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Modeling Plastic Deformation of Steel Plates in Hypervelocity Impact Experiments

Shawoon Roy

PhD Student, Department of Mechanical Engineering
University of Nevada-Las Vegas

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Center for Materials and Structures (CMS), UNLV Collaborators

Brendan O’Toole, Mohamed Trabia, Richard Jennings, Melissa Matthes

National Security Technologies, LLC, Collaborators

Robert Hixson, Michael Pena, Edward Daykin, Steven Becker, Carlos Perez, Eric Machorro

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Outline

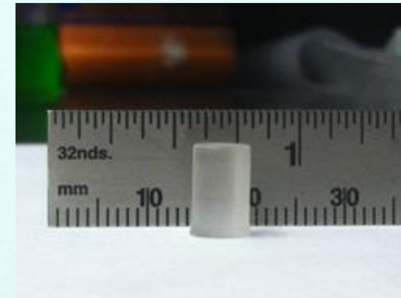
- Objective
- Experimental Setup
- Results & Discussion
- Computational Simulation
- Simulation Comparison
- Conclusion
- Future Work

Objective

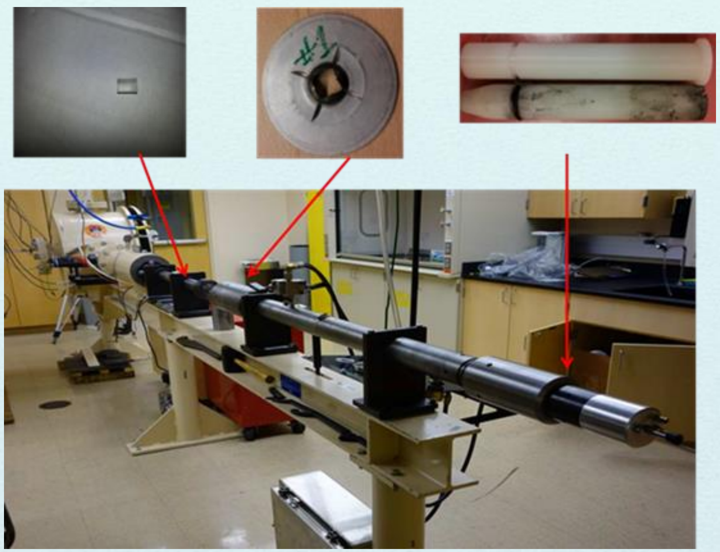
- A common technique to perform hypervelocity impact research in laboratory settings: gas gun experiments.
- Metallic plates experience tremendous amounts of shockwave and pressure within a short time, which results large localized plastic deformation.
- Characterizing materials under this type of dynamic experiment often poses multiple challenges in terms of experimental design and computational modeling.
- Most of the time, gas gun experiments include expensive instrumentation and high-fidelity diagnostic systems.
- Therefore, predictive modeling is an alternate way to simulate this type of experiment.
- Computational tools developed to simulate these experiments must consider the complexities and nonlinearities arising from such projectile-target interactions.

Experimental: Two-Stage Light Gas Gun

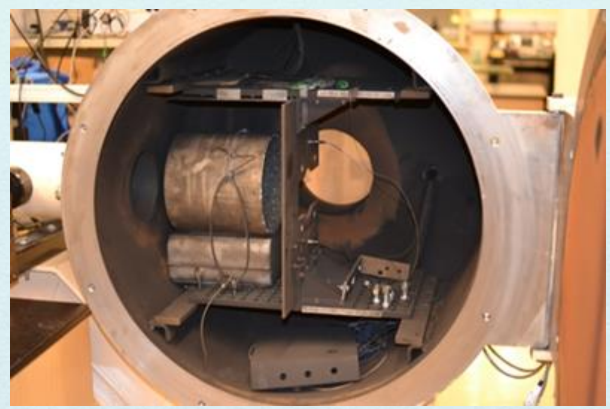
- A two-stage light gas gun is used to launch a cylindrical projectile into a target plate at a velocity from 4.5 to 6 km/s
- The gun uses either hydrogen or helium
  - Projectile: Lexan (5.6 mm diameter)
  - Target: A36 steel plate (152.4 × 152.4 × 12.7 mm)
- The target is bolted on a mounting plate during the experiment
- A laser intervalometer system is used to measure projectile velocity



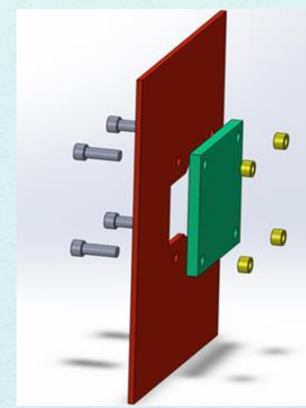
Lexan projectile



UNLV two-stage light gas gun



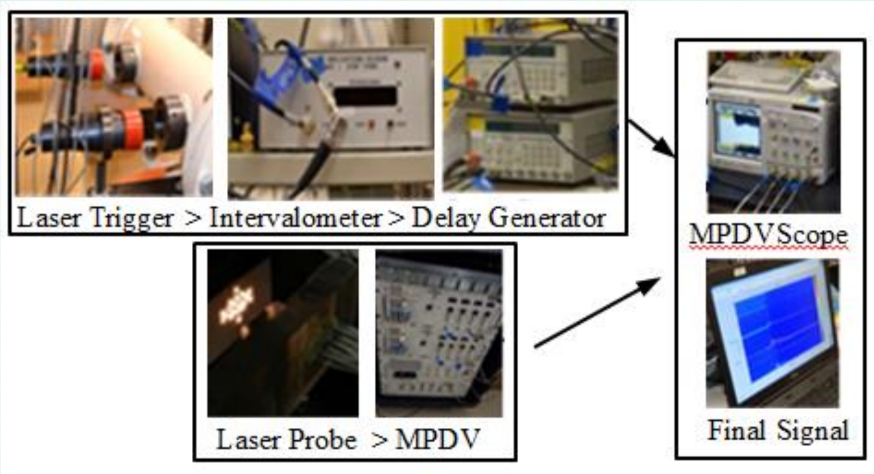
Target chamber assembly



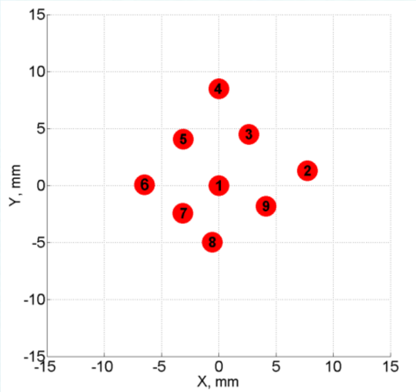
Target mounting plate

Multiplexed Photonic Doppler Velocimetry

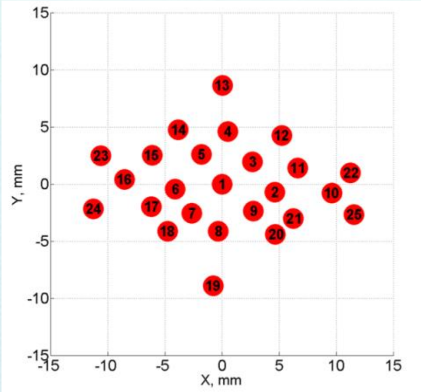
- A Multiplexed Photonic Doppler Velocimetry (MPDV) system has been used as a diagnostic tool to collect the velocimetry data
- PDV is a heterodyne interferometric technique that can record velocity data in terms of displacement using Doppler shift of reflected light frequency from a moving surface
- In the case of the MPDV system, data are collected from multiple points with multiple optical fiber probes
- So far, 9-probe and 25-probe arrangements have been used with the MPDV system in gas gun experiments



Schematic of MPDV data acquisition



Typical 9-probe pattern



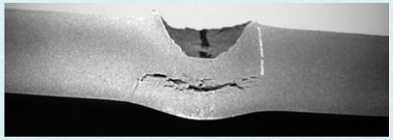
Typical 25-probe pattern

Results & Discussion

- In all experiments, the Lexan projectiles disintegrated due to the enormous stress and the heat generated upon impact with the target surface
- A small crater with a bulge on the back side of the target plate is created as a result of impact
- **Spall failure**
  - Spalling happens close to the rear side of the target
  - Shock waves reach a free surface end and reflect back, resulting in tensile pressure in the material
  - The material fails when the tensile pressure is above the material strength

Crater (front side)

Bulge (back side)



Spall (Sectioned)

Typical target plate after experiment

Results & Discussion

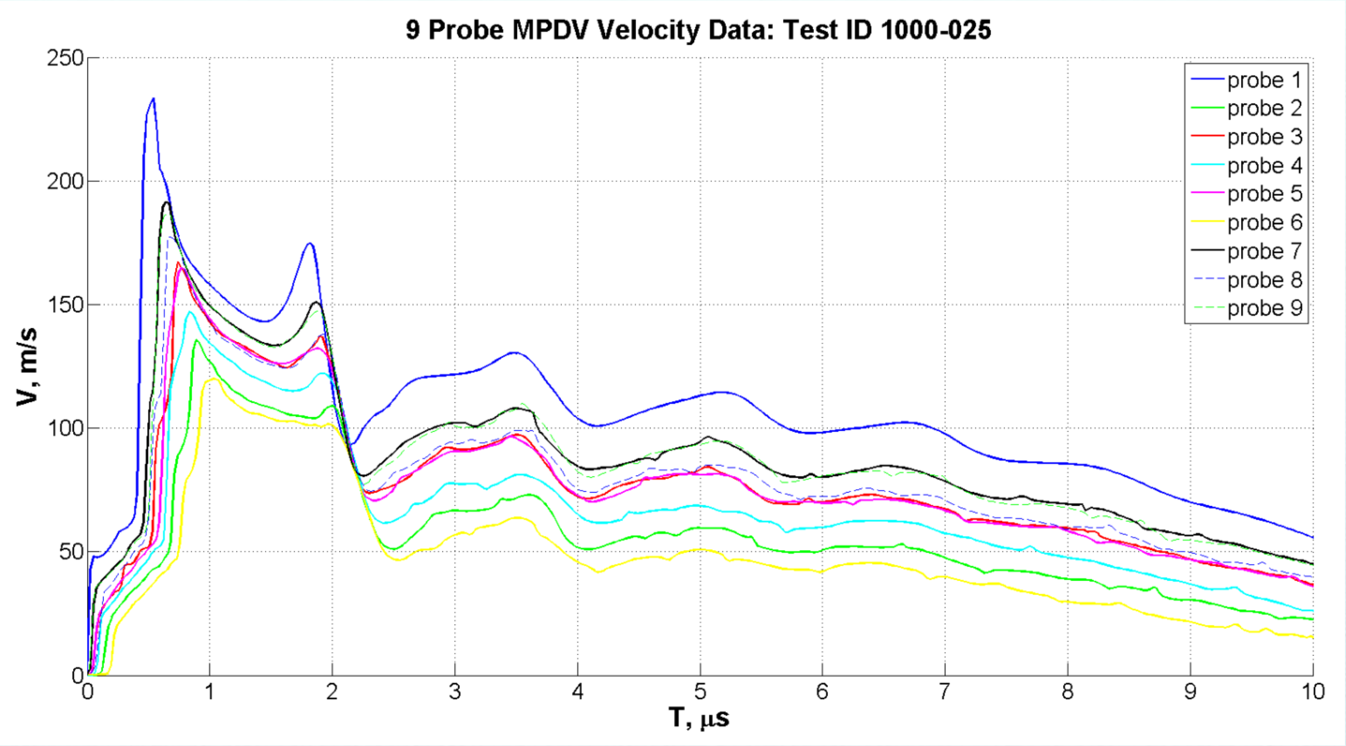
- **Physical measurements** of crater and bulge are taken typically after every experiment.

Test ID	MPDV system details	Impact velocity, km/s	Crater diameter, mm	Penetration depth, mm	Bulge, mm	Spall crack details	
						Diameter, mm	Width, mm
1000-024	9 probe	5.708	17.2 ± 0.3	7.7 ± 0.3	3.1 ± 0.3	21.4 ± 0.2	1.9 ± 0.1
1000-025	9 probe	4.763	15.4 ± 0.3	6.5 ± 0.3	1.4 ± 0.1	14.5 ± 0.2	0.2 ± 0.1
1000-026	25 probe	4.823	15.1 ± 0.2	6.5 ± 0.5	1.5 ± 0.1	n/a	n/a
1000-027	25 probe	5.088	16.9 ± 0.8	7.0 ± 0.4	2.3 ± 0.2	n/a	n/a
1000-028	25 probe	5.157	15.9 ± 0.4	6.5 ± 0.5	1.7 ± 0.2	18.5 ± 0.1	0.7 ± 0.1

- Damage trends seem reasonable: Higher impact velocity results in larger crater and bulge. (Although some minor discrepancies in damage dimensions still exist!)
- All the values listed above are an average of typical physical measurements of crater and the bulge on the back side

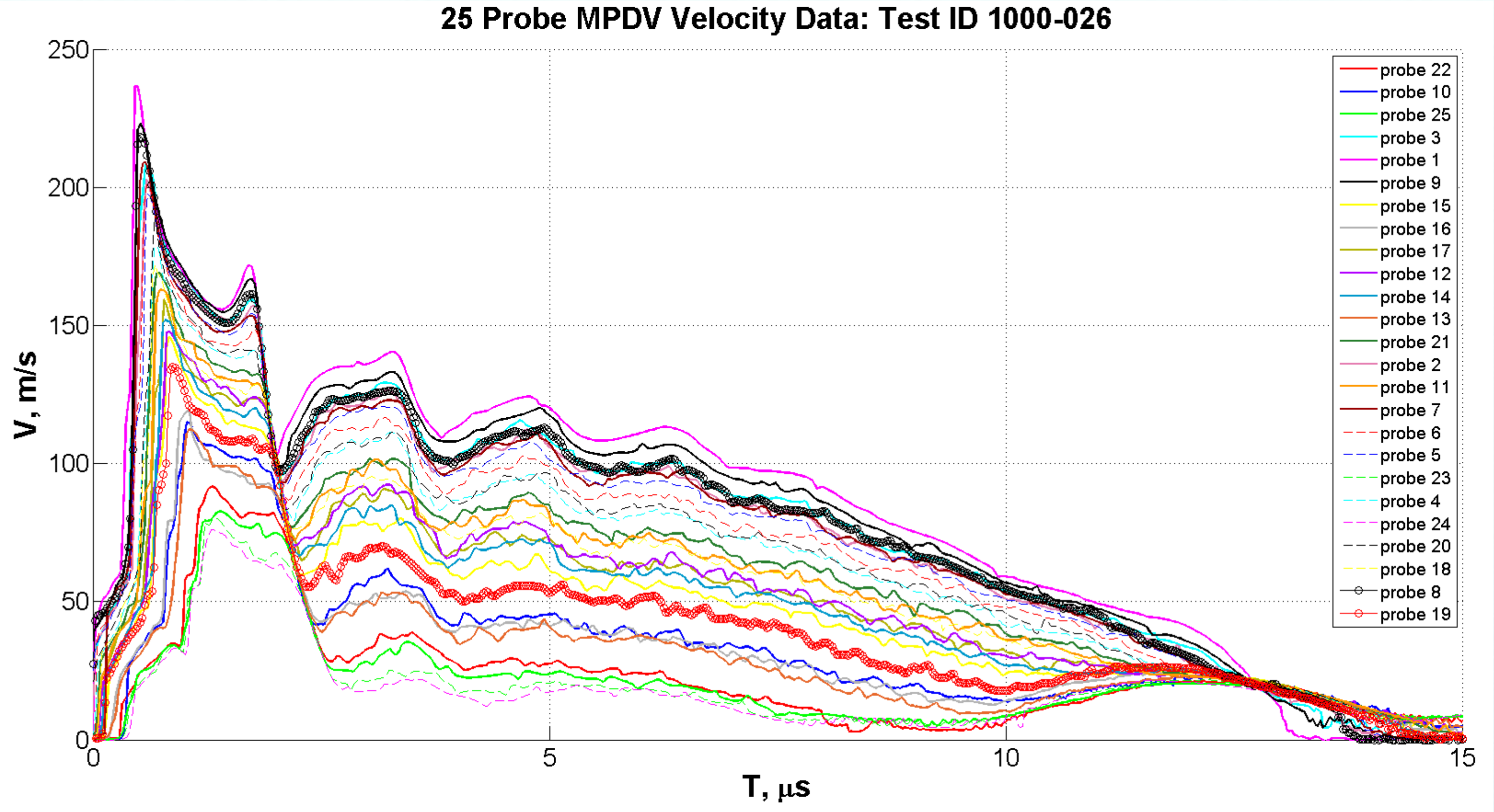
Results & Discussion

- Free surface velocity is measured by MPDV systems
- Probe locations and velocity signal arrival time are very important for MPDV systems



Typical 9-probe MPDV data

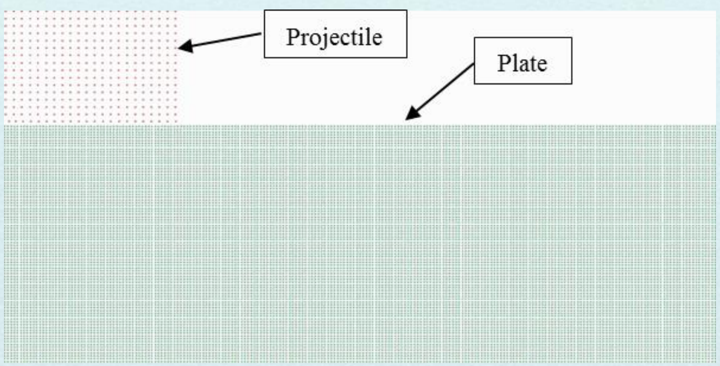
Results & Discussion



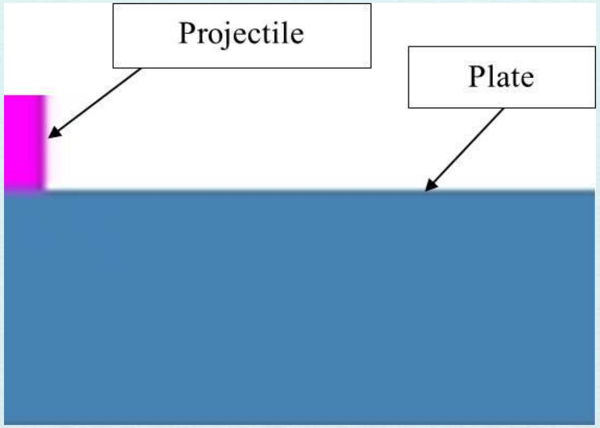
Typical 25-probe MPDV data

Computational Simulation

- Two finite element methods are used to simulate the impact phenomena computationally:
  - Lagrangian-based Smooth Particle Hydrodynamics (SPH) in LS-DYNA
  - Eulerian-based Hydrocode in CTH
- 2-D axi-symmetric models are developed
- Both models have no boundary conditions
- An extensive parametric study has been performed in both models
- For LS-DYNA model, a general SPH particle spacing of 0.05 mm is chosen
- For CTH, a zone size of 0.05×0.05 mm is chosen



LS-DYNA SPH Model (zoomed in)



CTH Model (zoomed in)

Computational Simulation: Material Model

- Both LS-DYNA and CTH models use Johnson-Cook material model for both Lexan projectiles and A36 steel target plates
- Parameters of Johnson-Cook material model are taken from the available literature

Material	A, MPa	B, MPa	C	M	N	T_{melt},°K
Lexan (Littlewood)	75.8	68.9	0	1.85	1.004	533
A36 Steel (Seidt)	286.1	500.1	0.022	0.917	0.2282	1811

Littlewood, D.J., "Simulation of dynamic fracture using peridynamics, finite element modeling, and contact," *ASME 2010 International Mechanical Engineering Congress & Exposition,* Vancouver, British Columbia, Canada, November 12–18, 2010.

Seidt, J.D. et al., "High strain rate, high temperature constitutive and failure models for EOD impact scenarios," *Proceedings of the 2007 SEM Annual Conference and Exposition on Experimental and Applied Mechanics,* Springfield, MA, June 2007.

Computational Simulation: Equation of State

- Both LS-DYNA and CTH models use a Grüneisen equation of state for both Lexan and A36 steel
- EOS parameters are also taken from the available literatures

Material	ρ, kg/m^3	C_0, m/s	S_1	Υ
Lexan (Steinberg)	1190	1933	1.42	0.61
A36 Steel (Seidt)	7890	4569	1.49	2.17

Steinberg, D. J., *Equation of State and Strength Properties of Selected Materials,* UCMRL−MA−106439; Lawrence Livermore National Laboratory: Livermore, CA, 1996.

Seidt, J.D. et al., “High strain rate, high temperature constitutive and failure models for EOD impact scenarios,” *Proceedings of the 2007 SEM Annual Conference and Exposition on Experimental and Applied Mechanics,* Springfield, MA, June 2007.

Computational Simulation: Spall Parameter

- In both LS-DYNA and CTH, spall failure is defined as a pressure cut-off (i.e., P_{min}) value in Johnson-Cook material model
- Spall happens in both models if tensile stress exceeds a certain P_{min} value
- P_{min} value is also taken from literature:

Lexan: P_{min} = –160 MPa (Steinberg)

A36 steel: P_{min} = – 1200 MPa (calculated based on 1-D assumption)

Steinberg, D. J., *Equation of State and Strength Properties of Selected Materials*, UCMRL−MA−106439; Lawrence Livermore National Laboratory: Livermore, CA, 1996.

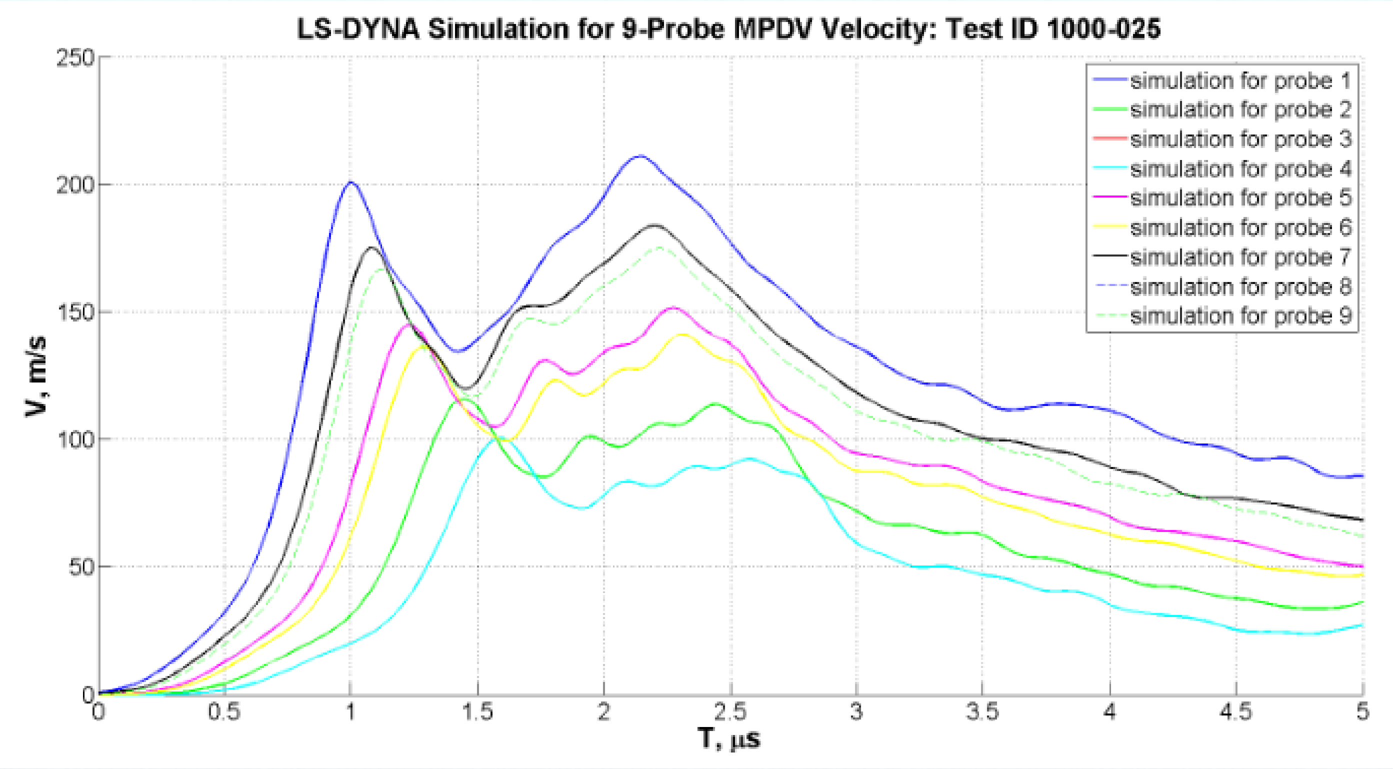
Simulation Comparison: Crater Details

- Both LS-DYNA and CTH simulations have been able to capture the deformation progression due to impact.

Material	Crater diameter, mm	Difference (%)	Penetration, mm	Difference (%)	Bulge, mm	Difference (%)
Experiment	15.37	N/A	4.83	N/A	1.42	N/A
LS-DYNA (SPH)	16.20	–5.4	4.44	8.07	1.39	2.11
CTH	16.20	–5.4	4.50	6.83	1.40	1.41

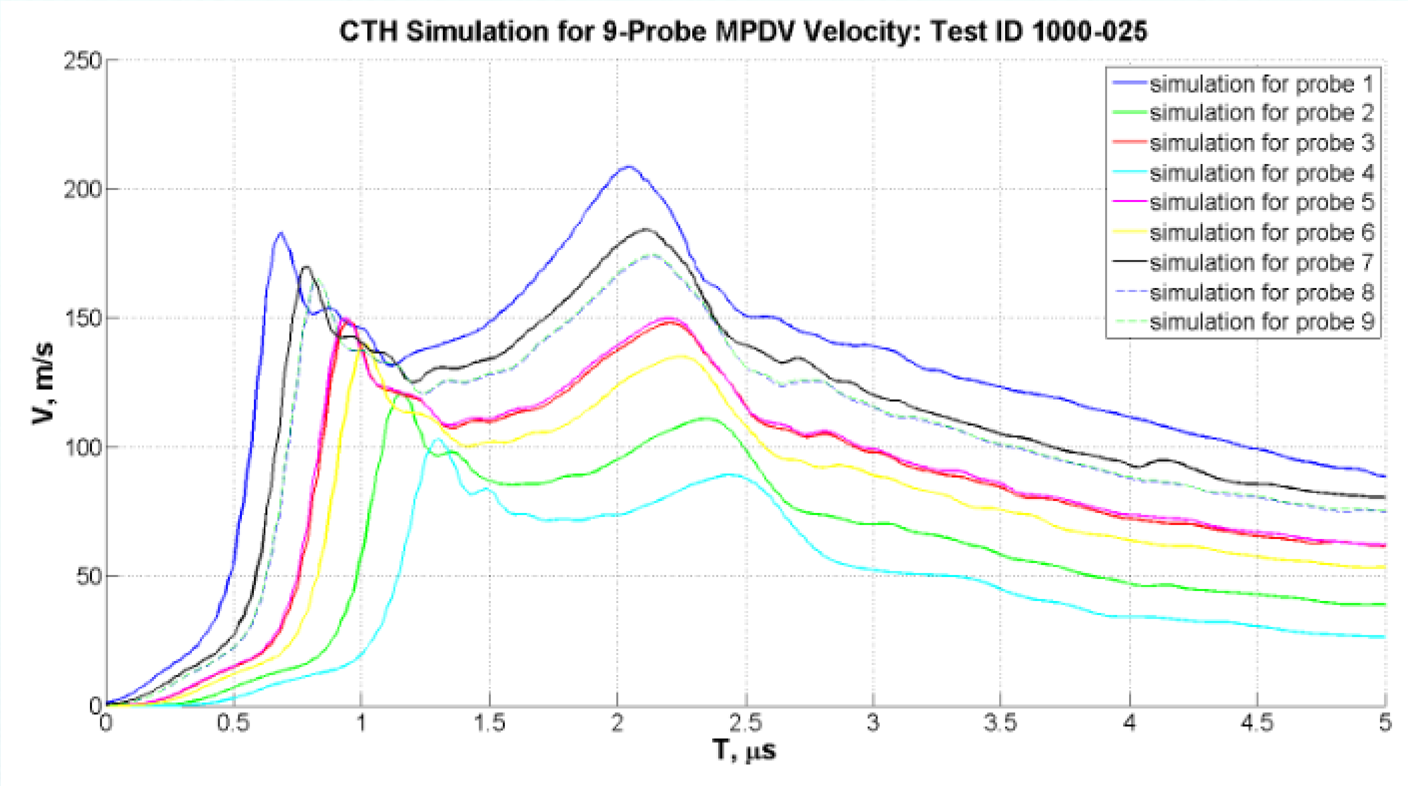
Simulation Comparison: Free Surface Velocity

- Free surface velocity profiles are also in reasonable agreement
- Further refinement of the models is still in progress



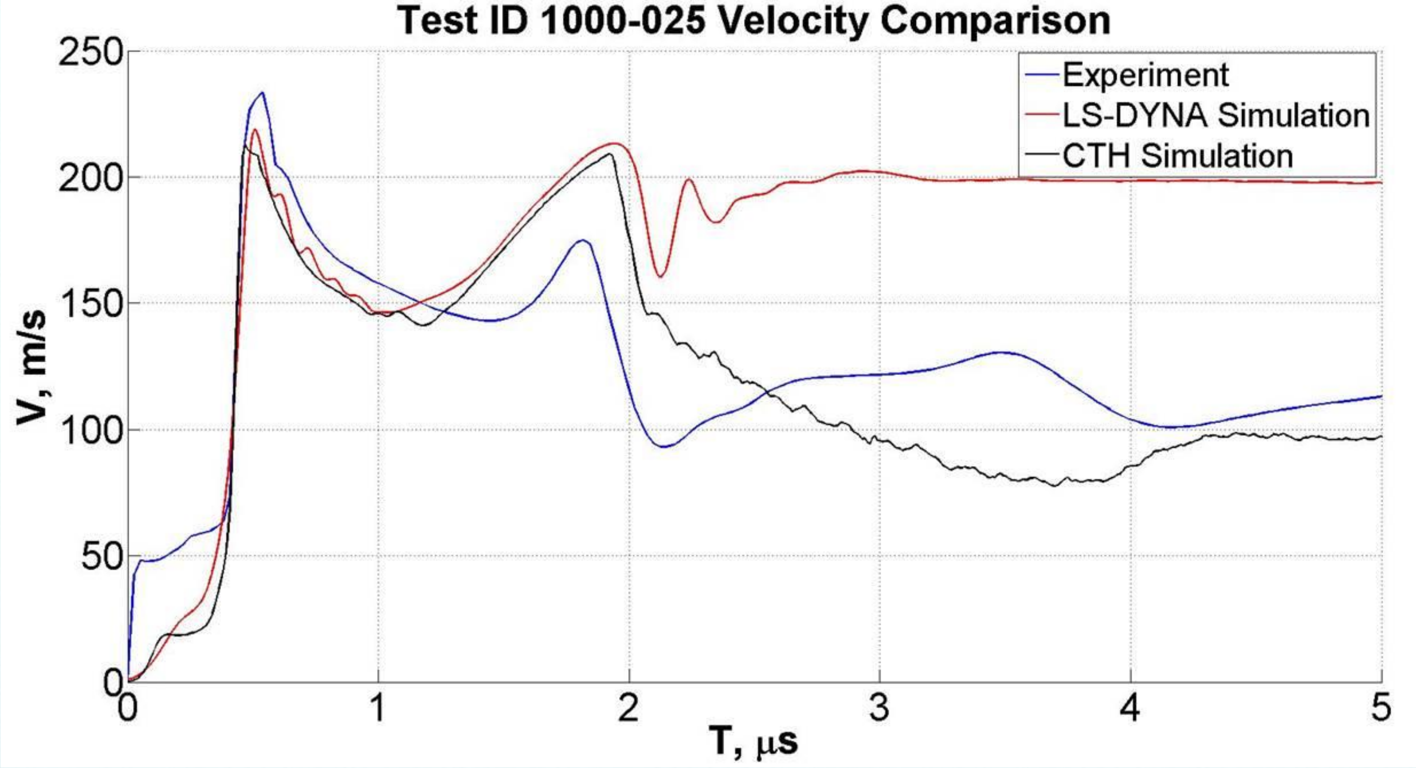
Typical free surface velocity from LS-DYNA simulation

Simulation Comparison: Free Surface Velocity



Typical free surface velocity from CTH simulation

Simulation Comparison: Free Surface Velocity



- Both simulation models capture the overall trend of the free surface velocity in terms of HEL, plastic wave rise, peak velocities, and spall signature
- However, the magnitude of these features vary in the process of further tuning

Conclusion

- A series of two-stage light gas gun experiments were performed to study the plastic deformation of steel plates during hypervelocity impact.
- Free surface velocity from back of the plate was measured using MPDV system during these experiments.
- Simulation models developed in LS-DYNA SPH solver and CTH hydrocode reasonably simulated the experiments.
- The results of this study may be used to conduct a parametric study of the material models and the equation of the state to determine their sensitivities in accurately predicting the behavior of metallic materials during dynamic penetration events.

Future Work

- Representation of MPDV data
- Benchmark MPDV data with high-speed camera data
- Tuning of parameters in simulation models to get better match

THANK YOU!