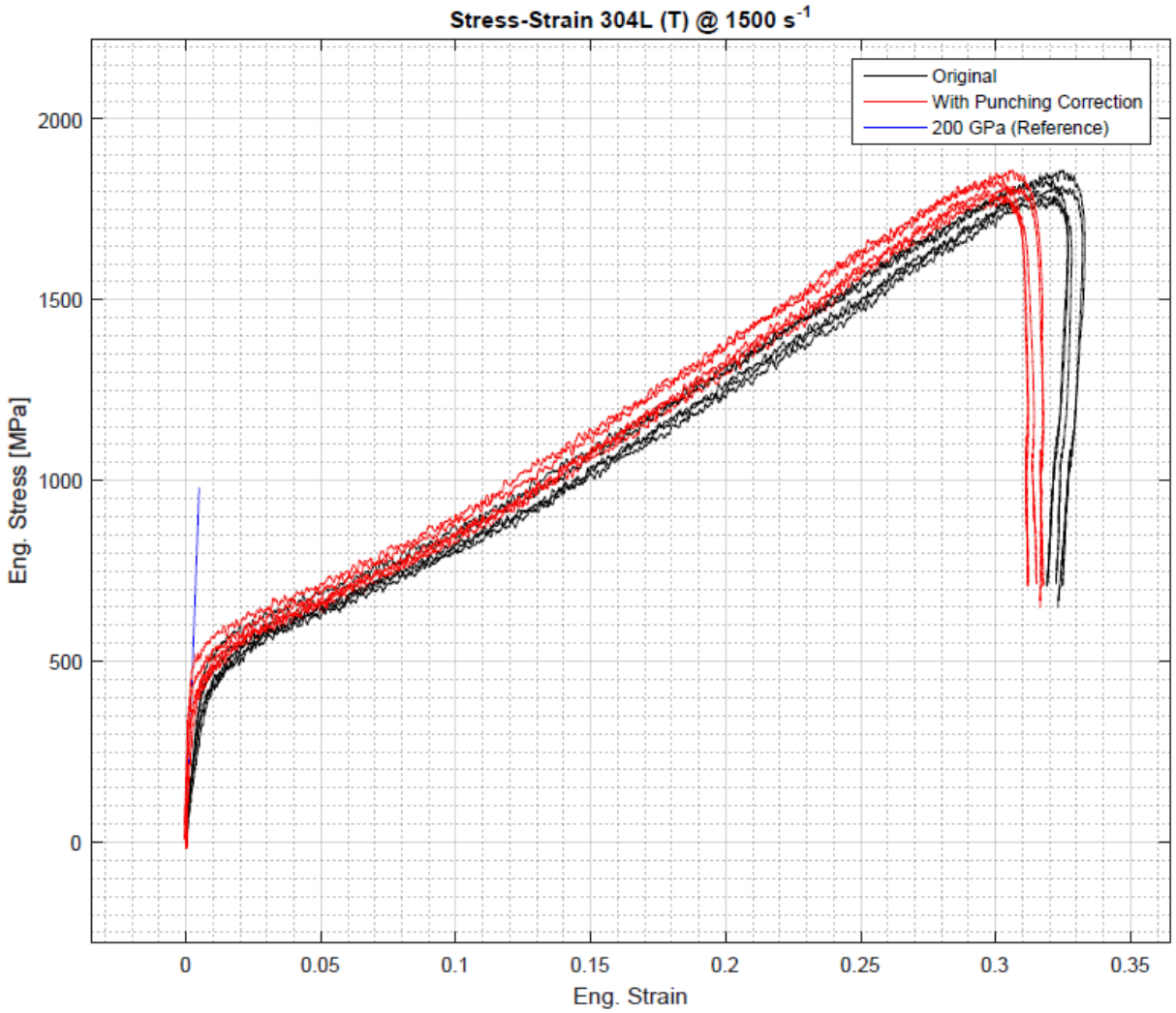

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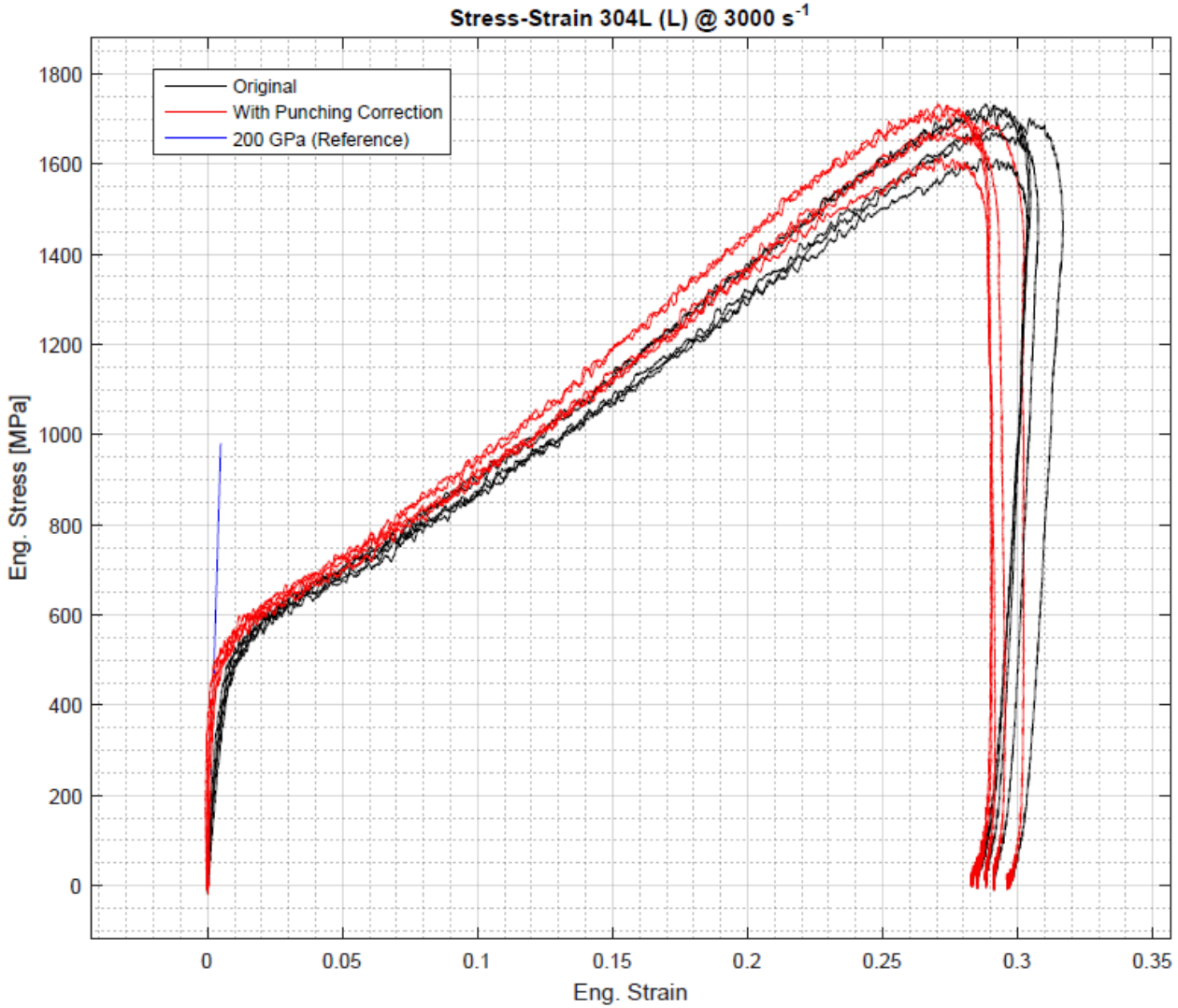

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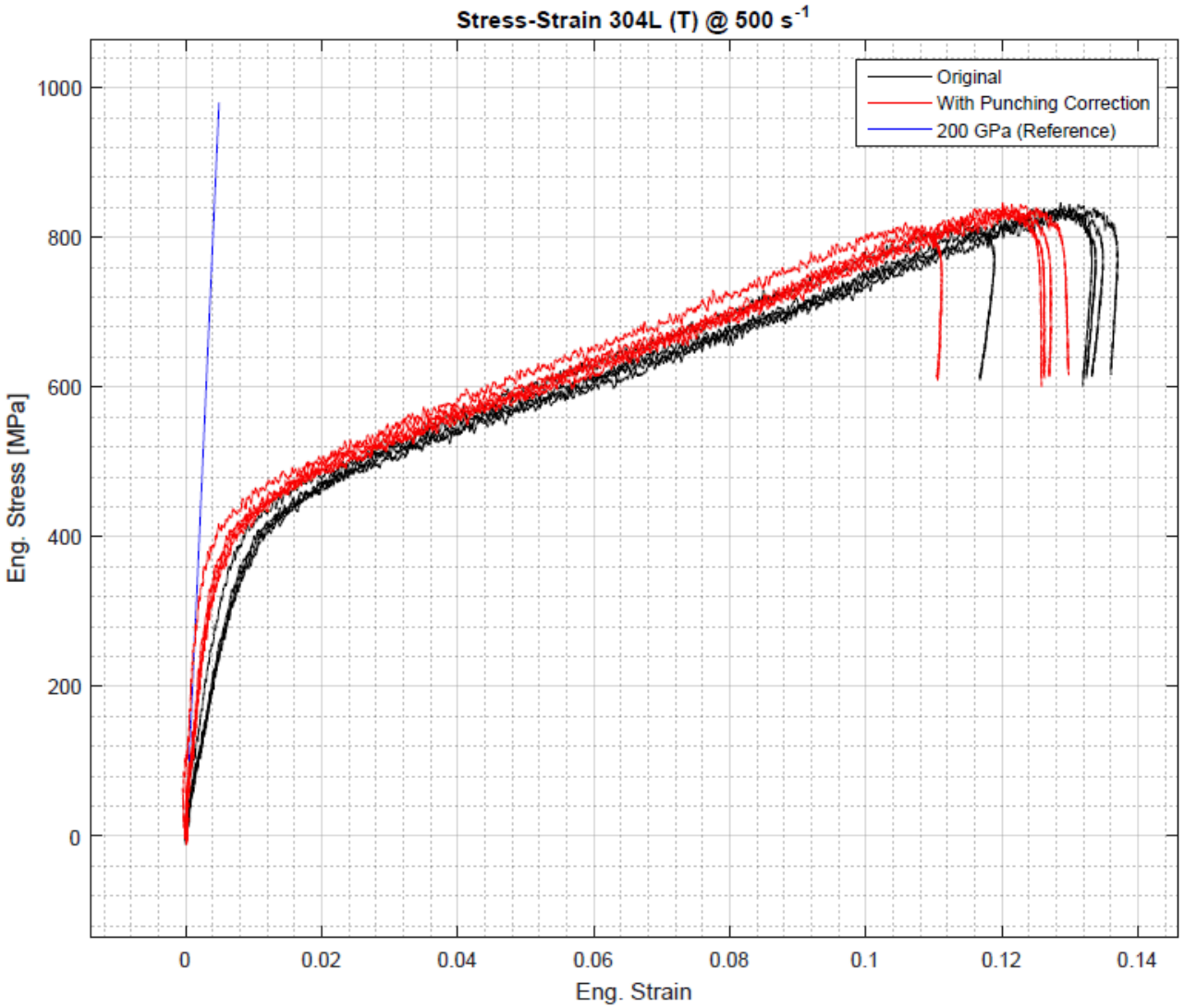

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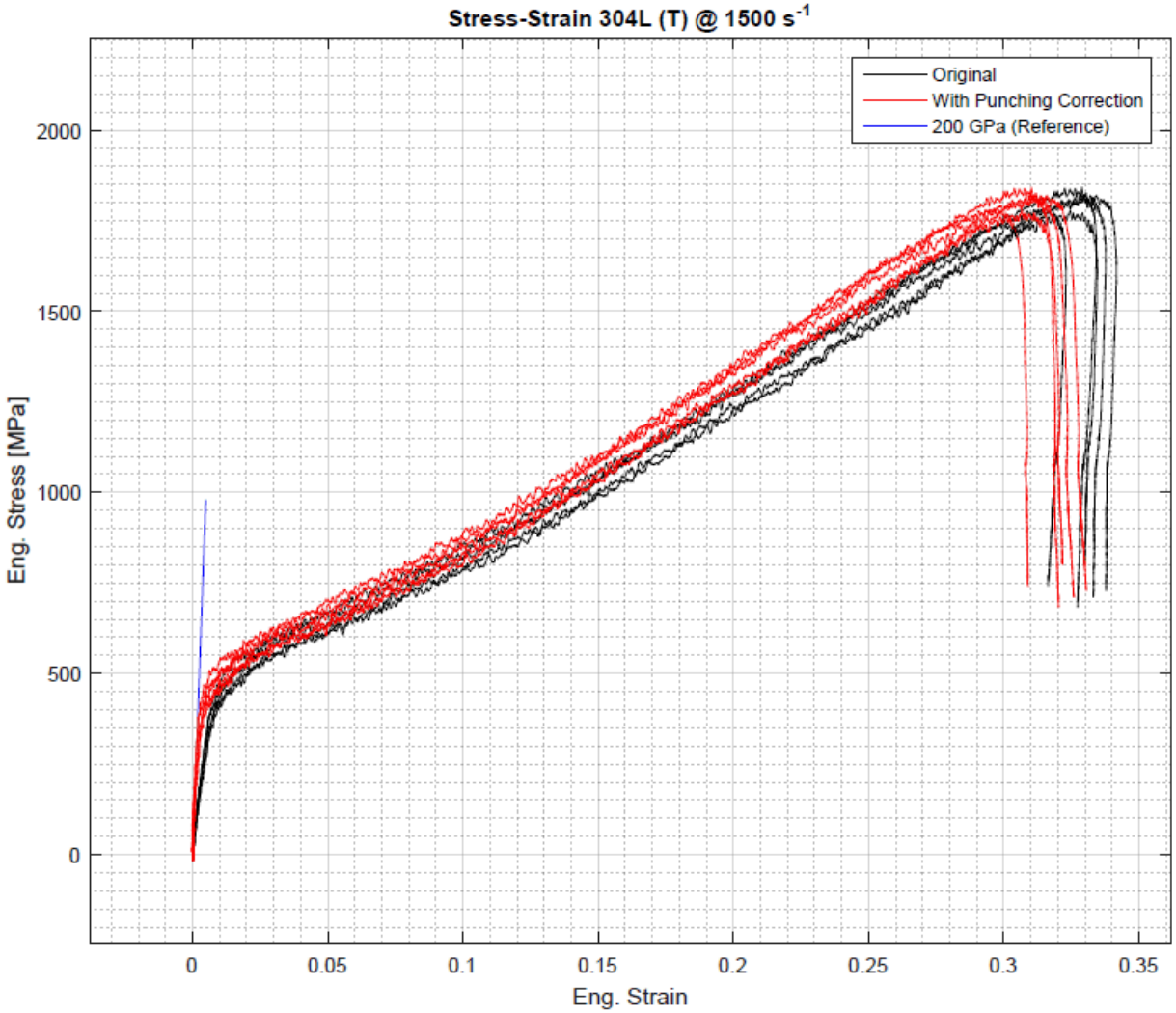

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