INL/CON-22-66791-Revision-0

Dimensionless parameters to categorize the failure modes of ductile plate perforation

May 2022

Changing the World's Energy Future

Zherui Guo

INL/CON-22-66791-Revision-0

Dimensionless parameters to categorize the failure modes of ductile plate perforation

Zherui Guo

May 2022

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

May 12th, 2022

Zherui Guo
Postdoctoral Associate
Idaho National Laboratory

32nd International Symposium on Ballistics

Dimensionless parameters to categorize the failure modes of target plate perforation

Introduction
Objectives

First order approximations for critical velocities of plate perforation

↓

Non-dimensionalization – independent of relative length scales

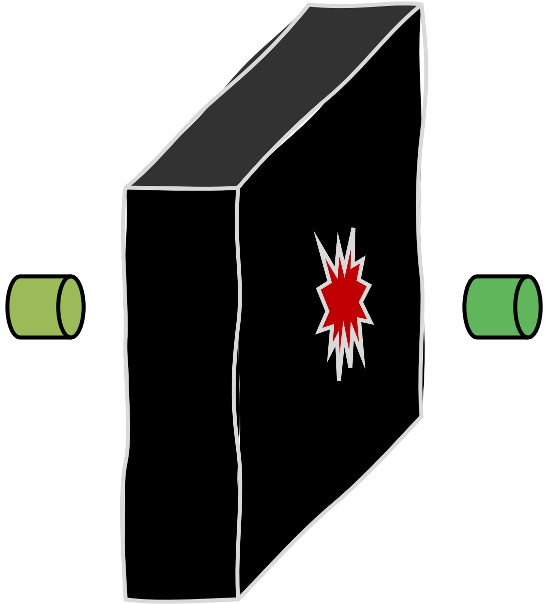
↓

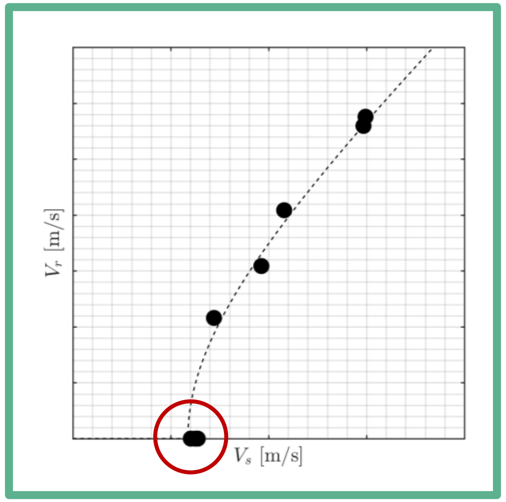
Rapid deployment of target systems

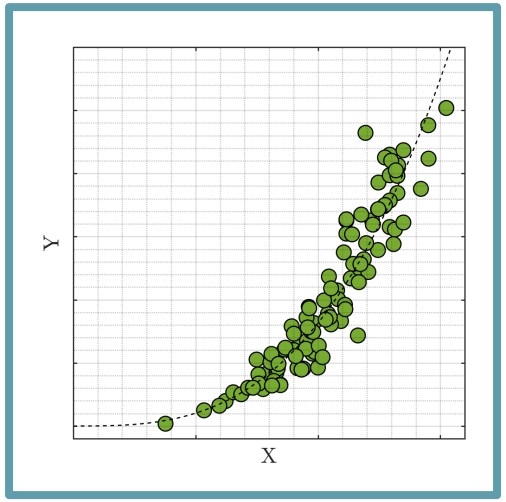
Introduction

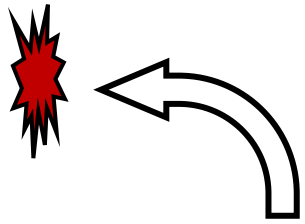
Ballistic perforation experiments

Record impact velocity V_s → Record exit velocity V_r → Calculate ballistic limit V_{bl} → Relate V_{bl} to parameters → Derive equations for V_{bl}









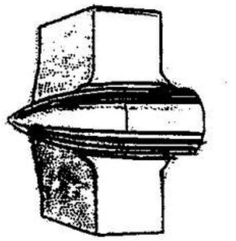
Usually need a priori information as to what happened here

Introduction

Cylindrical cavity expansion model for AP rounds

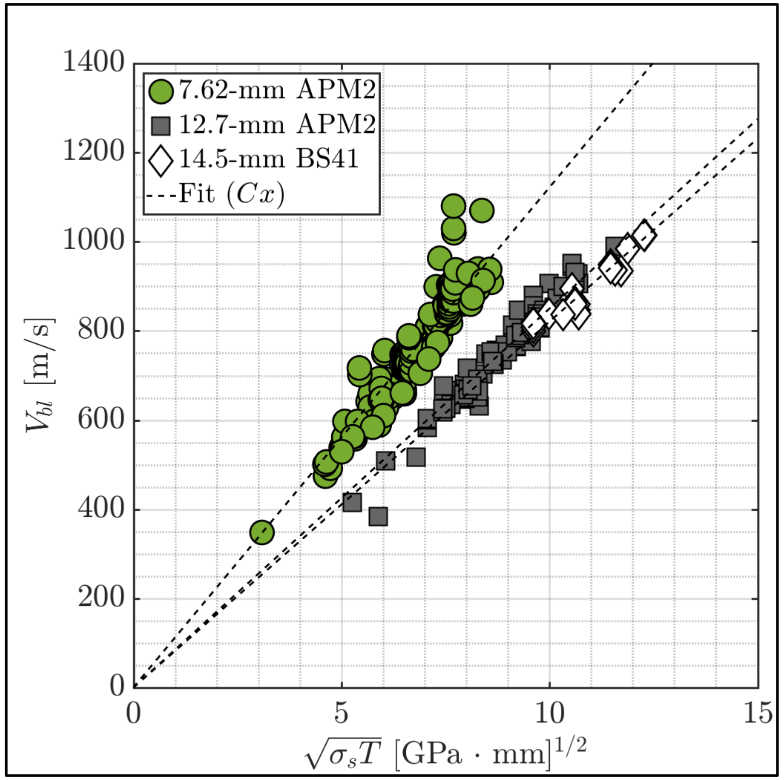
- AP perforation modeled using Forrestal cavity expansion (Ryan et al., 2018)

$$V_{bl} = \sqrt{\frac{2}{\rho_p(L + k_1 L_n)}} \cdot \sqrt{\sigma_s T} = K\sqrt{\sigma_s T}$$



Ductile Hole Growth

V_{bl}	target ballistic limit
ρ_p	projectile density
L	projectile shank length
L_n	projectile nose length
k_1	projectile nose shape factor
T	target thickness
$\boldsymbol{\sigma_s}$	**cavity expansion strength**



★ Requires coefficient ***K*** for each caliber

Image from Chinella et al. (1998)

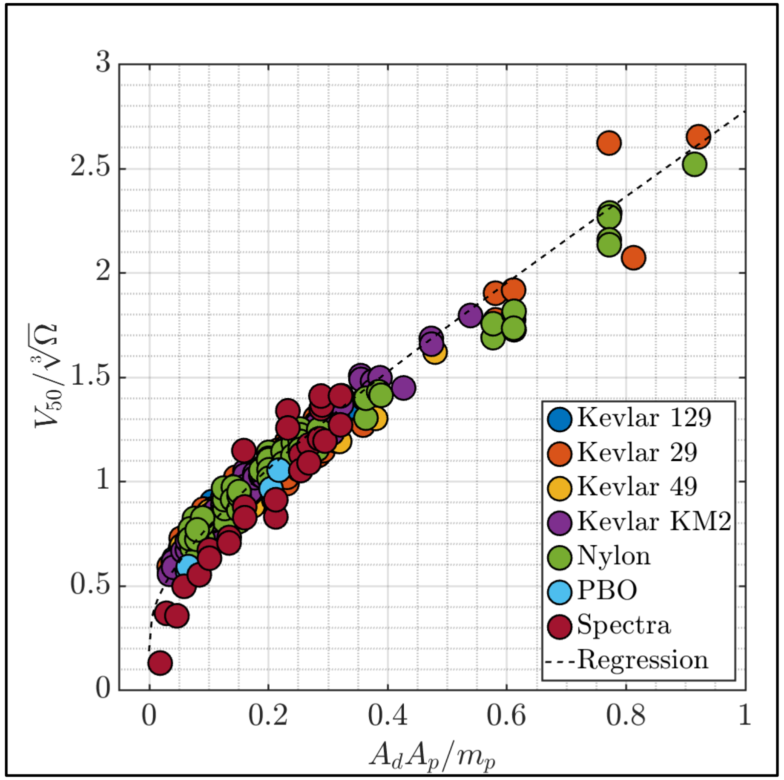
Introduction

Cunniff parameter for soft armor targets

- Woven textiles, composites impacted by various projectile geometries and masses

$$\frac{V_{bl}}{\sqrt[3]{\Omega}} = f\left(\frac{A_d A_p}{m_p}\right), \qquad \Omega = \frac{\sigma_f \varepsilon_f}{2\rho} \cdot c_0$$

A_d	target areal density
A_p	projectile presented area
σ_f, ε_f	fiber failure stress, strain
c_0	fiber axial wavespeed
$\sqrt[3]{\Omega}$	Cunniff parameter

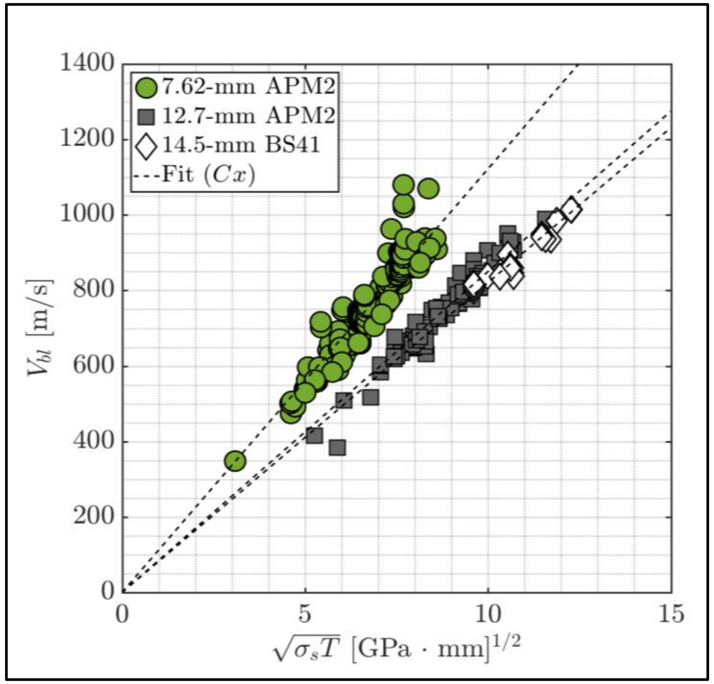


★ Predictive capability for several polymer fibers that fail in tension

Image from Chinella et al. (1998)

Introduction

Deriving dimensionless parameters for AP rounds



Empirical coefficient *K* for each caliber

- Derivation already includes non-dimensional params. (Guo, 2021)

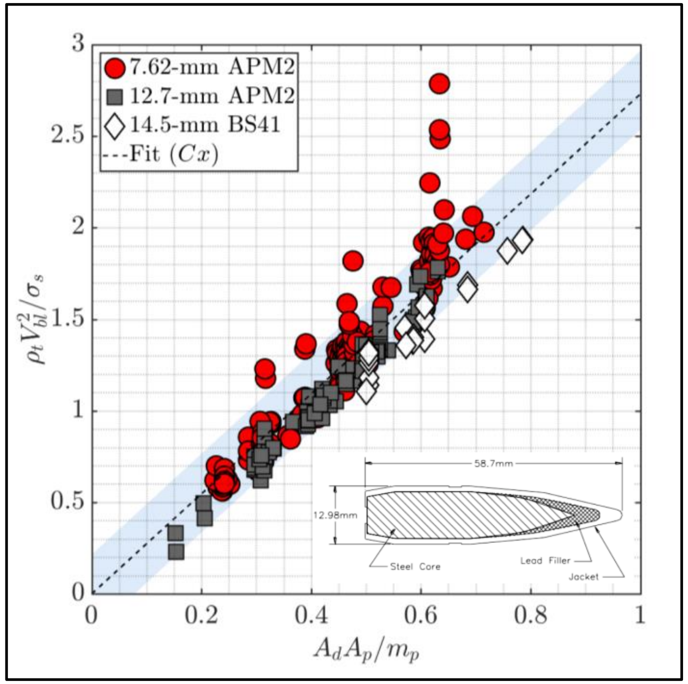
$$V_{bl} = \sqrt{\frac{2}{\rho_p(L + k_1 L_n)}} \cdot \sqrt{\sigma_s T}$$

$$\frac{m_p}{A_p} = \rho_p(L + k_1 l), \qquad \rho_t \cdot T = \frac{m_t}{A_t} = A_d$$

$$\frac{\rho_t V_{bl}^2}{\sigma_s} = f\left(\frac{A_d A_p}{m_p}\right)$$

(Inertia effects in full CCE model can be non-dimensionalized too)

$$\frac{\rho_t V_{bl}^2}{\sigma_s} = 2\frac{A_d A_p}{m_p}\left[1 + \left(\frac{A_d A_p}{m_p} B_0 N\right) + \frac{2}{3}\left(\frac{A_d A_p}{m_p} B_0 N\right)^2\right]$$



Data collapses along a linear curve independent of caliber

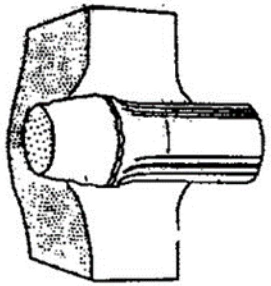
Introduction

Shear-plugging model for FSP rounds

- Modified Recht-Ipson shear plugging model (Guo & Forrestal, 2019)

$$\frac{V_{bl}}{\sqrt{\sigma_0/\rho_p}} = \left\{\frac{4}{\sqrt{3}}\left(\frac{L}{D}\right)\left(\frac{T}{L}\right)^2\left[1+\left(\frac{T}{L}\right)\left(\frac{\rho_t}{\rho_p}\right)\right]\right\}^{1/2}$$

V_{bl}	target ballistic limit
ρ_p	projectile density
ρ_t	target density
L	projectile length
T	target thickness
$\boldsymbol{\sigma_0}$	**target compressive strength**



Plugging

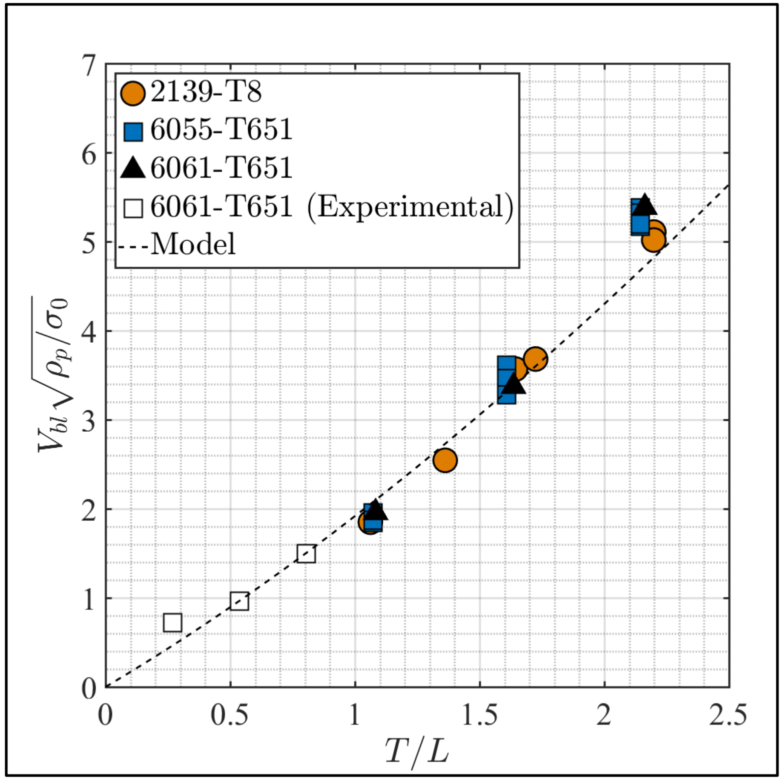


Image from Chinella et al. (1998)

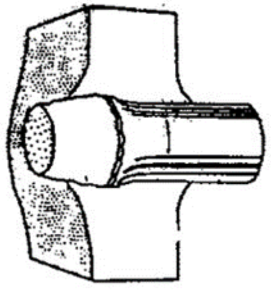
Introduction

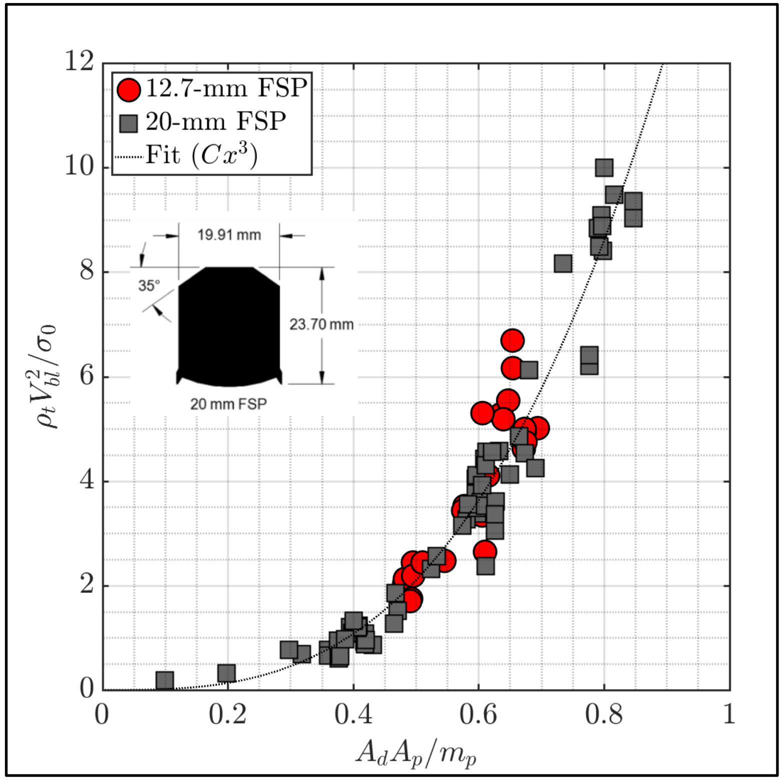
Deriving dimensionless parameters for FSPs

- Can express in the similar functional form as cavity expansion equation (compressive strength σ_0 in LHS term)

$$\frac{\rho_t V_{bl}^2}{\sigma_0} = \frac{4}{\sqrt{3}}\left(\frac{L}{D}\right)\left(\frac{\rho_p}{\rho_t}\right)\left(\frac{A_d A_p}{m_p}\right)^2\left[1+\frac{A_d A_p}{m_p}\right]$$

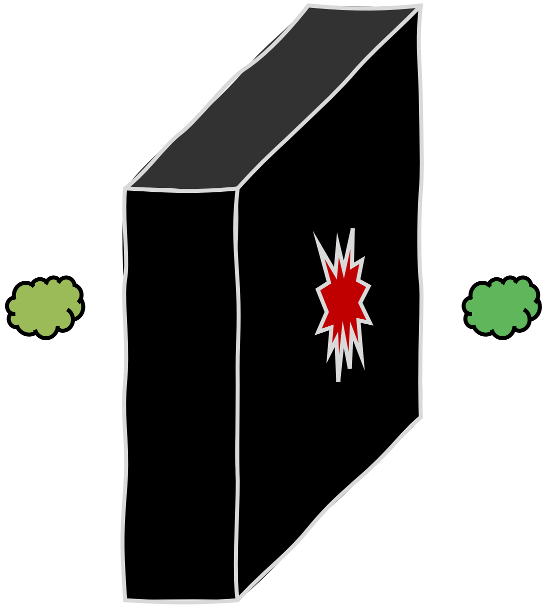
$$\boxed{\frac{\rho_t V_{bl}^2}{\sigma_0} = f\left(\frac{A_d A_p}{m_p}\right)}$$


Plugging

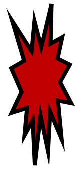


Homologous scaling

Ballistic perforation of a “black box” target



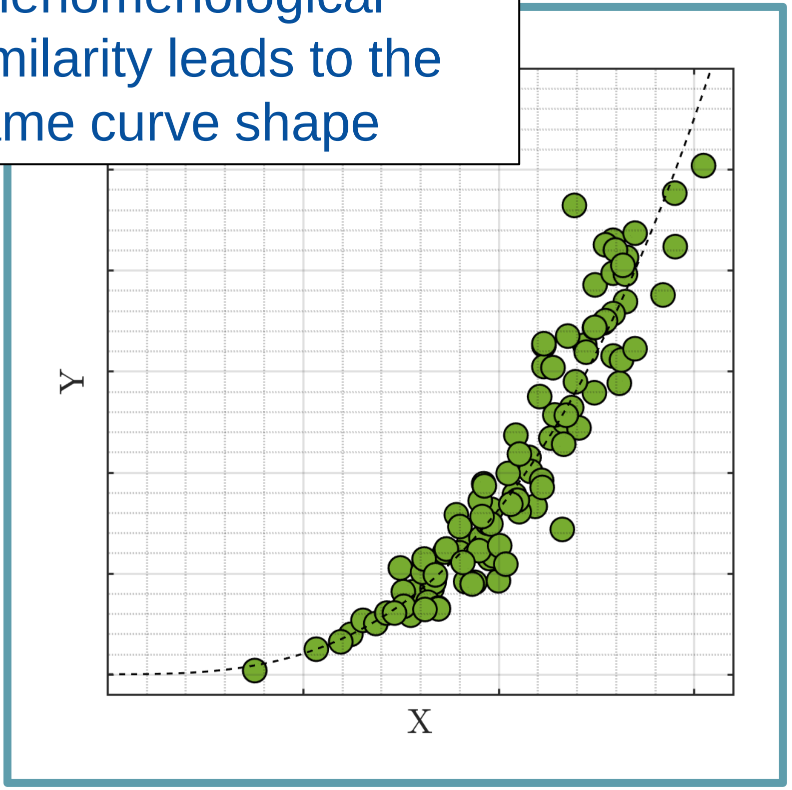
Some “black box” target plate



- Cavity expansion or shear plugging
- Projectile deformation
- Spallation
- Discing
- Delamination

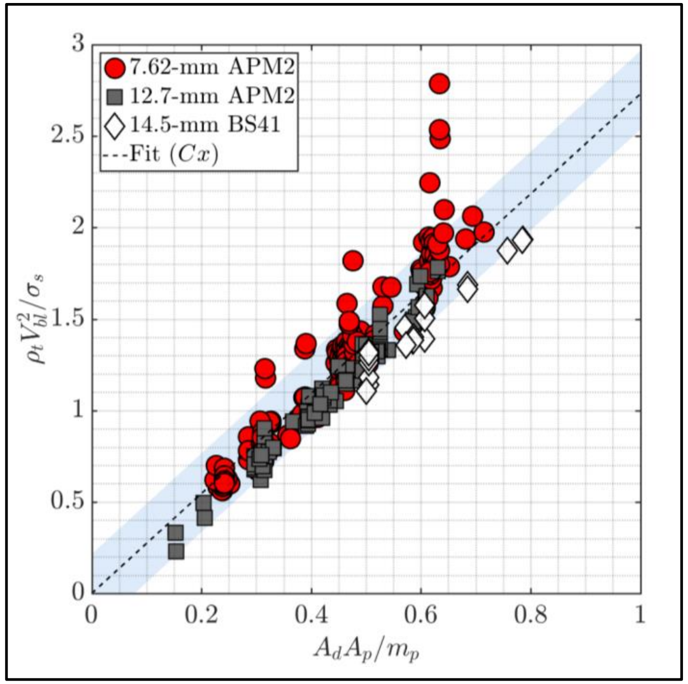
⋮

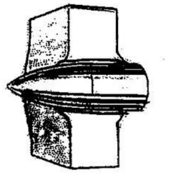
★ Phenomenological similarity leads to the same curve shape



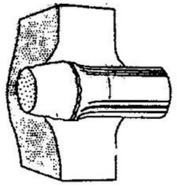
Homologous scaling

Characteristic target strength

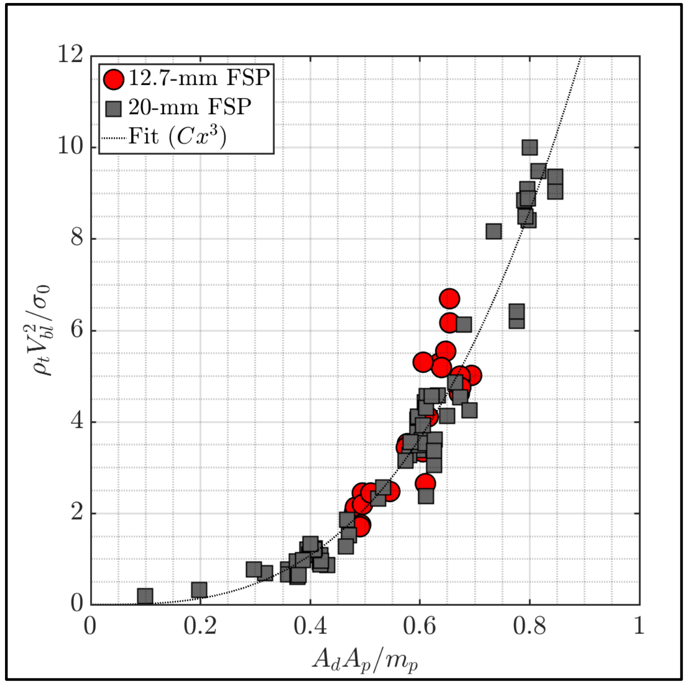




Ductile Hole Growth



Plugging



For each failure phenomenon, there is some associated characteristic strength

$$\frac{\rho_t V_{bl}^2}{\sigma_c} = f\left(\frac{A_d A_p}{m_p}\right)$$

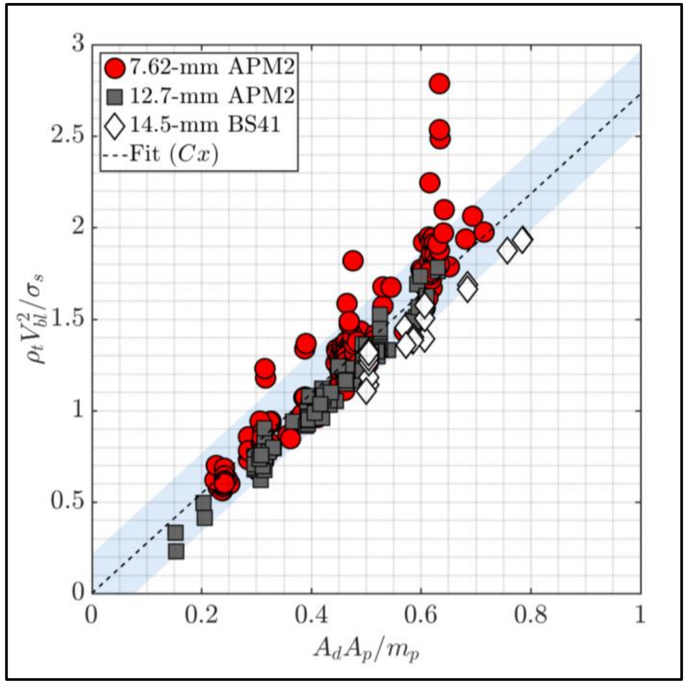
σ_c characteristic failure strength

$$\frac{\rho_t V_{bl}^2}{\sigma_s} = f\left(\frac{A_d A_p}{m_p}\right)$$

$$\frac{\rho_t V_{bl}^2}{\sigma_0} = f\left(\frac{A_d A_p}{m_p}\right)$$

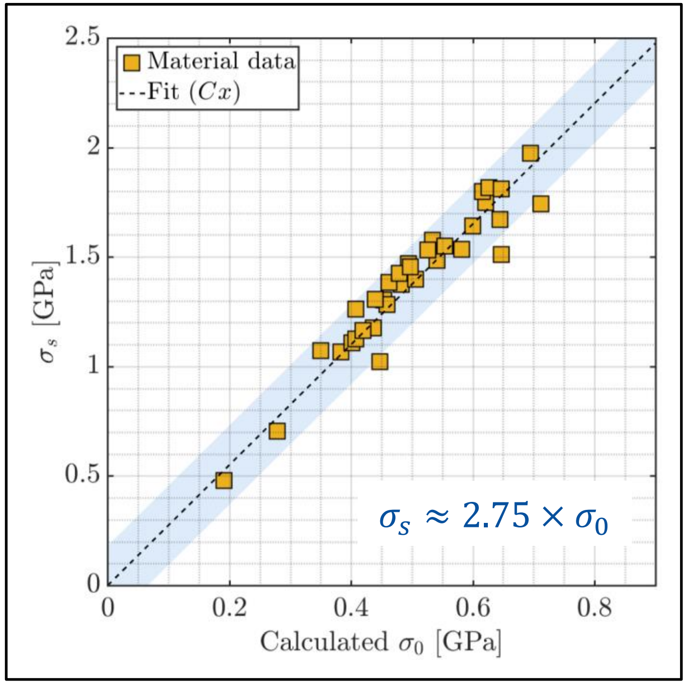
Homologous scaling

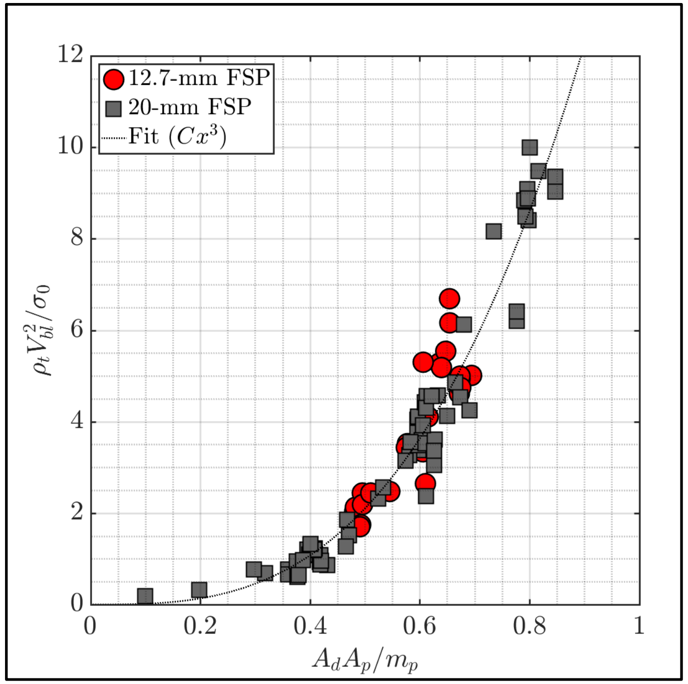
Relationship between strength parameters



$$\frac{\rho_t V_{bl}^2}{\sigma_s} = f\left(\frac{A_d A_p}{m_p}\right)$$

Cavity expansion strength and compressive strength strongly correlated (Guo, 2021)



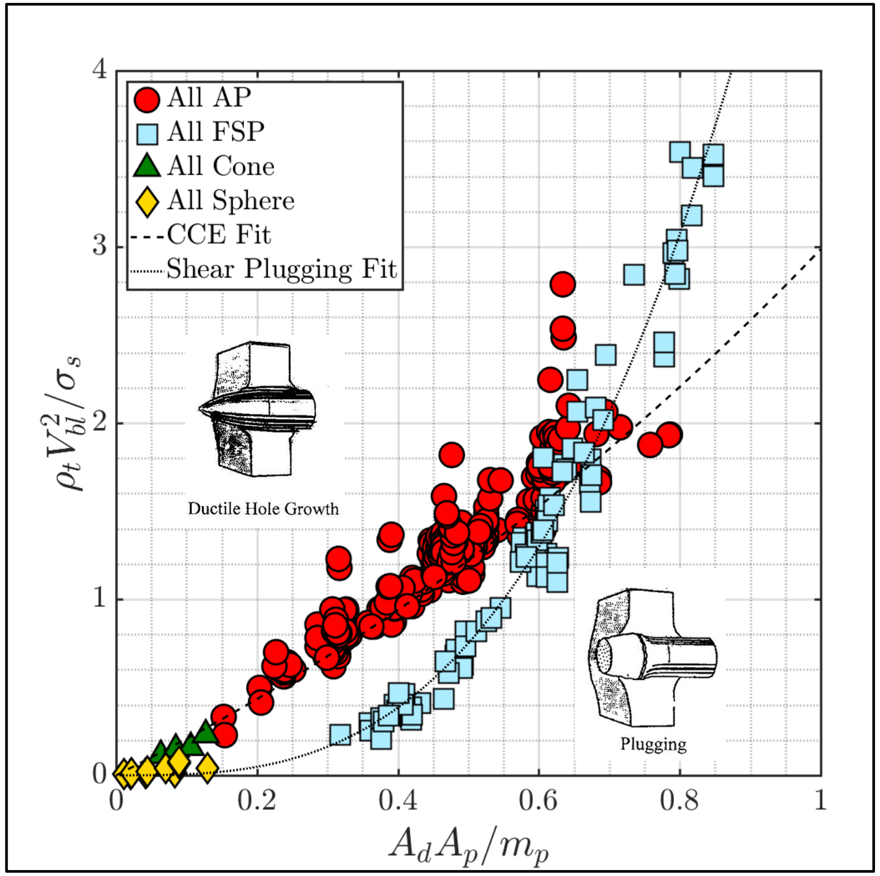


$$\frac{\rho_t V_{bl}^2}{\sigma_0} = f\left(\frac{A_d A_p}{m_p}\right)$$

Homologous scaling

Collapsed data for aluminum plates

- Loci construction for both failure modes
- Cones/conical-nosed rods impacting stacked Al alloy plates (Borvik et al.)
- Small spheres impacting thin Al plates

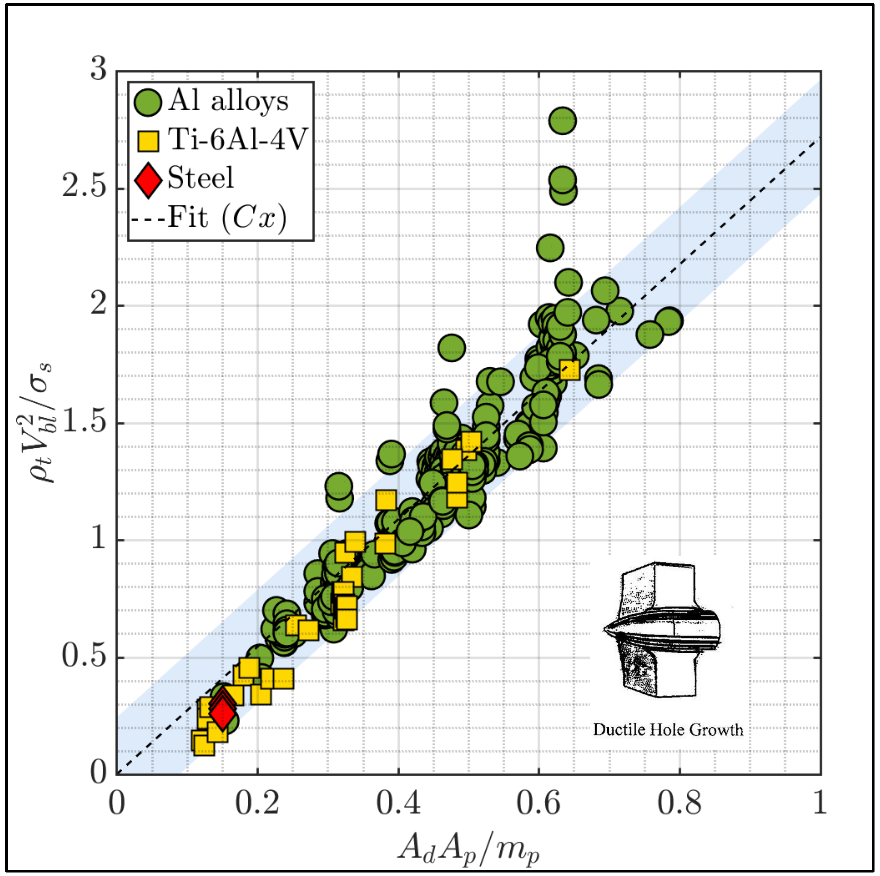


Homologous scaling

Collapsed data for ductile metal plates

- Weldox steel data for conical rods
- Wrought, cast, vacuum arc remelted (VAR) Ti-6Al-4V
- Failure modes for APM2 impact similar for α-β and β-processed plates (Gooch, 2009)

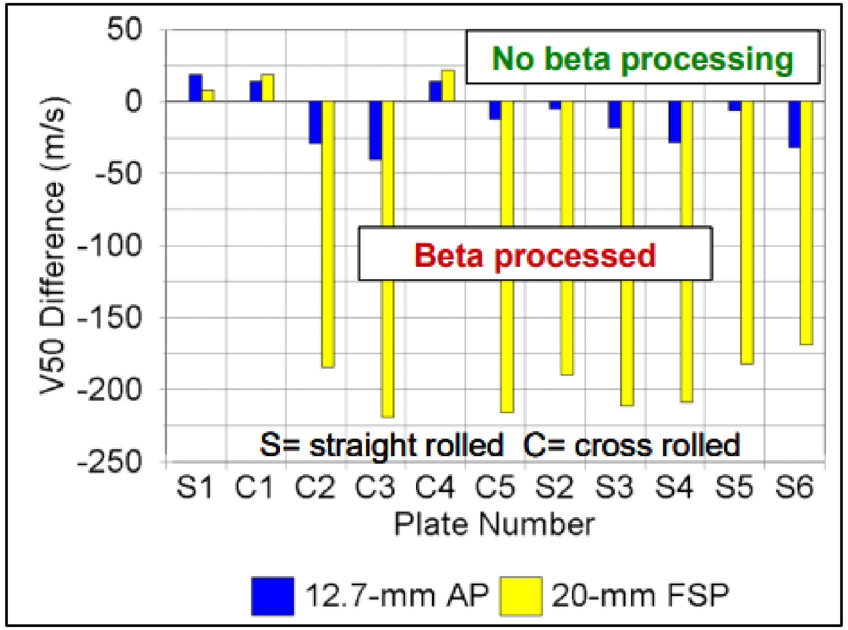
Problems arise when we apply same scaling to FSP impact of Ti-64 plate

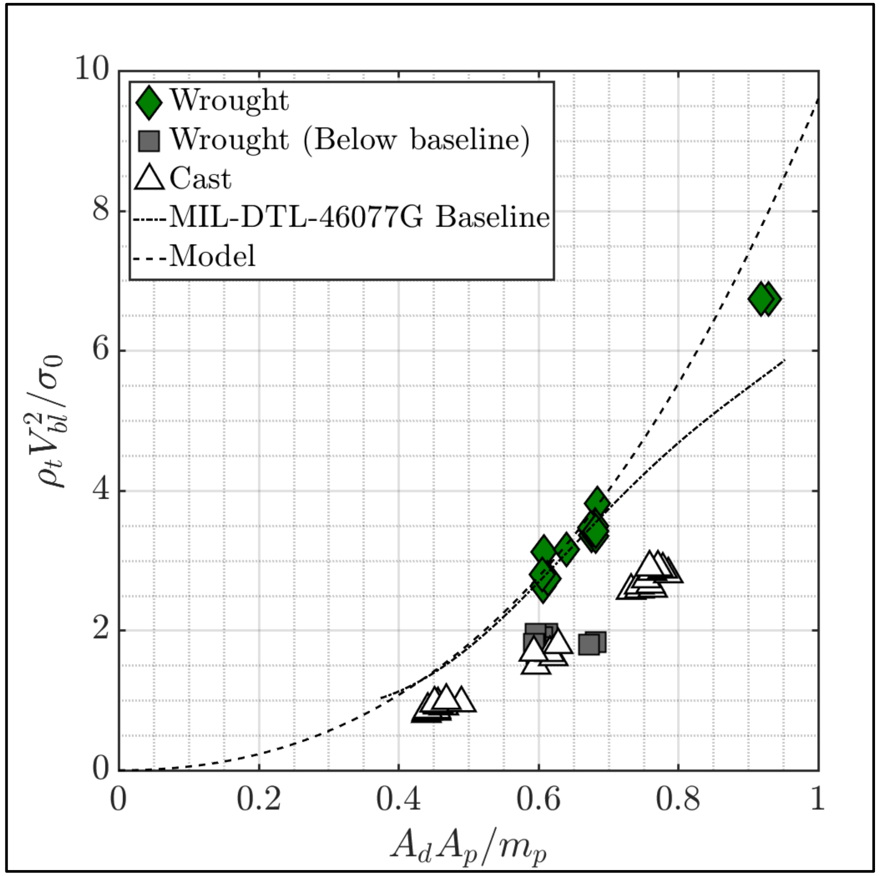


Homologous scaling

FSP ballistic performance on processed Ti-64 plates

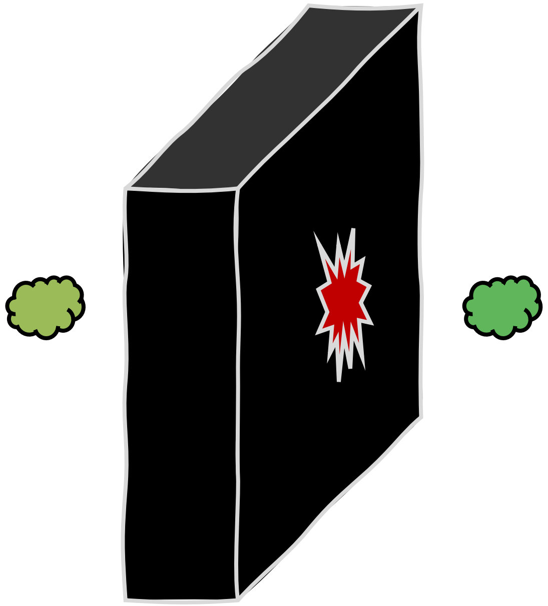
- Failure mode highly influenced by processing (Gooch, 2009)
  - β-processed: adiabatic shear banding
  - α-β processed: shearing, spalling, delamination etc. (multi-mode, multi-axial)



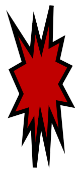


Homologous scaling

Phenomenological similarity

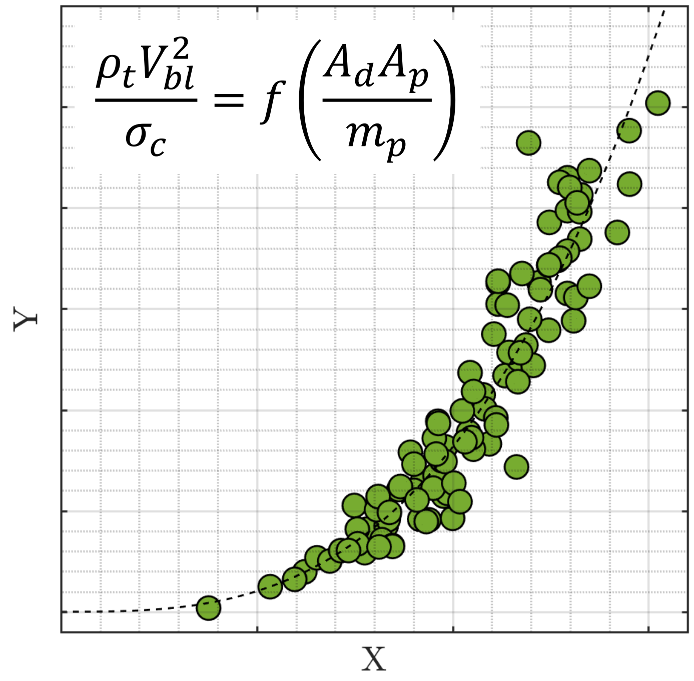


Some “black box” target plate



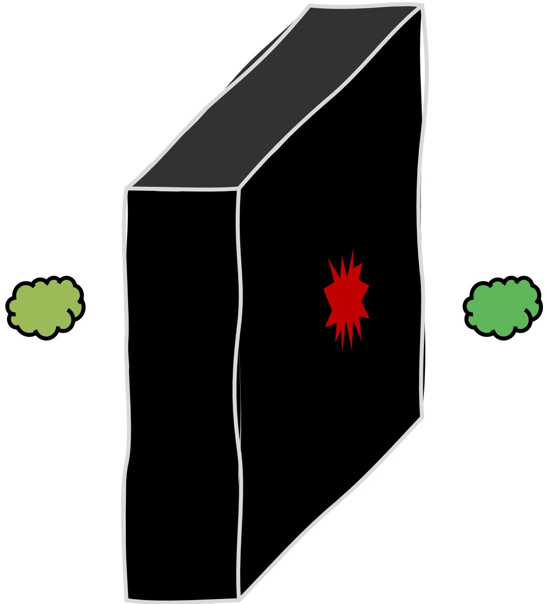
- Cavity expansion or shear plugging
- Projectile deformation
- Spallation
- Discing
- Delamination

⋮



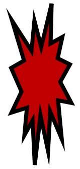
Homologous scaling

Known projectile, “black box” target response



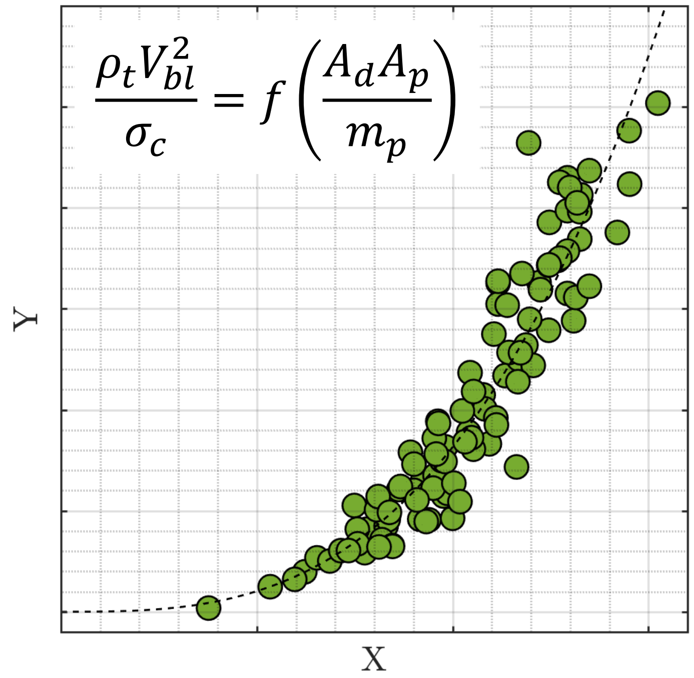
Some “black box” target plate

Ceramic-faced



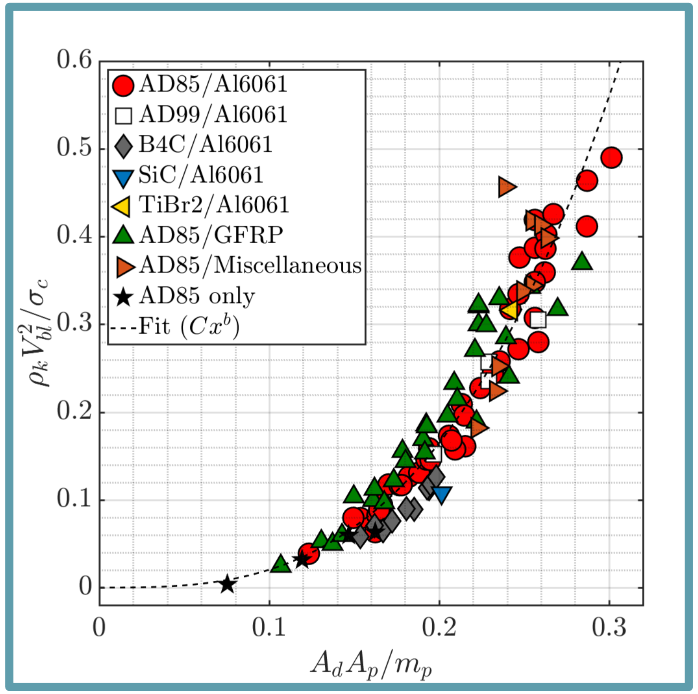
- Front failure mode
- Rear failure mode
- Projectile damage
- Fracture & fragmentation
- Interface interaction

⋮



Homologous scaling

Bicomponent systems

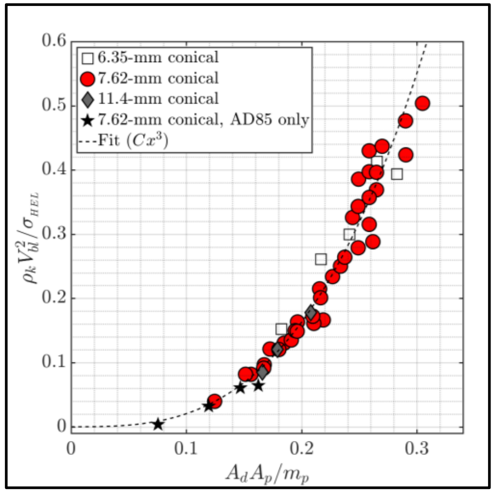


$$\frac{\rho_k V_{bl}^2}{\sigma_c} = f\left(\frac{A_{d,0}A_p}{m_p}\right)$$

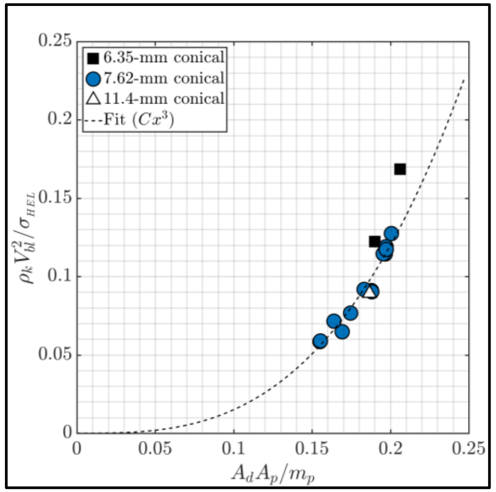
$$\sigma_c = \sigma_{HEL}$$

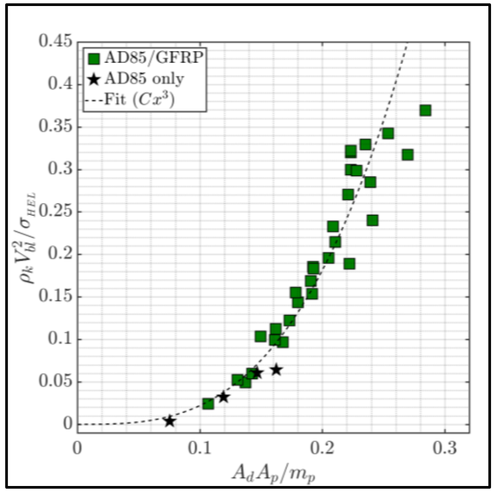
$$\rho_k(h_1 + h_2) = \rho_1 h_1 + \rho_2 h_2$$

AD85/Al6061

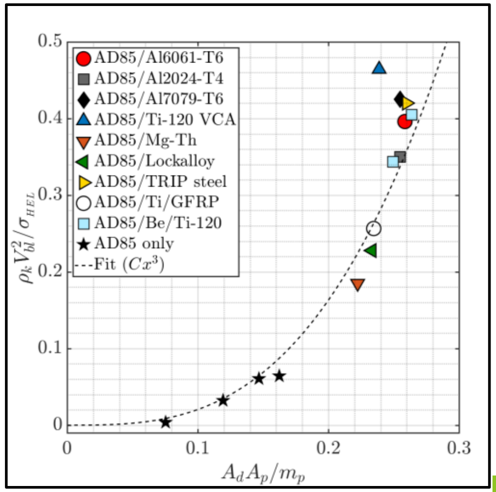


Boron carbide/Al6061





AD85/Fiberglass



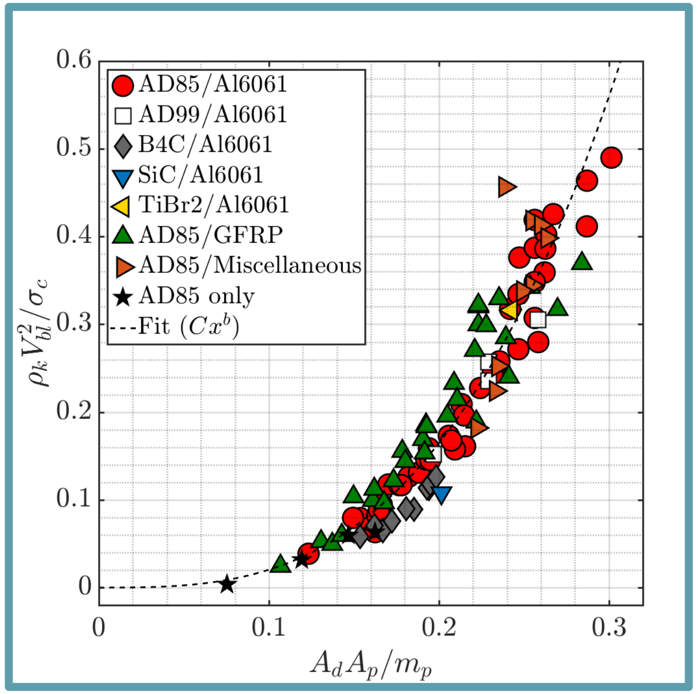
AD85/Misc.

Data from Wilkins

- 4 different calibers
- 5 frontal ceramics
- 10 backing materials
- Various fractions
- Monolithic ceramic

Homologous scaling

Bicomponent systems

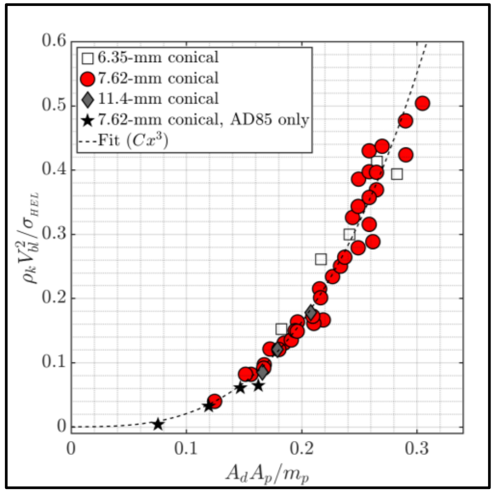


$$\frac{\rho_k V_{bl}^2}{\sigma_c} = f\left(\frac{A_{d,0} A_p}{m_p}\right)$$

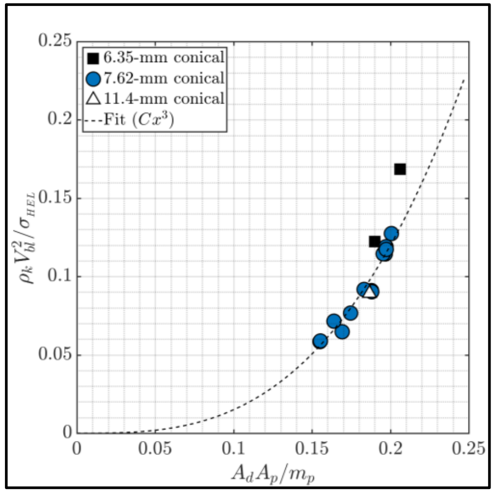
$$\sigma_c = \sigma_{HEL}$$

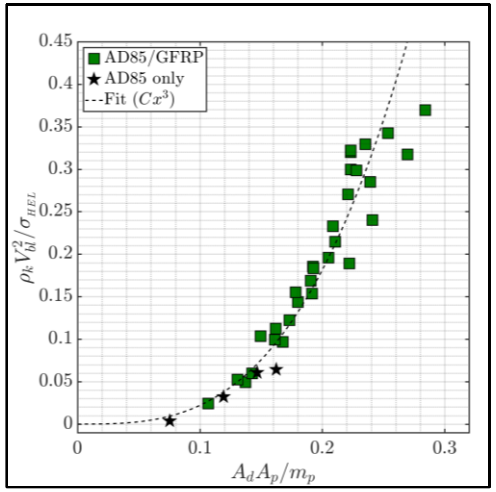
$$\rho_k (h_1 + h_2) = \rho_1 h_1 + \rho_2 h_2$$

AD85/Al6061

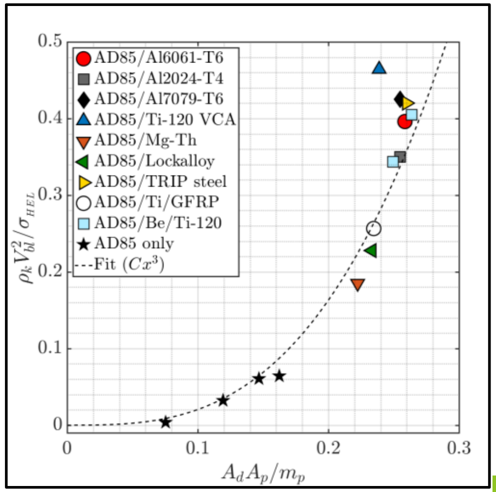


Boron carbide/Al6061





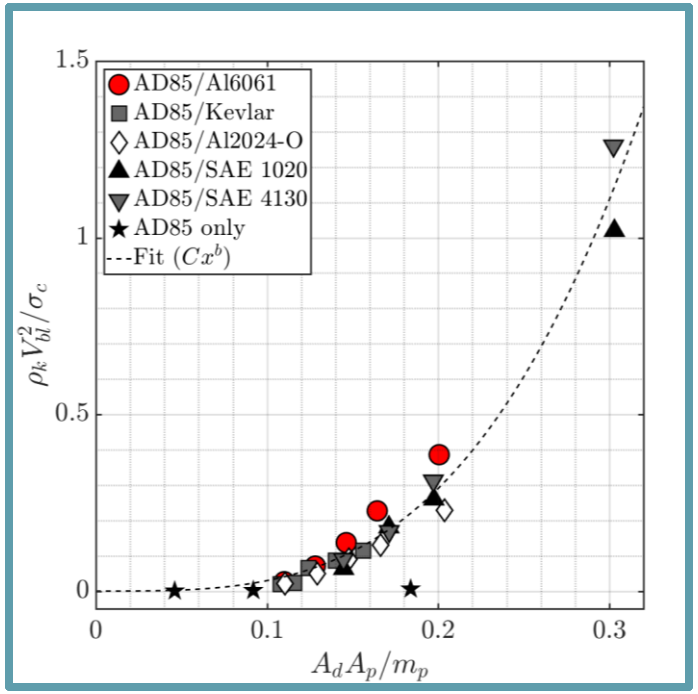
AD85/Fiberglass



AD85/Misc.

Data from Mayseless (1987)

Different boundary conditions



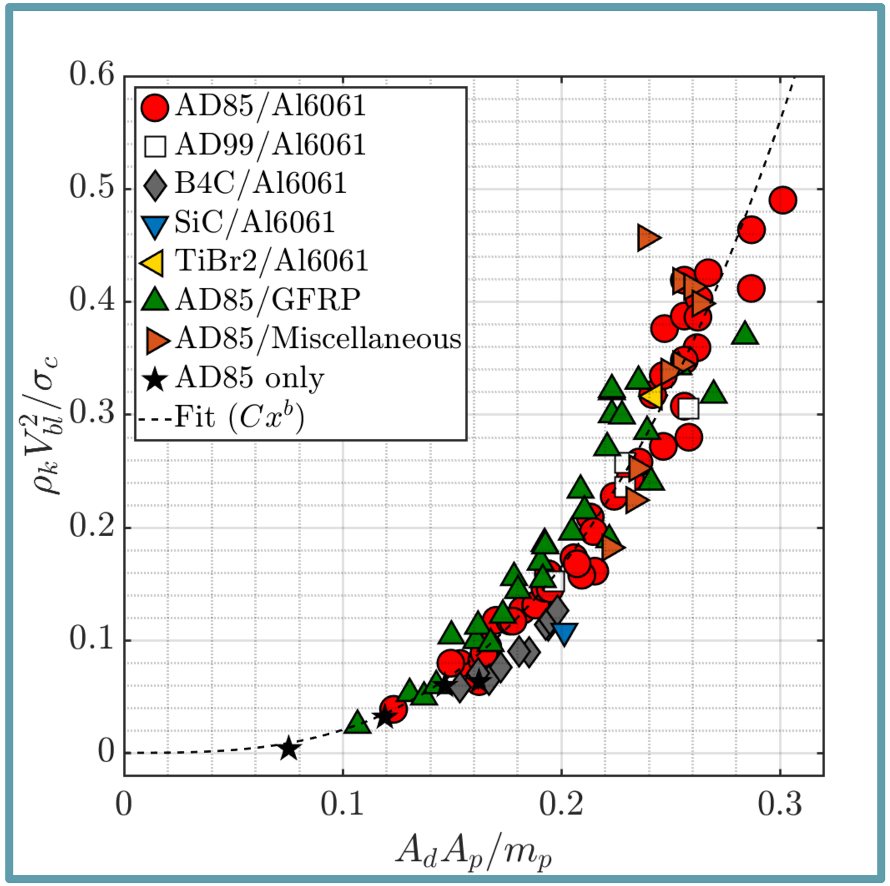
Further discussion

Analytical models

Why not use existing analytical models?

- Many material/mechanical properties
  - Not always available
  - Not always easily measured

- Order of magnitude of effects don't always scale with the effort to experimentally determine them

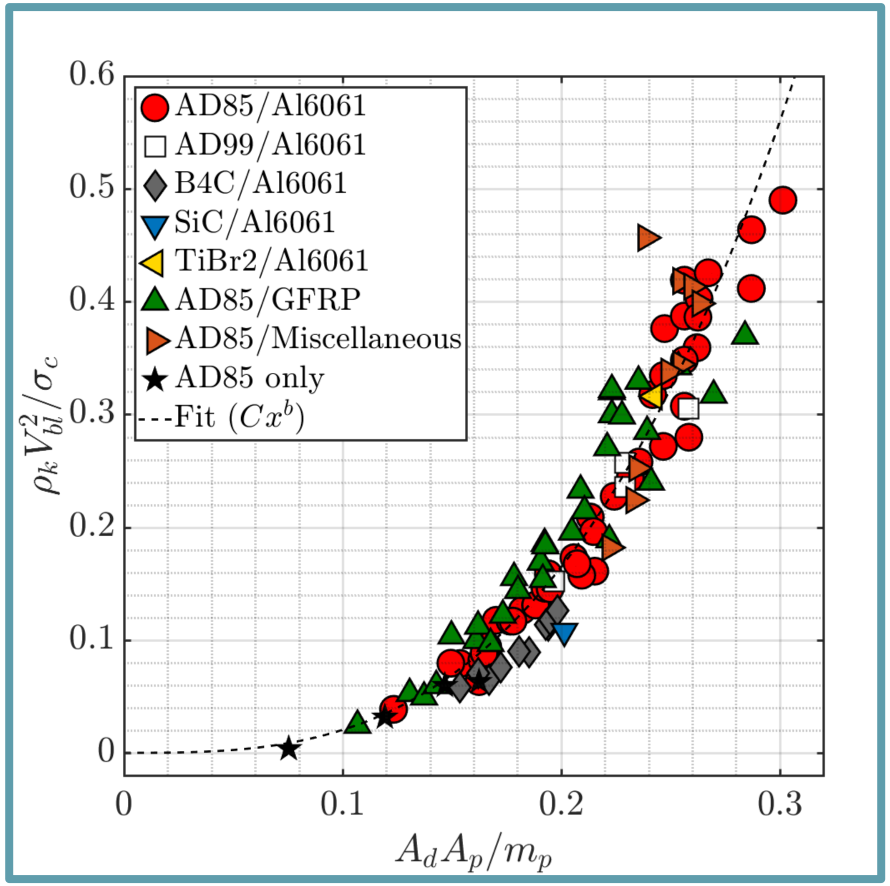


Further discussion

Machine learning methods

Why not machine learning?

- “Brute force” algorithms can perform well sometimes
- Buckingham Pi/sparse regression algos.
  - E.g. SLAW, PyDimension, BuckiNet require strictly independent parameters
- Need a priori knowledge of relations
  - Problematic for strength terms



Final words

Contributions & Future work

$$\frac{\rho_t V_{bl}^2}{\sigma} = f\left(\frac{A_d A_p}{m_p}\right)$$

★ Rapid systems deployment via first-order predictions

- Few parameters
- Reduce high-dimensional data

- **Future directions**
  - Other failure modes
  - Possible link to microstructural models

Acknowledgments

- Work supported through INL Laboratory Directed Research & Development (LDRD) Program under DOE Idaho Operations Office Contract DE-AC07-05ID14517

- Michael Forrestal for insightful discussions on the CCE model

Zherui Guo

National & Homeland Security
Idaho National Laboratory

zherui.guo@inl.gov

Google Scholar, ResearchGate

References

1. Wadley, H. N. G., Dharmasena, K. P., O'Masta, M. R., & Wetzel, J. J. (2013). Impact response of aluminum corrugated core sandwich panels. International Journal of Impact Engineering, 62, 114-128.
2. Sarva, S., Nemat-Nasser, S., McGee, J., & Isaacs, J. (2007). The effect of thin membrane restraint on the ballistic performance of armor grade ceramic tiles. International Journal of Impact Engineering, 34(2), 277-302.
3. Mendez, Patricio F., and Fernando Ordonez. "Scaling laws from statistical data and dimensional analysis." (2005): 648-657.
4. Langhorst, B., Cooka, C., Schondela, J., & Chu, H. S. (2010). Material systems for blast-energy dissipation. In IMPLAST 2010 Conference (pp. 12-14).
5. Wilkins, M. (1967). Second progress report of light armor program (No. UCRL-50349 (Rev. 1)). Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States).
6. Wilkins, M. L. (1968). Third progress report of light armor program. University of California Berkeley, Berkeley United States.
7. Wilkins, M. L., Cline, C. F., & Honodel, C. A. (1969). Fourth progress report of light armor program (No. UCRL-50694). California Univ., Lawrence Radiation Lab.
8. Wilkins, M. L., Landingham, R. L., & Honodel, C. A. (1971). Light-armor program. Fifth progress report (No. UCRL-50980). Lawrence Livermore National Lab., CA (USA).
9. Mayseless, M., Goldsmith, W., Virostek, S. P., & Finnegan, S. A. (1987). Impact on ceramic targets.
10. Den Reijer, P. C. (1993). Impact on ceramic faced armour.
11. Guo, Z, Chen, W., and Zheng, J. "A semi-empirical design parameter for determining the inelastic strike-face mass fraction of soft armor targets." IJIE 125 (2019): 83-92.
12. Guo, Z., & Chen, W. (2020). A merit parameter to determine the stacking order of heterogeneous diphasic soft armor systems. Comp Struct, 241, 112086.
13. Cimpoeru, S. J., Alkemade, S. J., Szymczak, M., Rupert, N. L., Green, W. H., & Wells, J. M. (2002). BALLISTIC ASSESSMENT OF A LOW-COST Ti-6 Al-4 V TITANIUM ALLOY. In Applied Mechanics: Progress and Applications (pp. 237-242).
14. Rosenberg, Z. (1993). On the relation between the Hugoniot elastic limit and the yield strength of brittle materials. Journal of applied physics, 74(1), 752-753.
15. Bavdekar, S., Parsard, G., Subhash, G., & Satapathy, S. (2017). An improved dynamic expanding cavity model for high-pressure and high-strain rate response of ceramics. International Journal of Solids and Structures, 125, 77-88.
16. Guo, Z. et al. (2019). Perforation of Aluminum Armor Plates with Fragment-Simulating Projectiles. Journal of Dynamic Behavior of Materials, 5(4), 409-415.