INL/CON-23-75115-Revision-0

Response of Graphite to Dynamic Loading and Hypervelocity Jet Impacts

November 2023

Changing the World's Energy Future

Bradley Davis Huddleston, Thomas A Mason, Cody James Gibson, Colter Z Angell, Nikki Rasmussen

Idaho National Laboratory

INL/CON-23-75115-Revision-0

Response of Graphite to Dynamic Loading and Hypervelocity Jet Impacts

Bradley Davis Huddleston, Thomas A Mason, Cody James Gibson, Colter Z Angell, Nikki Rasmussen

November 2023

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

ASME

IMECE® 2023

International Mechanical Engineering Congress & Exposition®

New Orleans, LA

Response of Graphite to Dynamic Loading and Hypervelocity Jet Impacts

Bradley D. Huddleston, Thomas A. Mason, Cody Gibson, Colter Angell, Nikki Rasmussen
Idaho National Laboratory

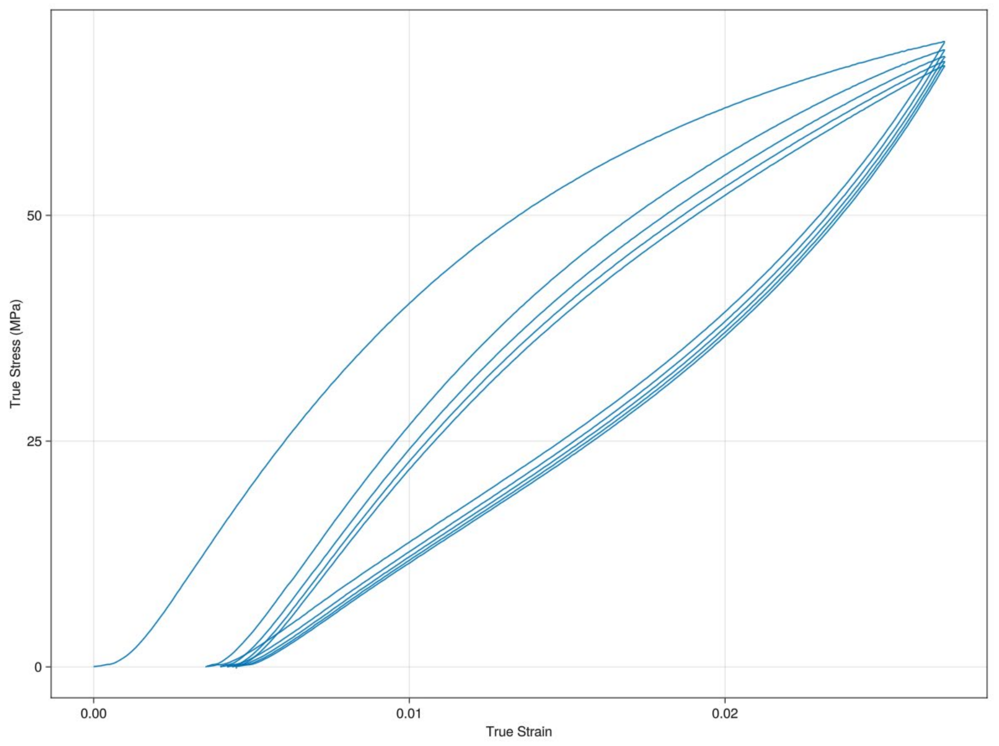
Introduction to Graphite

- Unique combination of thermal, mechanical, and chemical properties
- Use in refractory applications, as anodes and conductors
  - Most work has focused on thermal, chemical, and quasistatic mechanical properties.
- Three grades of graphite considered:
  - PCEA
  - NBG-18
  - NBG-25

Parameter	PCEA	NBG-18	NBG-25
Density (g/cc)	1.834	1.846	1.82
Grain size	760 µm max.	1.6 mm	60 µm
Porosity	16-20%	14%	20%

Typical Mechanical Response of Graphite

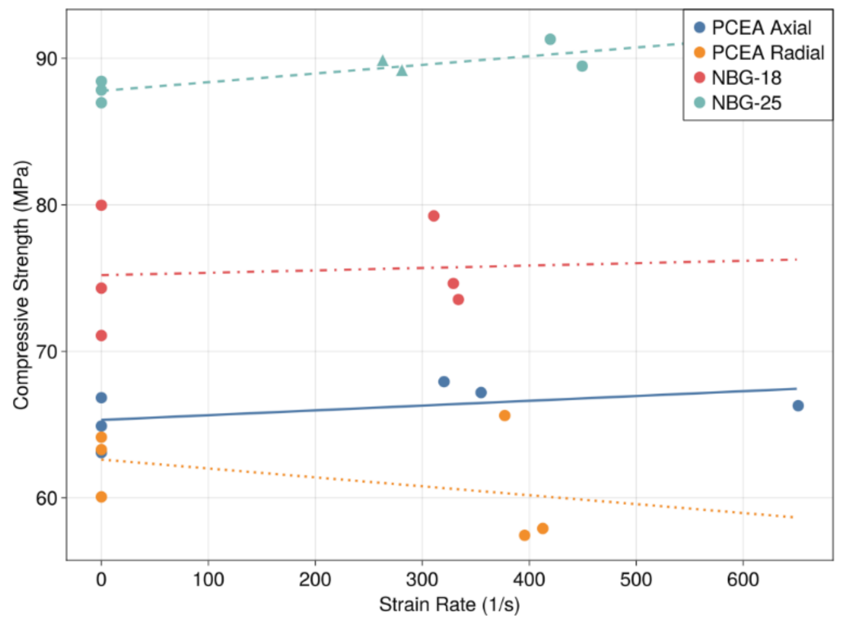
- Considered a quasi-brittle material
  - Brittle under tensile loads
  - Non-linear elastic + inelastic (with hysteresis) under compression
  - Little to no strain rate sensitivity in compressive strength
- Fracture response can vary significantly based on microstructural properties of the graphite
  - Grain size
  - Porosity



Stress response of PCEA Graphite under cyclic compressive loading

Quasistatic and Dynamic Mechanical Test Results

- Strength varies significantly among the grades studied
  - Low strength when compared to structural materials
  - PCEA strength had the most variation
- Split Hopkinson Pressure Bar (SHPB) testing done with aluminum bars
  - Strain rates around 300-500 1/s
  - Samples are ½" dia. x ½" cylinders



Rate-dependent compressive strength for three different grades of graphite

Tensile and Shear Failure Modes in Graphite

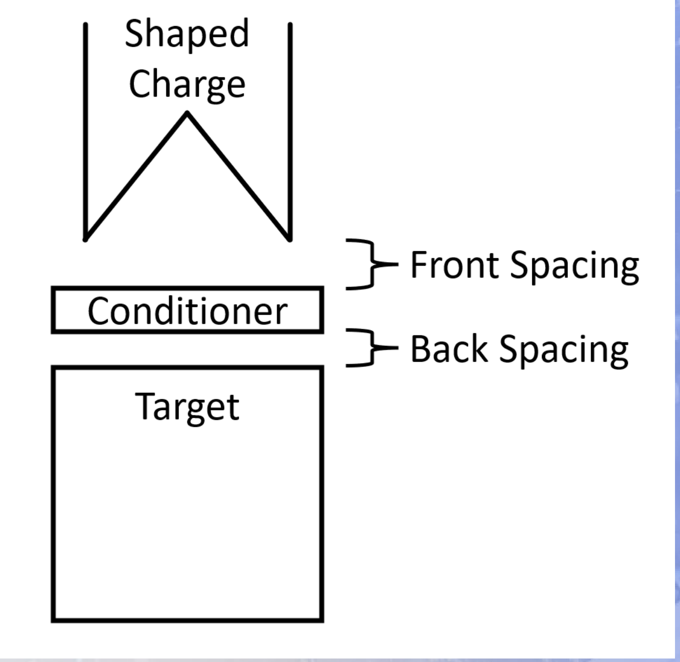
- Graphite test specimen failure is dominated by shear-initiated fracture modes.
- PCEA had significant fracture planes approximately on the 45° maximum shear stress plane.
- Higher strength grades had shear initiations with stronger tensile fracture planes.

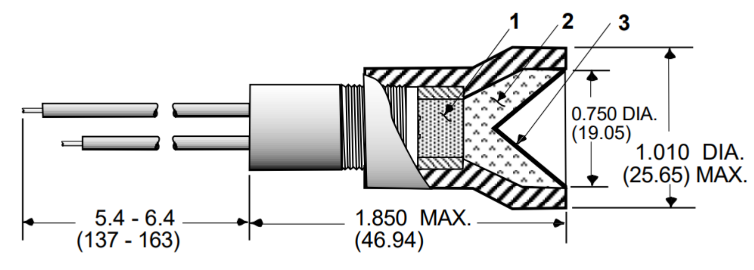
High Speed Video of SHPB compression of PCEA

Left: Failed PCEA compression specimen.
Right: Failed NBG-25 compression specimen.

Small Scale Shaped Charge Test Setup

- Shaped charge penetration tests probe a different region of dynamic material behavior.
- Two small scale shaped charges were chosen:
  - RP-1: 0.410 diameter charge with 530 mg PETN
  - RP-4: 0.75 diameter charge with 3.44 g of RDX (RP-80 initiated)
- Aluminum 6061 conditioners were used at various thicknesses and spacings to moderate the penetration into graphite.





Teledyne Energetics, RISI RP-4 SC EBW Technical Data Sheet

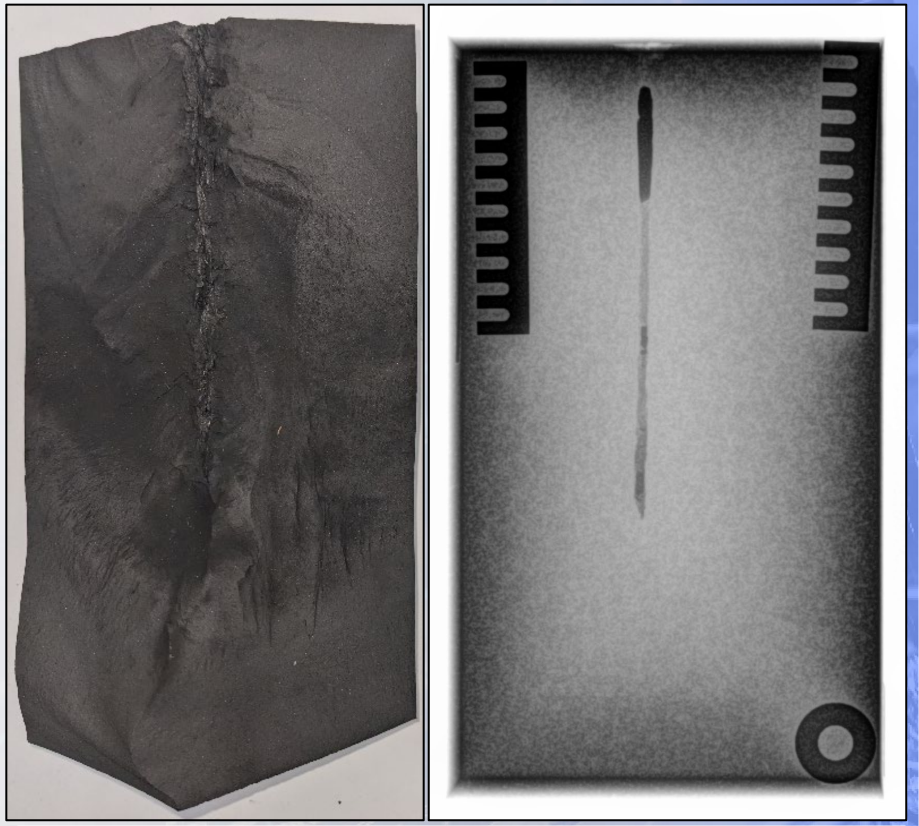
Jet Penetration was Consistent Across Graphite Grades

- Shaped charge jet penetration was similar for all grades of graphite tested.
  - Nominal penetration for each grade varied from about 10 to 12.5 cm.
- Occasional anomalously low penetrations did occur.
  - Attributed to variability and lack of precision in the small-scale shaped charges.

X-Ray Computed Tomography of RP-4 Jet Penetration into PCEA Graphite

Graphite Penetration Sample Failure Mechanisms

- Some graphite samples fractured radially emanating out from the wound channel.
- Fracture was predictable with strength – the lower the strength, the less likely the fracture:
  - No PCEA samples fracture,
  - All NBG-25 samples fracture.
- Fractures initiated after the jet penetration.
  - No evidence of jet intrusion into cracks.



Left: Fracture surface of jet penetration into NBG-25 graphite.
Right: Static X-Ray of jet penetration into NBG-18 graphite.

Modeling of Graphite Behavior

- There are no models available that are designed for graphite – very few models designed for graphite at all
  - Johnson Holmquist 2 (JH2) ceramic model was the primary choice for this study
- Equation of state portion is a fit to literature data for POCO EDM3 graphite (Hebert, *et al.* 2014)
- Strength and damage portions of JH2 do not represent graphite very well

<u>Johnson Holmquist II Ceramic Model</u>

$$P = K_1\mu + K_2\mu^2 + K_3\mu^3 + P_{Bulk}$$

$$\sigma = (1 - D) \cdot Y_{NF} + D \cdot Y_F$$

$$Y_{NF} = \sigma_{HEL} \cdot A \cdot \left(\frac{P}{P_{HEL}} - \frac{T}{P_{HEL}}\right)^N \cdot (1 + C \ln(\dot{\varepsilon}))$$

$$Y_F = \min\left(\sigma_{HEL} \cdot B \cdot \left(\frac{P}{P_{HEL}}\right)^M \cdot (1 + C\, ln(\dot{\varepsilon})), SFMax\right)$$

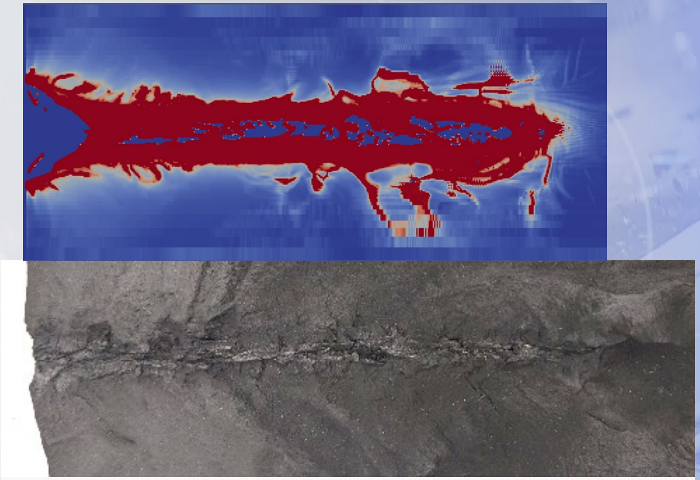
$$D = \sum \frac{\dot{\varepsilon}_p}{D1 \cdot \left(\frac{P}{P_{HEL}} - \frac{T}{P_{HEL}}\right)^{D2}} \Delta t$$

Hebert, David, et al. "Plate impact experiments and simulation on porous graphite." *Journal of Physics: Conference Series*. Vol. 500. No. 18. IOP Publishing, 2014.

Simulation Results

Test	Charge	Material	Standoff (cm)	DOP (cm)	Simulation DOP (cm)
1	RP-1	PCEA	0.35	3.98	2.62
2	RP-1	PCEA	0.35	4.55	
3	RP-4	PCEA	0.32	10.24	6.12
4	RP-4	PCEA	0.32	8.45	
5	RP-4	PCEA	0.32	7.35	
6	RP-4	PCEA	2.86	6.87	12.03
7	RP-4	PCEA	2.86	12.58	
8	RP-4	PCEA-Radial	2.86	12.34	
9	RP-4	PCEA-Radial	2.86	9.41	
10	RP-4	NBG-18	2.86	10.1	10.46
11	RP-4	NBG-18	2.86	11.2	
12	RP-4	NBG-25	2.86	11.44	11.35
13	RP-4	NBG-25	2.86	11.12	

- The failed strength parameter “B” was tuned to result in the penetration observed in the RP-4 experiments for each material.
  - Additional specialized calibration experiments would be required to independently calibrate this parameter.
- The material calibration did not able to capture the penetration of the RP-1 charge or distinguish changes in standoff (outlined in orange).
- The geometry of the wound channel is very different.
  - Diameter of the real wound channel is around 0.3 +/- 0.05 cm compared to approximately 1 cm in the simulation.



Comparison of RP-4 wound channels in NBG-25 graphite

Future Work for Modeling Graphite

- The JH2 material model does not represent the necessary physics to predict the penetration of a shaped charge in graphite.
  - Work is needed to develop a material model that accurately represents the physics causing the unique behavior of graphite
  - Additional characterization of graphite is necessary to support model development and calibration
- We have a funded lab directed R&D project to work on this problem at Idaho National Laboratory and are looking for a graduate student who wants to work on a challenging mechanics and materials problem!

Acknowledgements

This research made use of the resources of the High Performance Computing Center at Idaho National Laboratory, which is supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract No. DE-AC07-05ID14517.

Questions?