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Developing data-driven strength models incorporating temperature and strain-rate dependencies

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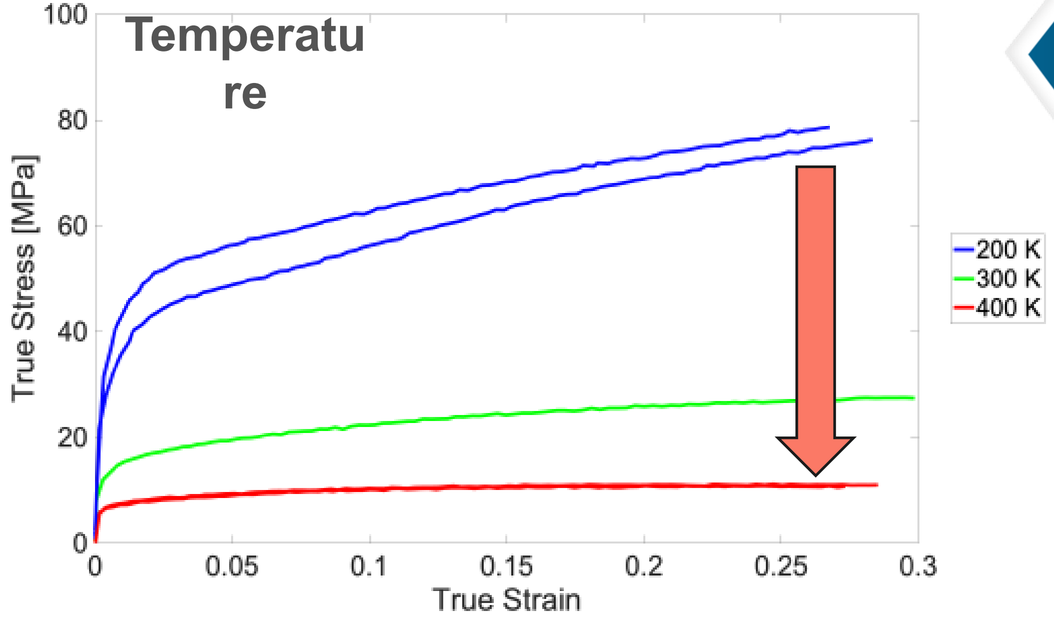
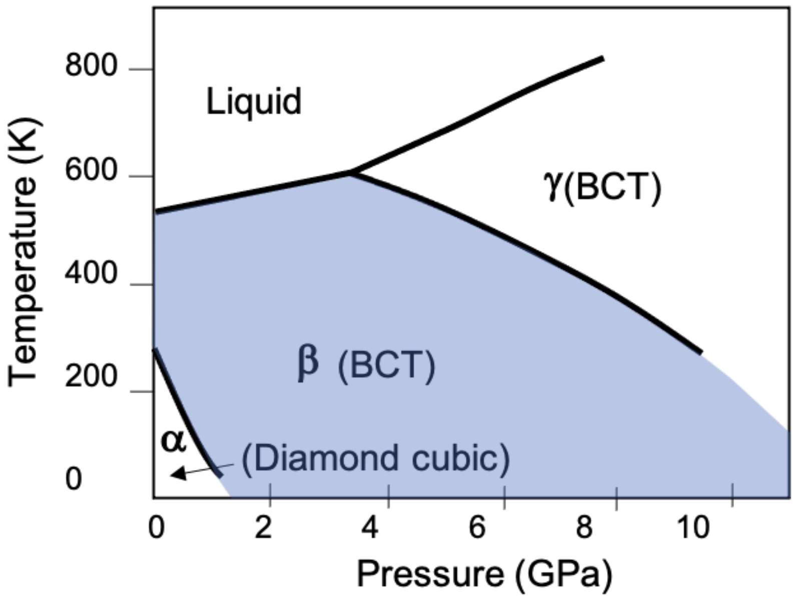
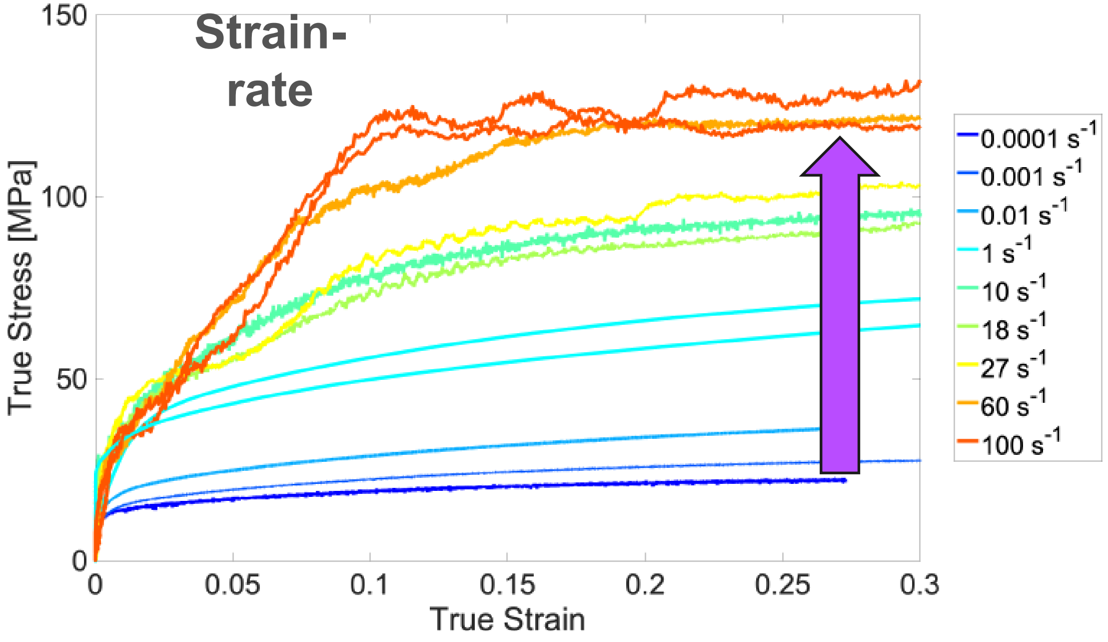
SAND2024-#####C

Tin displays complex behavior

- Used in plating, soldering, and alloying
- Low melting temperature (505 K) and low recrystallization temperature (303 K)
- Difficulty in predicting performance
  - Complex microstructural evolution
  - Large distributions in mechanical response



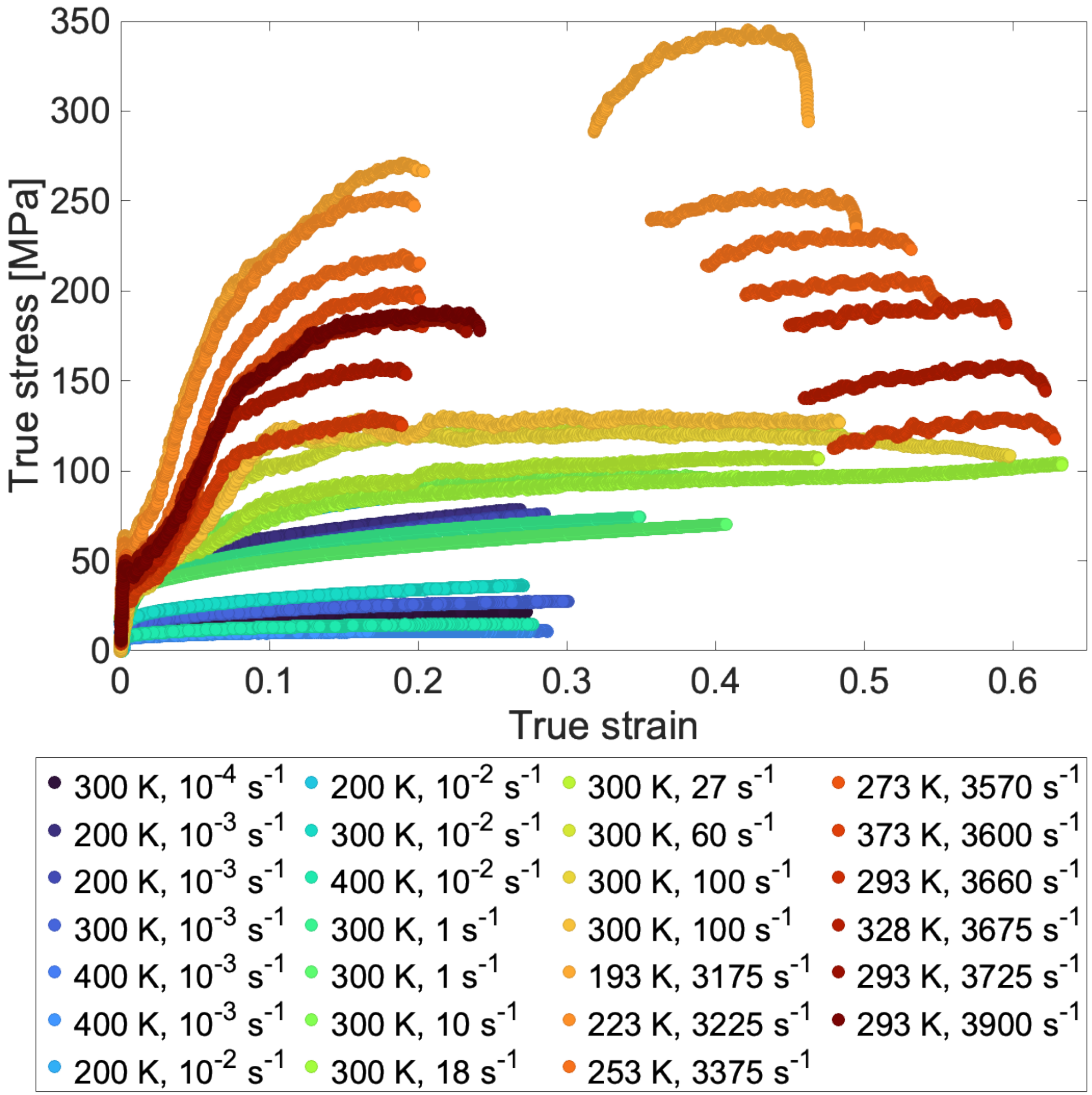




H. Lim et al., SAND Report (2022) - SAND2022-

Experimental characterization of β-Tin

- Characterize temperature and strain-rate dependencies
- Compression tests
  - Experiments done at Sandia
  - Temperature: $200 \sim 400\ K$
  - Strain-rate: $10^{-4} \sim 10^{2}\ s^{-1}$
- Split-Hopkinson Pressure Bar (SHPB) tests
  - Experiments done at Los Alamos
  - Temperature: $190 \sim 375\ K$
  - Strain-rate: $3175 \sim 3900\ s^{-1}$



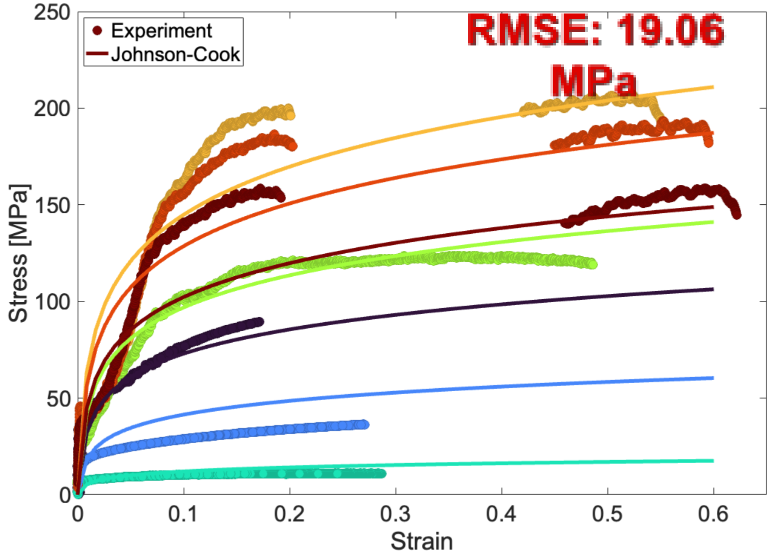
H. Lim et al., SAND Report (2022) - SAND2022-

Traditional strength models $\sigma = f(\varepsilon, \dot{\varepsilon}, T)$

- Traditional model limitations
  - Fixed form
  - Difficult to extrapolate
  - Multiple parameters to fit
  - Assumption-based

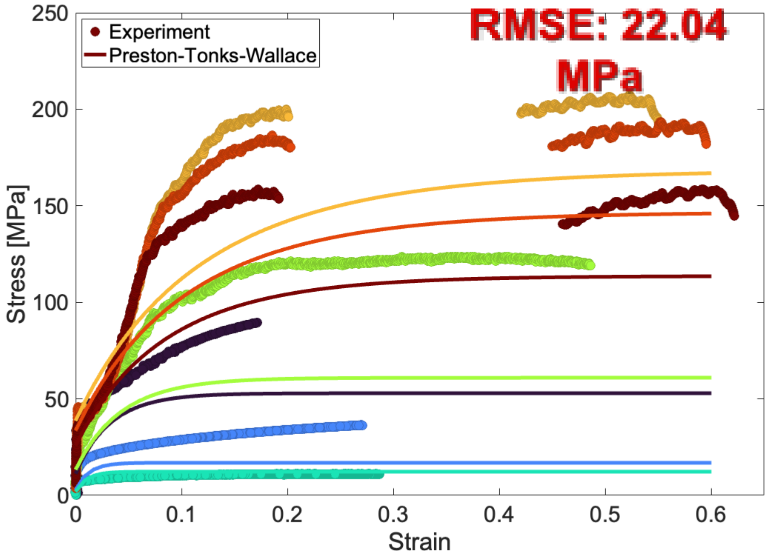
Johnson-Cook (JC): 5 parameters

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



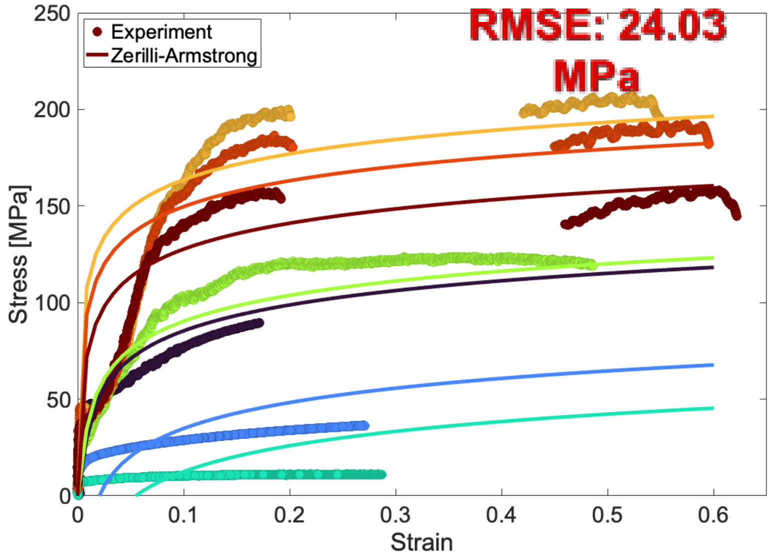
Preston-Tonks-Wallace (PTW): 12 parameters

$$\sigma = 2\mu\left[\hat{\tau}_s + \frac{1}{p}(s_0 - \hat{\tau}_y)\ln\left[1 - \left(1 - \exp\left(-p\frac{\hat{\tau}_s - \hat{\tau}_y}{s_0 - \hat{\tau}_y}\right)\right)\exp\left(-\frac{p\theta\psi}{(s_0 - \hat{\tau}_y)\left[\exp\left[p\left(\frac{\hat{\tau}_s - \hat{\tau}_y}{s_0 - \hat{\tau}_y}\right)\right] - 1\right]}\right)\right]\right]$$

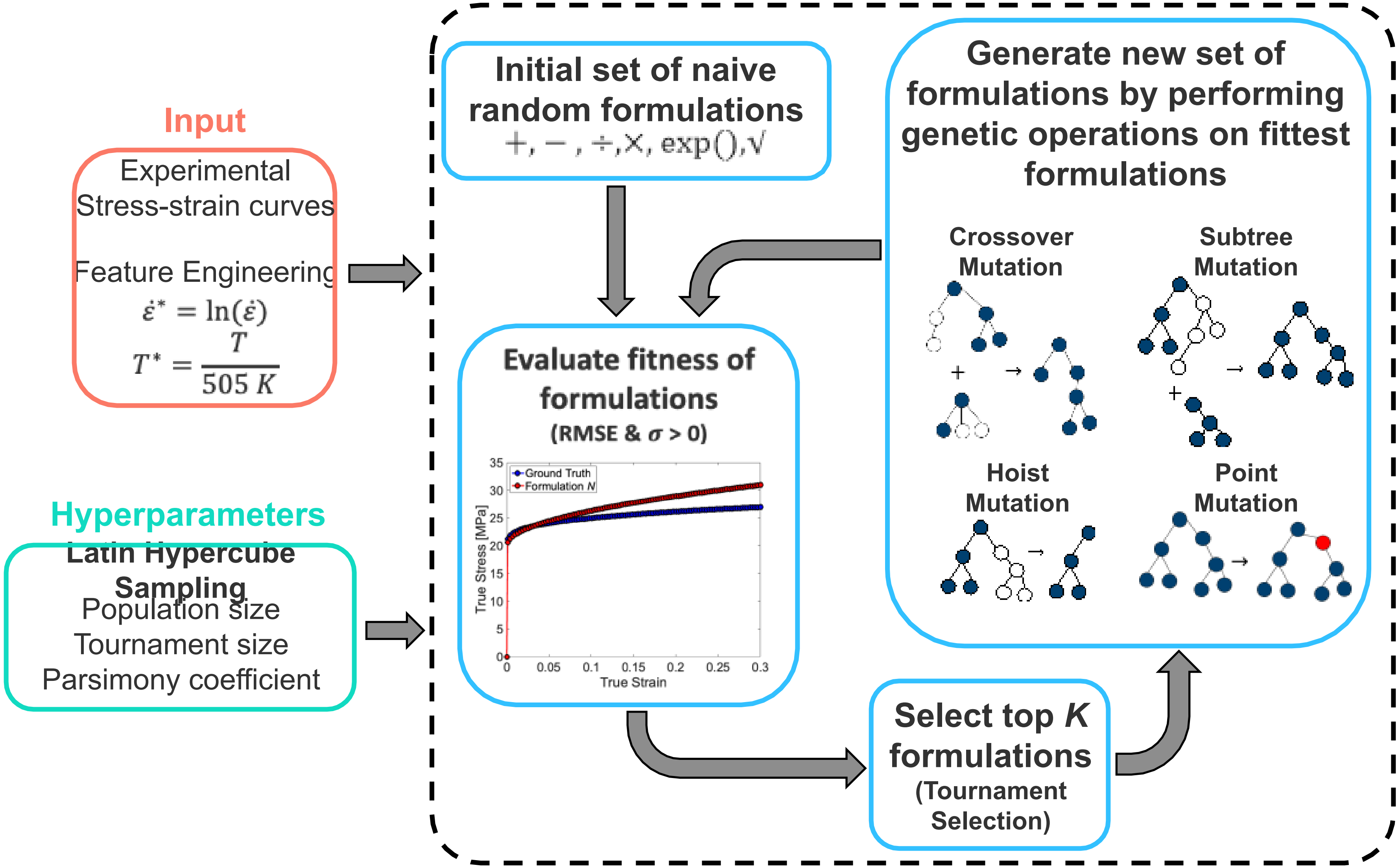


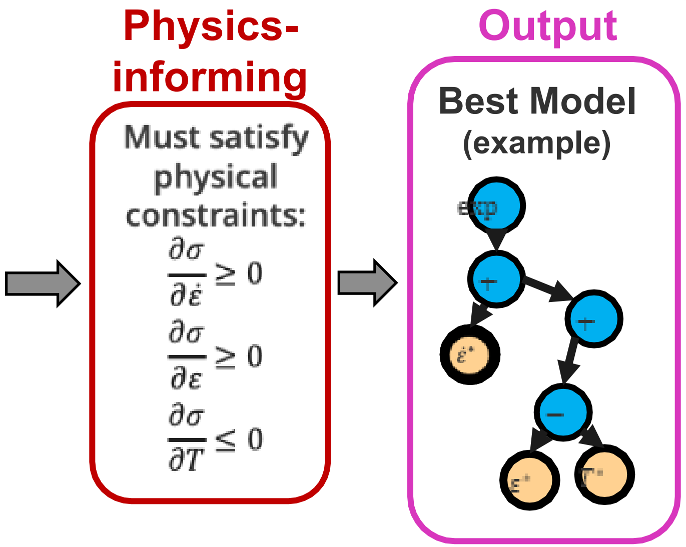
Zerilli-Armstrong (ZA): 6 parameters

$$\sigma = C_0 + C_1\exp(-C_3 T + C_4 T\ln\dot{\varepsilon}) + C_5\varepsilon^{n'}$$



Physics-informed genetic programming (GP) model





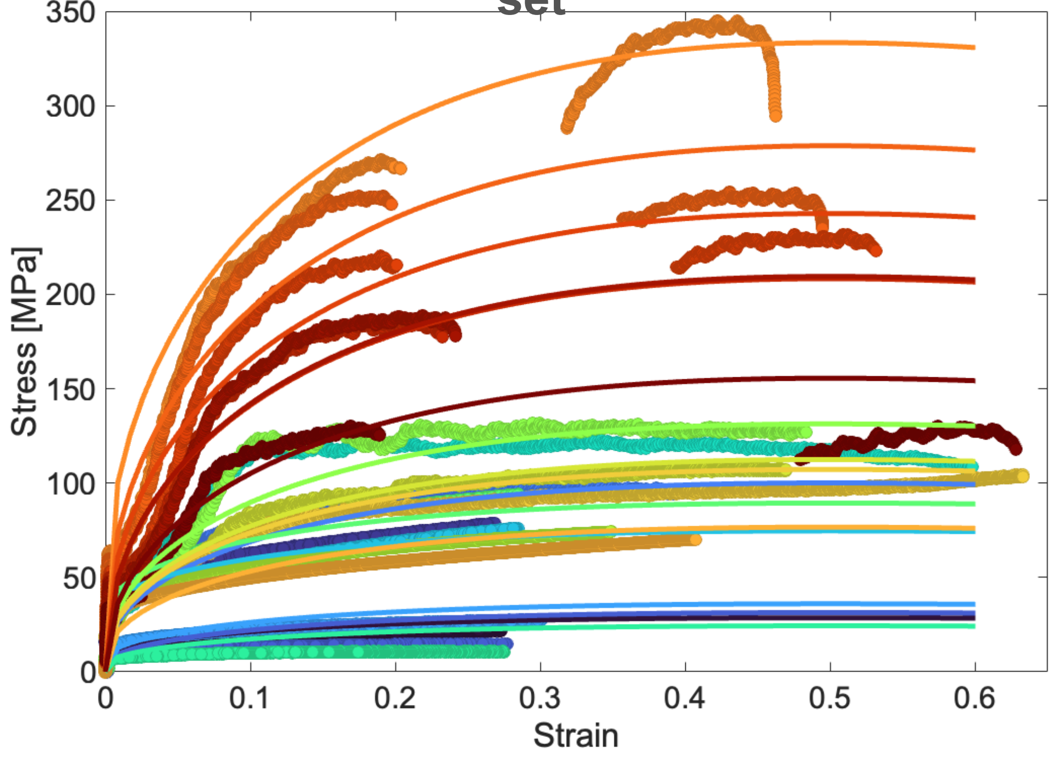
- Best model had:
  - RMSE < 13 MPa
  - Smallest change in RMSE between training & test sets

D. Montes de Oca Zapiain et al., Comp. Mat. Sci. (2022)

Physics-informed GP strength model

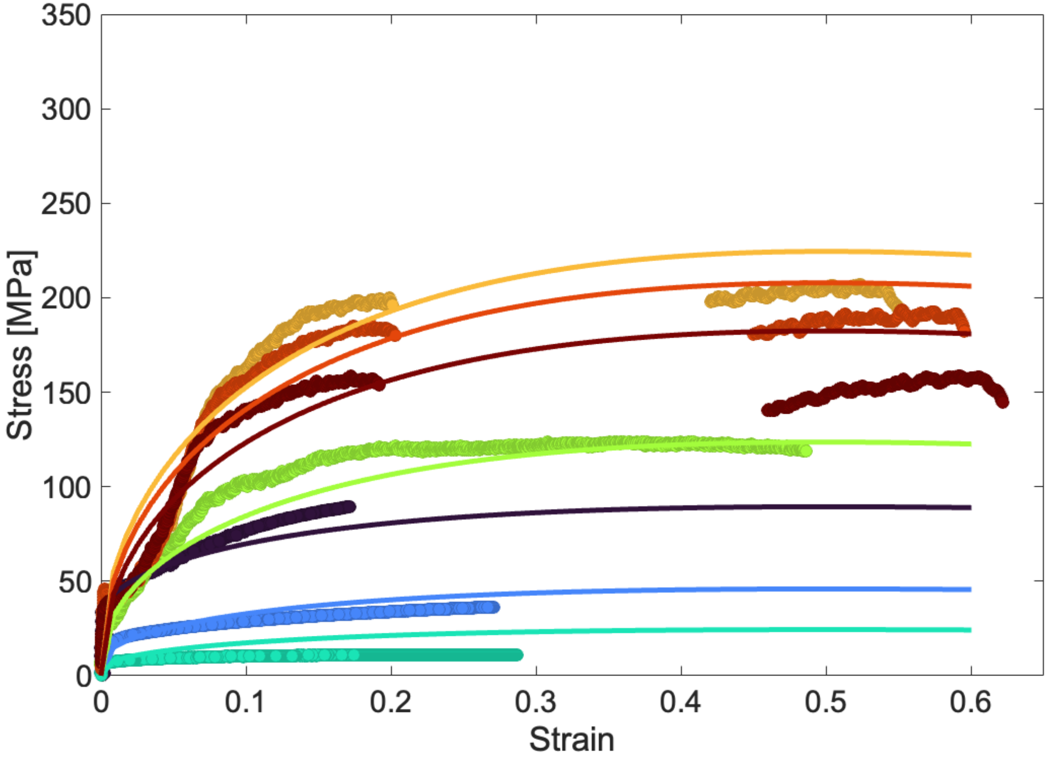
$$\sigma = \frac{\exp\left(-\varepsilon - \frac{\dot{\varepsilon}^*}{C_1}\right)\left(-C_2 - \frac{\exp\left(\frac{\dot{\varepsilon}^*}{-C_3 T^*}\right)}{T^*}\right)\sqrt{C_4 \varepsilon}}{T^*}$$

Training set



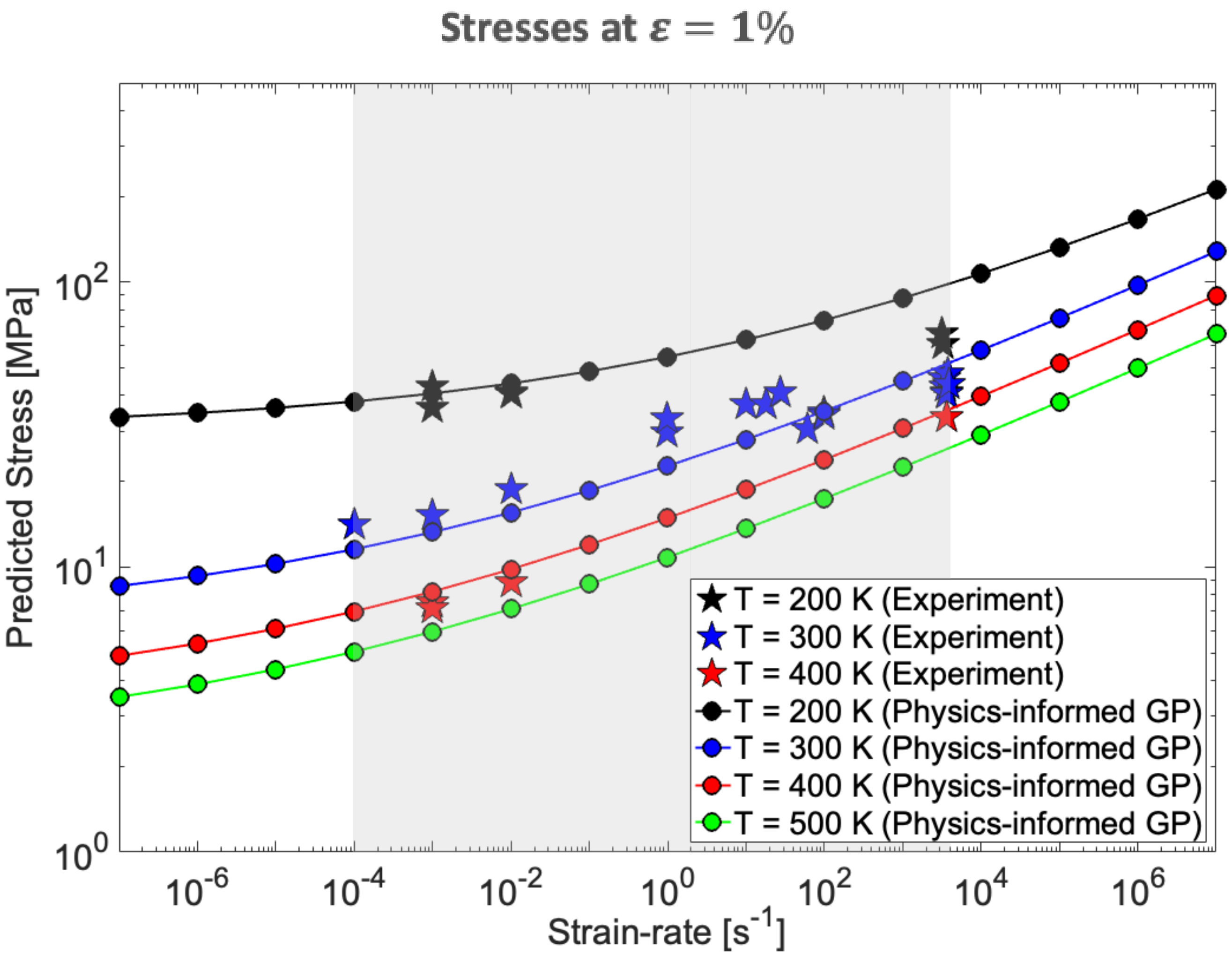
RMSE: 12.16 MPa

Test set



RMSE: 12.64 MPa

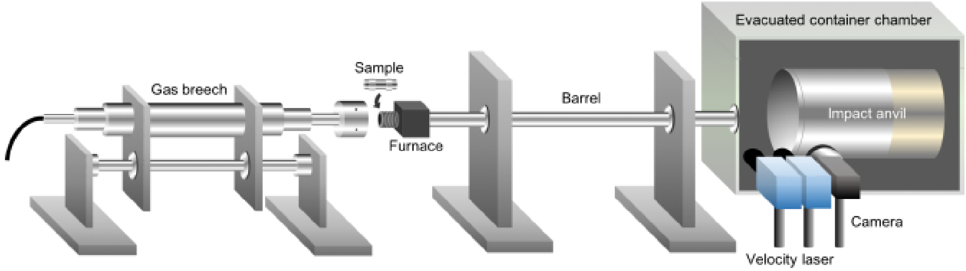
Benefits of the physics-informed GP strength model

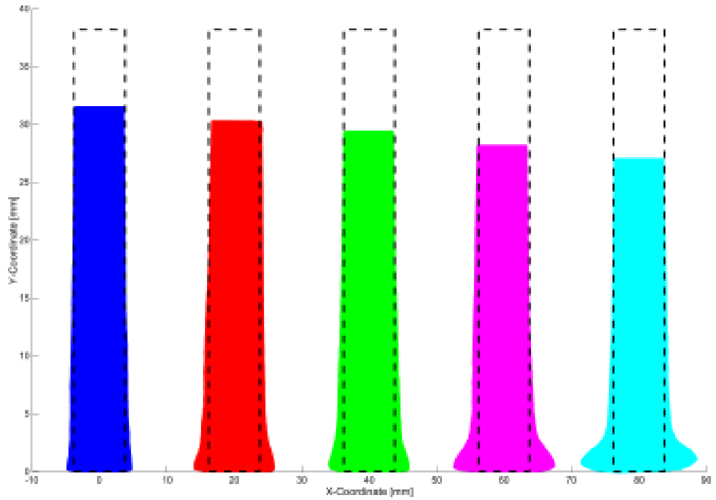


- Analytical model allows for extrapolation and easy implementation into finite element codes

Taylor impact test

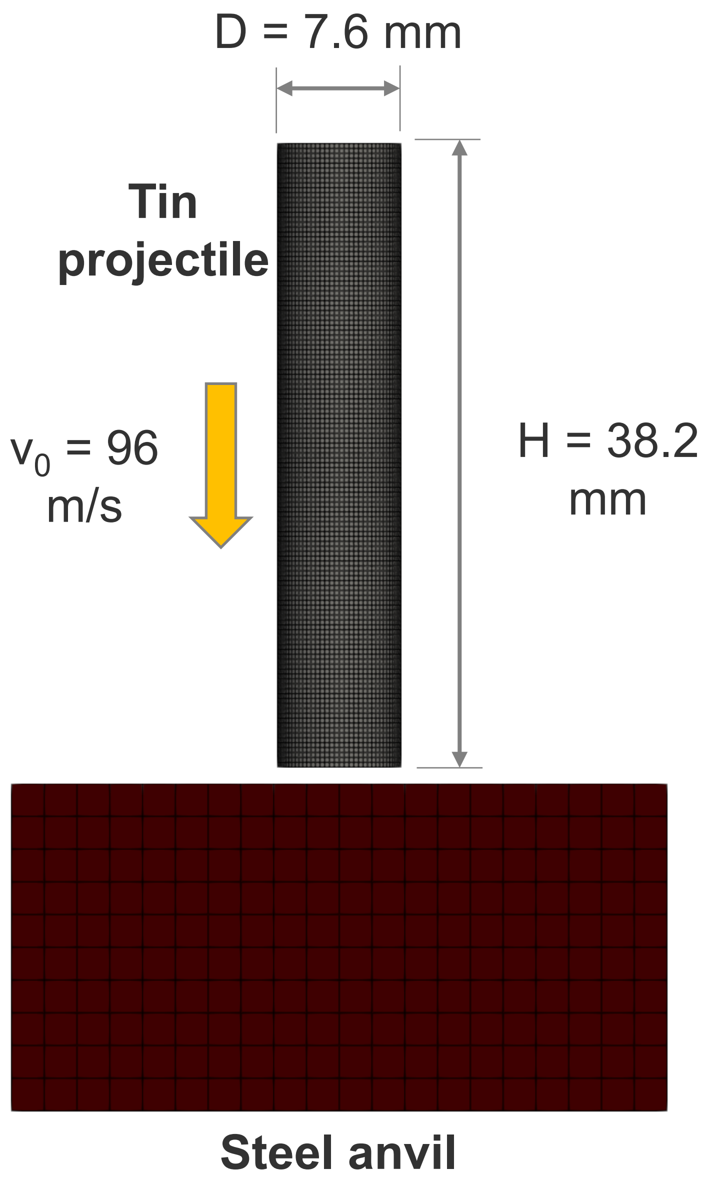
- Simple and robust technique to study dynamic behaviors
  - Strain-rates: $10^{-4} \sim 10^{4}\ s^{-1}$
- Experiments done at Los Alamos
  - Impact velocity: $96 \sim 141\ m/s$





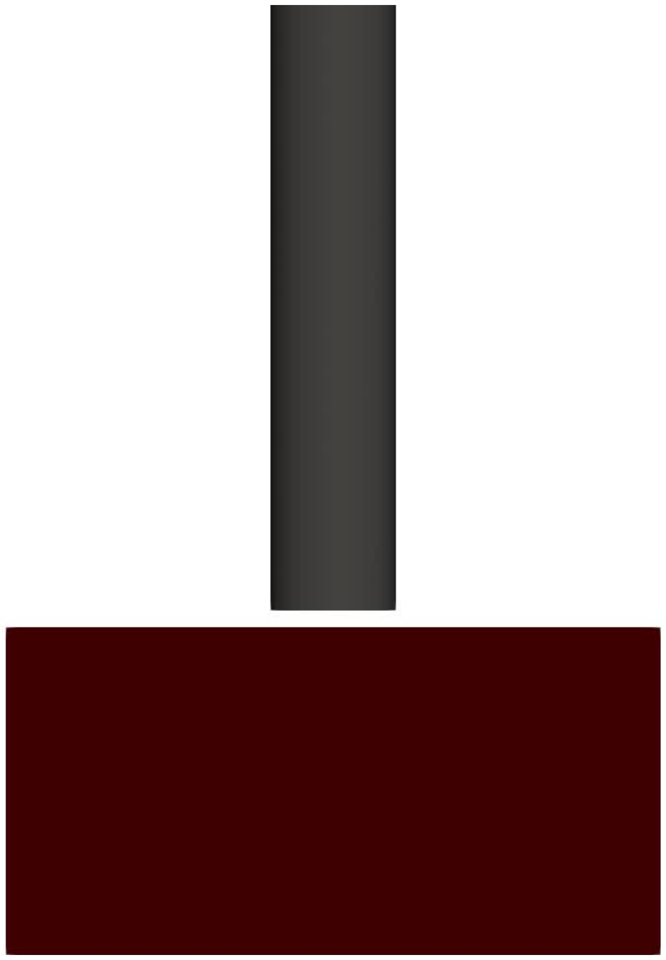
H. Lim et al., Sci. Rep. (2019), T. Nguyen et al., J. Appl. Phys.

Modeling the Taylor impact test

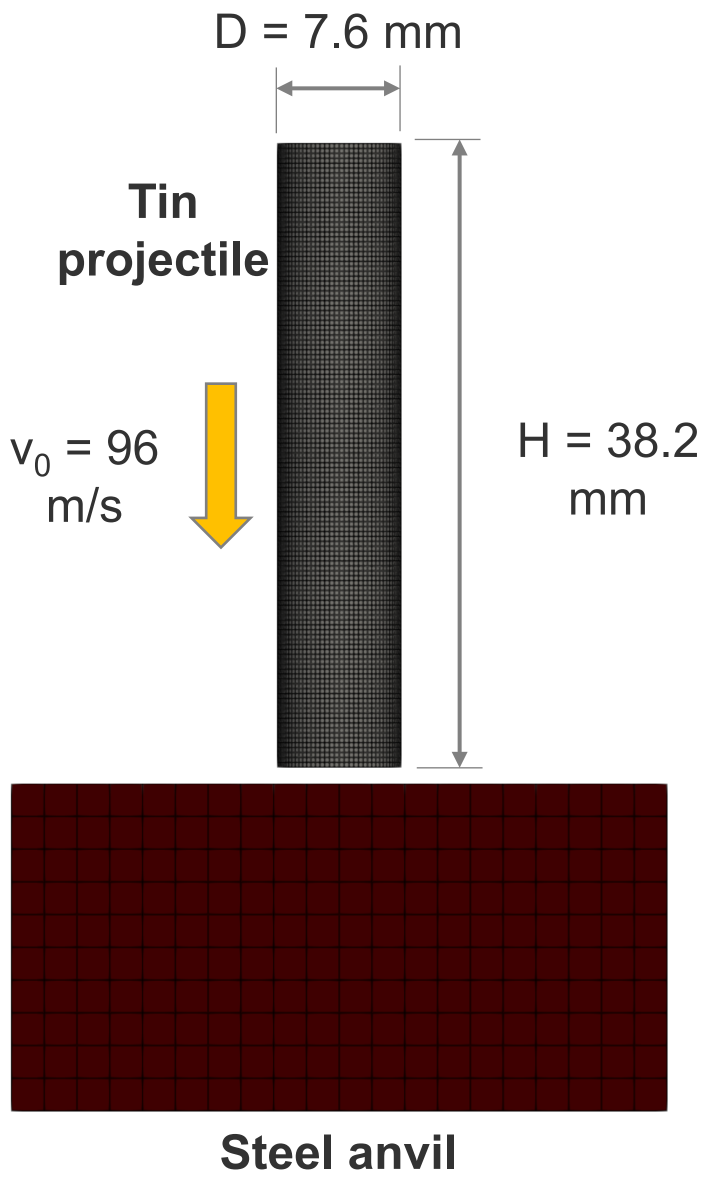


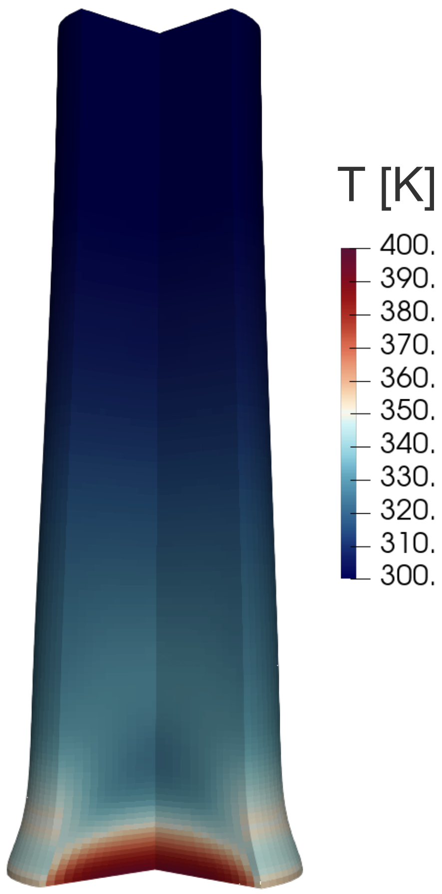
- Implemented within Sandia's multiphysics code (***ALEGRA***)
- Material definition:
  - Equation of State:
    - Sesame 2101
  - Yield model:
    - Physics-informed GP
    - Johnson-Cook
    - Zerilli-Armstrong
    - Preston-Tonks-Wallace

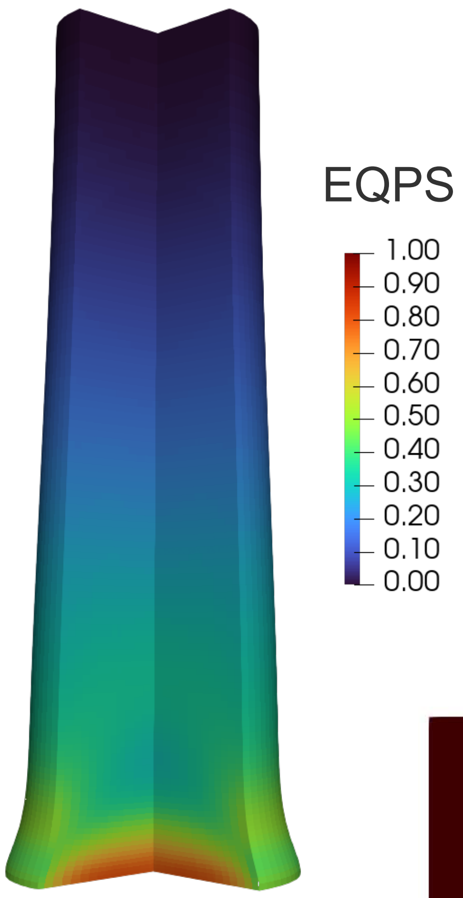
Physics-informed GP

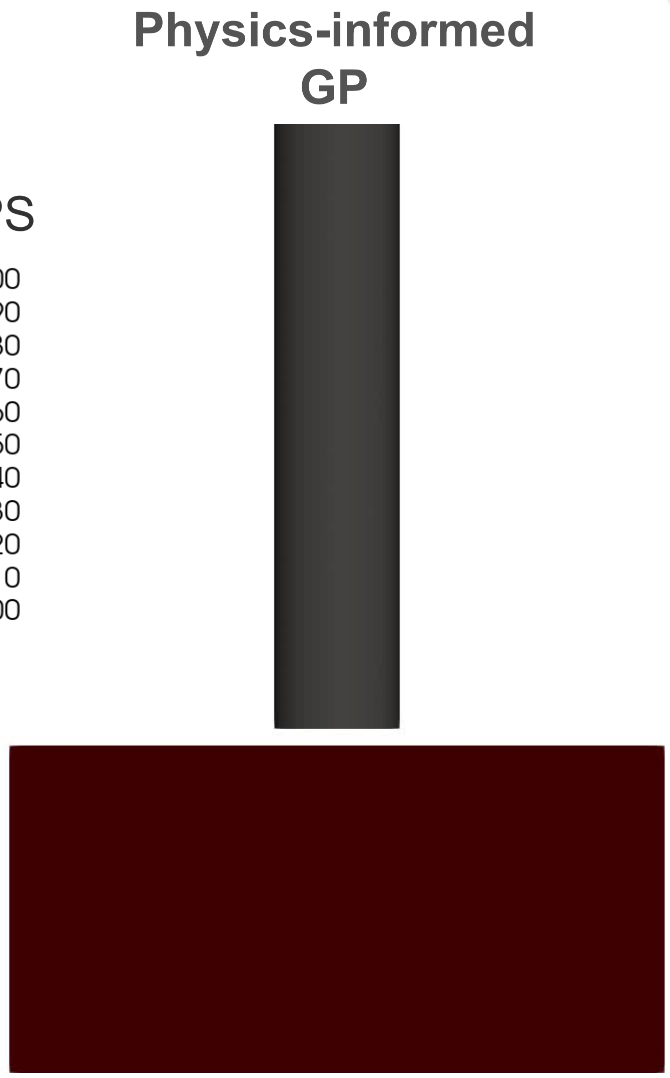


Modeling the Taylor impact test

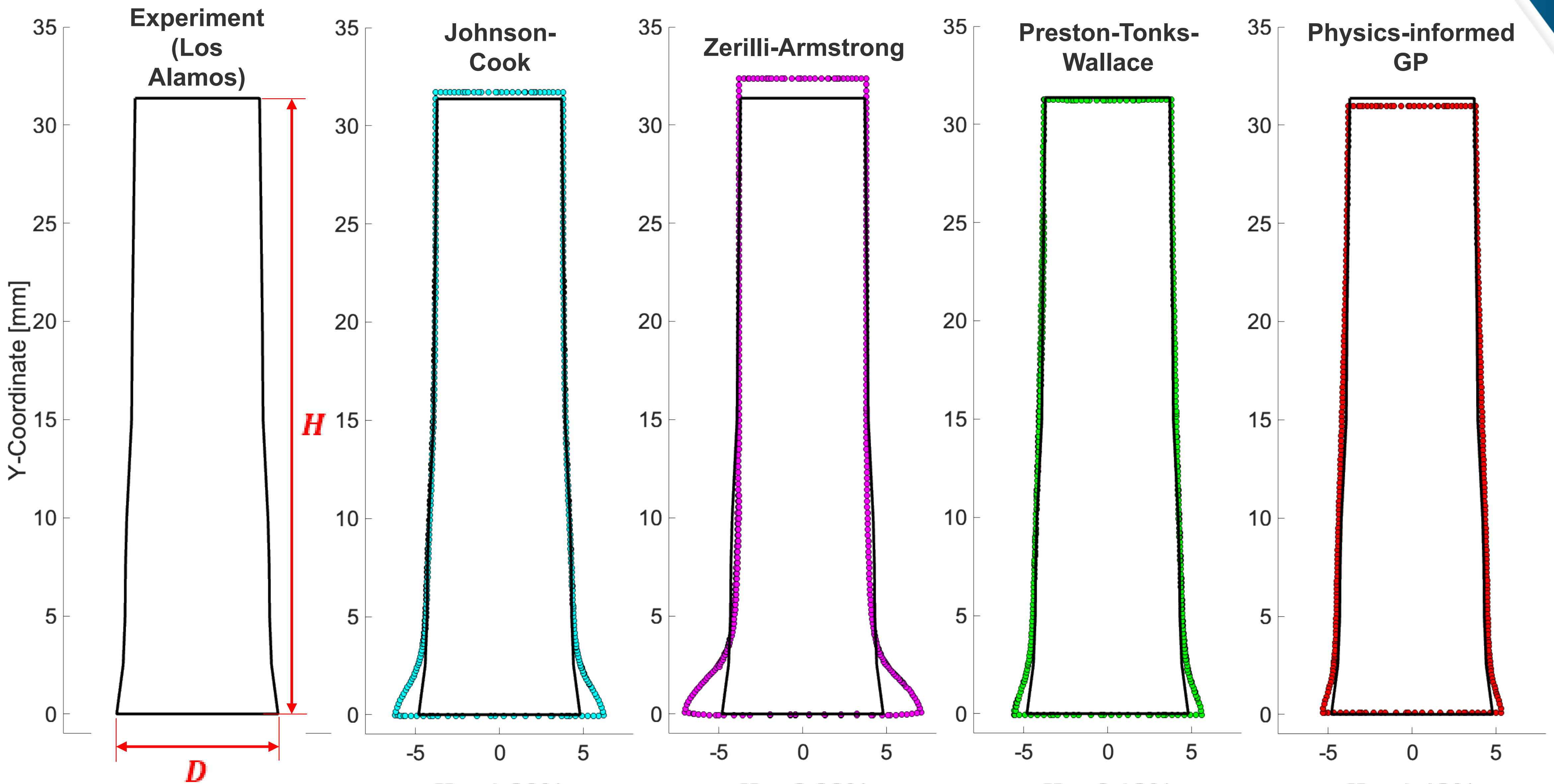








Quantitative comparison with experiment and traditional models

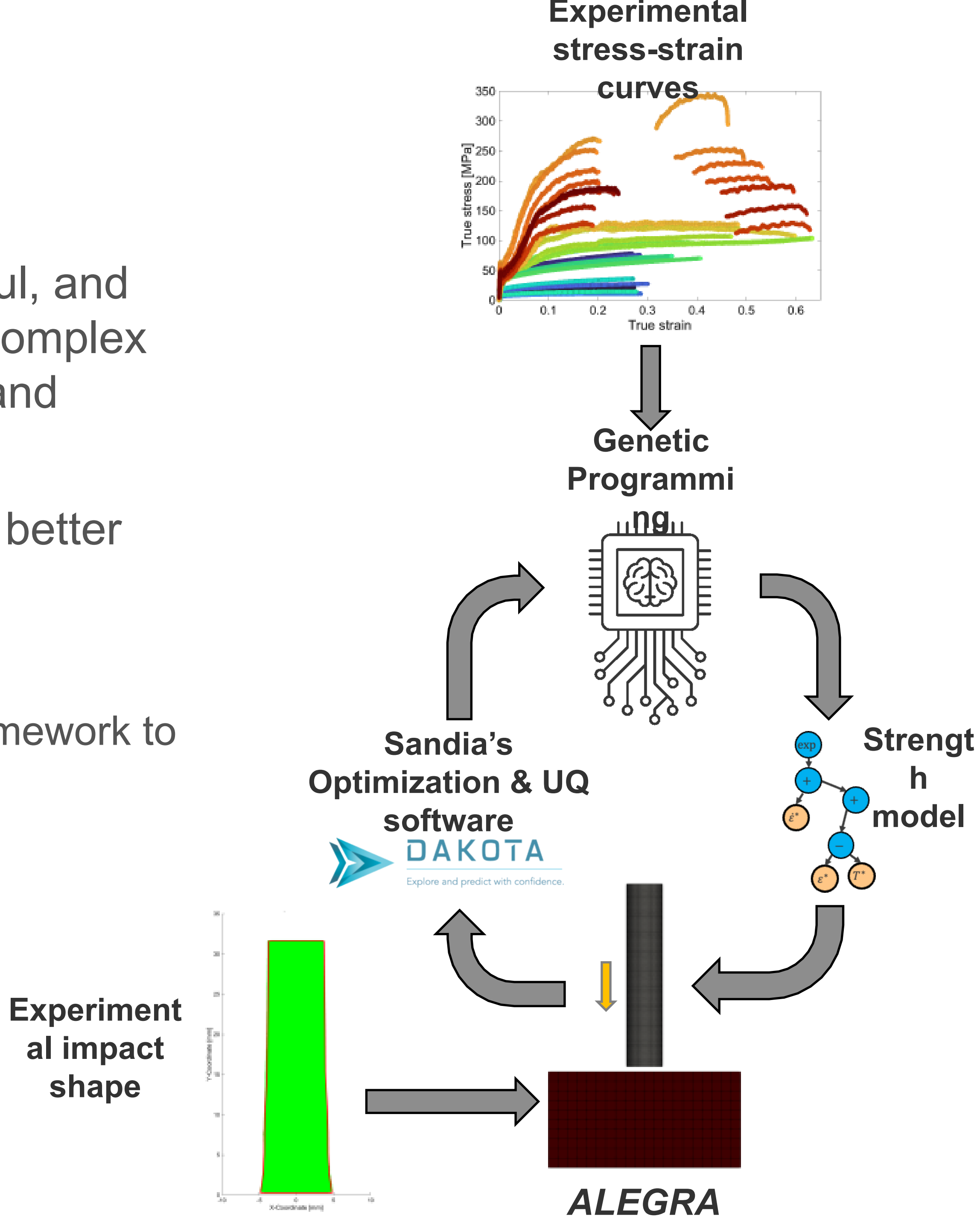


Percent Error:

Johnson-Cook	Zerilli-Armstrong	Preston-Tonks-Wallace	Physics-informed GP
$H \sim 1.20\%$	$H \sim 3.33\%$	$H \sim 0.19\%$	$H \sim 1.49\%$
$D \sim 28.95\%$	$D \sim 46.78\%$	$D \sim 16.10\%$	$D \sim 10.60\%$

Conclusions

- Genetic programming (GP) is a novel, useful, and easy way to generate strength models for complex materials at a wide range of temperatures and strain-rates
- Developed strength model conforms to data better than traditional strength models
- Future work
  - Incorporate Taylor impact results into the framework to improve proposed strength models



THANK YOU!

Genetic programming without physical constraints