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Plastic Deformation of Steel Plates under High Impact Loading

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Outline

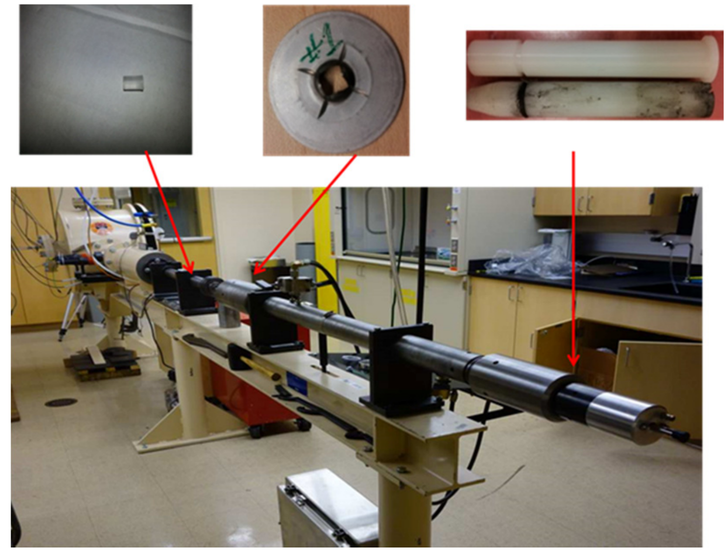
- Objective
- Experimental
- Computational Simulation
- Results and Discussion
- Simulation Comparison
- Conclusion
- Future Work

Objective

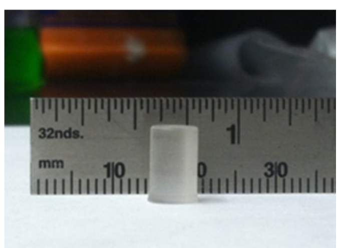
- During high velocity impact, the target plate bulges outward, and the dynamic tensile loads lead to fracture and eventually the spallation of material off the back face.
- We seek a better understanding of the role of material models in the plastic deformation that occurs during the high velocity impact experiments.
- Two-stage light gas gun is used for this experiment.
- The experiment includes measuring the velocity of the target plate back face surface using Photonic Doppler Velocimetry (PDV) technique.
- Experimental results are compared to corresponding computationally simulated data using multiple approaches.
- Depth of penetration and other post-impact geometric parameters are also compared.

Experiment: UNLV Two-stage Light Gas Gun

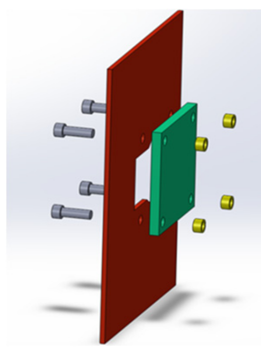
- A two-stage light gas gun is used to launch a cylindrical projectile into a target plate at a velocity range of 4.5-6 km/s.
- The gun uses either Hydrogen or Helium
  - Projectile: Lexan (5.6 mm diameter)
  - Target: A36 steel plate (152.4 × 152.4 × 12.7 mm)
- The target is bolted on a mounting plate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



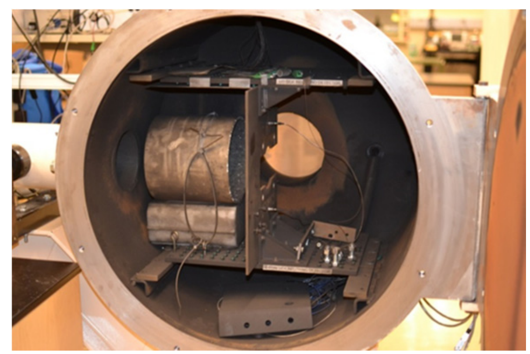
UNLV Two-stage Light Gas Gun



Lexan Projectile



Target Mounting Plate



Target Chamber Assembly

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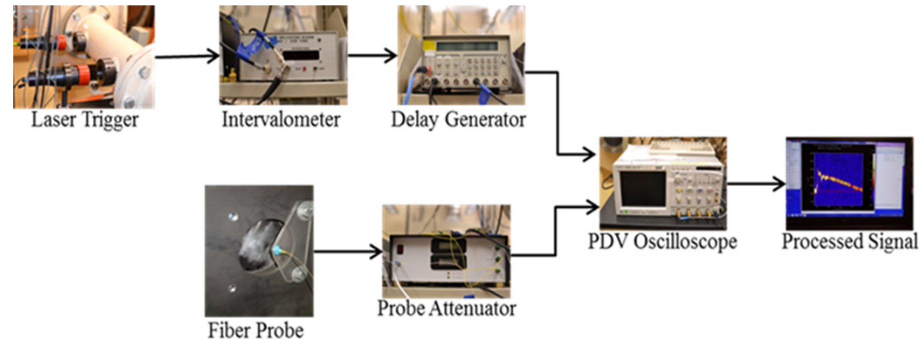
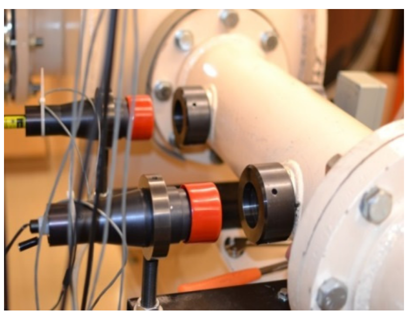
Experiment: Measurements

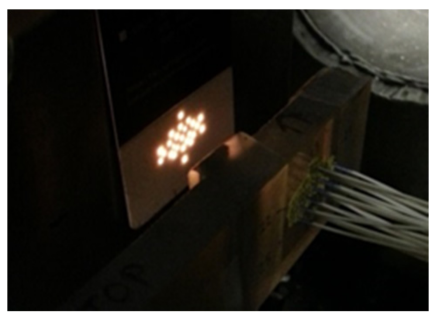
- Single/multi channel Photonic Doppler Velocimetry (PDV/MPDV) system is used to measure velocity from the back surface of the target plate.
- PDV is an interferometric technique which measures velocity using Doppler shift of reflected light from moving surface.
- For the MPDV system, 9-probe and 25-probe arrangements are used so far.



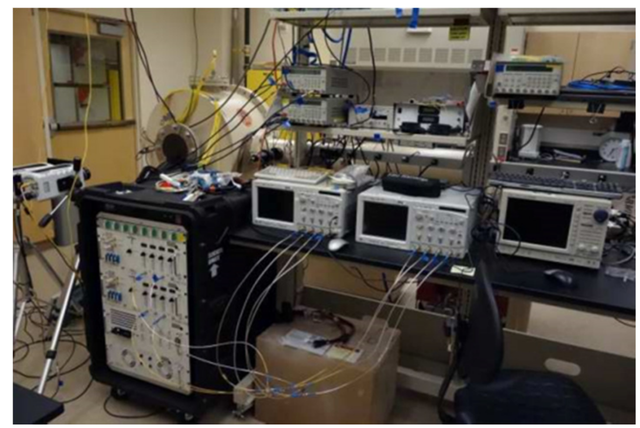
Flowchart of a single probe PDV system



Laser unit assembly



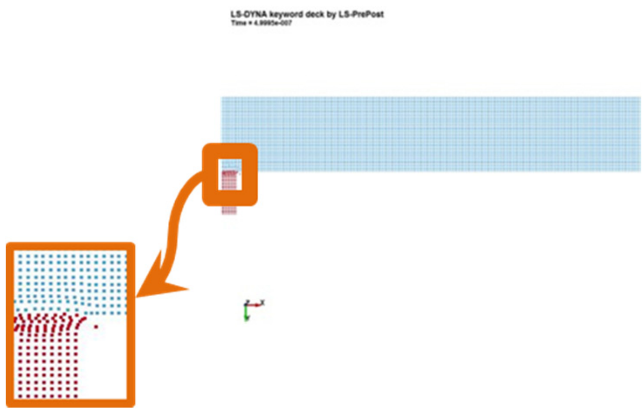
Typical 25-probe MPDV arrangement



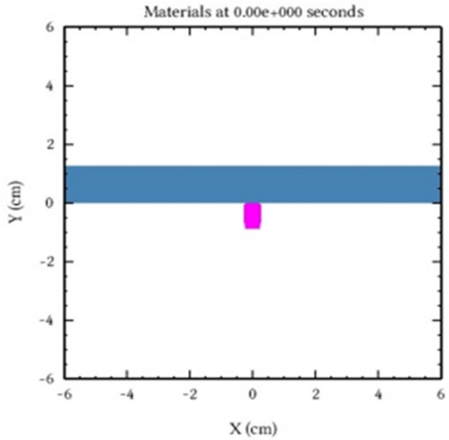
MPDV system assembly

Computational Simulation

- Two finite element methods are used to simulate the impact phenomena computationally:
  - Smooth Particle Hydrodynamics (SPH) in LS-DYNA
  - Hydrocode in CTH
- 2D axi-symmetric models are developed.
- Both models have no boundary conditions.



LS-DYNA SPH Model



CTH Model

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Computational Simulation: Material Model

- Both LS-DYNA and CTH models used the **Johnson-Cook material model** with damage parameters for Lexan projectile and A36 Steel plate.

Constitutive law:

$$\sigma_y = \left(A + B\bar{\varepsilon}^{p^n}\right)\left(1 + Cln(\dot{\varepsilon}^*)\right)\left(1 - T^{*m}\right)$$

Failure strain:

$$\varepsilon^f = \left(D_1 + D_2 e^{(D_3\sigma^*)}\right)\left(1 + D_4 ln(\dot{\varepsilon}^*)\right)\left(1 + D_5 T^*\right)$$

where, σ_y = flow stress

A, B, C, n, m = constants

$\bar{\varepsilon}^p$ = effective plastic strain

D_1, D_2, D_3, D_4 = damage constants

$$\dot{\varepsilon}^* = \frac{\dot{\varepsilon}^p}{\dot{\varepsilon}^0}$$

$$T^* = \frac{T - T_{room}}{T_{melt} - T_{room}}$$

$$\sigma^* = \frac{p}{\sigma_{eff}}$$

Computational Simulation: Material Model

- All parameters of **Johnson-Cook material model** for Lexan projectile and A36 Steel plate are listed in the following table.

Parameter	Lexan Projectile [Littlewood 2010]	A36 Target [Seidt 2007]
A	75.8 MPa	286.1MPa
B	68.9 MPa	500.1 MPa
C	0	0.022
M	1.85	0.917
N	1.004	0.2282
T_m	533 ºK	1811 ºK
γ	0.344	0.26
D_1	0	0.403
D_2	0	1.107
D_3	0	-1.899
D_4	0	0.00961
D_5	0	0.3

- Littlewood, D. J., '*Simulation of Dynamic Fracture using Peridynamics, Finite Element Modeling, and Contact*', Proceedings of the ASME 2010 International Mechanical Engineering Congress and Exposition. Vancouver, Canada, 2010.
- Seidt, J.D., Gilat, A., Klein, J.A., Leach, J.R., "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 (EOS)

- Both LS-DYNA and CTH simulations use **Grüneisen** equation of state (EOS) for Lexan projectile and A36 Steel plate to accompany the Johnson-Cook material model.
- Pressure for compressed materials:

$$p = \frac{\rho_0 C^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{a}{2}\mu^2\right]}{\left[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2}\right]^2} + (\gamma_0 + a\mu)E$$

where,

C is the intercept of the shock velocity-particle velocity curve

S_1, S_2, S_3 are dimensionless coefficients of the curve

γ_0 is the dimensionless Grüneisen gamma

a is the dimensionless first order correction to γ_0

$$\mu = \frac{\rho}{\rho_0} - 1$$

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Computational Simulation: Equation of State (EOS)

- Grüneisen EOS parameters are listed below:

Parameters	Lexan (Steinberg 1996)	A36 Steel (Elshenawy 2013)
ρ	1190 kg/m^3	7890 kg/m^3
C_0	1933 m/s	4659 m/s
S_1	1.42	1.49
γ_0	0.61	2.17

- Steinberg, D. J. *'Equation of State and Strength Properties of Selected Materials';* UCMRL–MA–106439; Lawrence Livermore National Laboratory: Livermore, CA, 1996.
- Elshenawy, T., Li, Q. M., *'Influences of Target Strength and Confinement on the Penetration Depth of An Oil Well Perforator'*, International Journal of Impact Engineering, V. 54, pp. 130-137, April 2013.

Computational Simulation: Spall Parameter

- In both LS-DYNA and CTH, spall failure is invoked when the tensile stress exceeds a certain pressure cut-off (i.e. P_{min}) value.

- In LS-DYNA , P_{min} value is defined in *MAT_JOHNSON_COOK card.

  Lexan: P_{min} = - 160 MPa [Steinberg 1996]

  A36 steel: P_{min} = - 700 MPa [Zurek 2003]

- Steinberg, D. J. *'Equation of State and Strength Properties of Selected Materials';* UCMRL−MA−106439; Lawrence Livermore National Laboratory: Livermore, CA, 1996.
- Zurek, A. K., Majita, J., Cerreta, E., & Trujillo, C. P. (2003). Experimental Study of A36 Steel Spall Fracture. Journal De Physique IV, 110, 863–867.

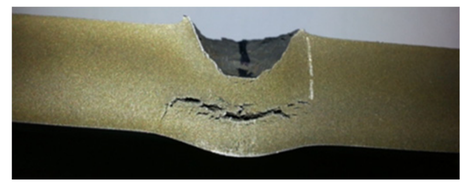
Results and Discussion

- 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 on the rear side of the target.
  - Shock wave reaches a free boundary surface and the surface is subjected to tensile force.
  - The material fails when the tensile pressure is above the material strength.
- **Physical measurements** of crater and bulge are taken typically after every experiment.

Front Side

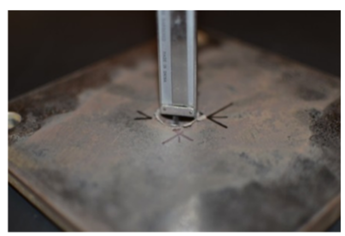
Back Side

Typical target plate after experiment

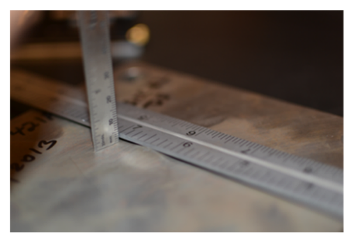


Spalling of target plate (sectioned)

Impact crater diameter measurement



Depth of penetration measurement



Bulge measurement

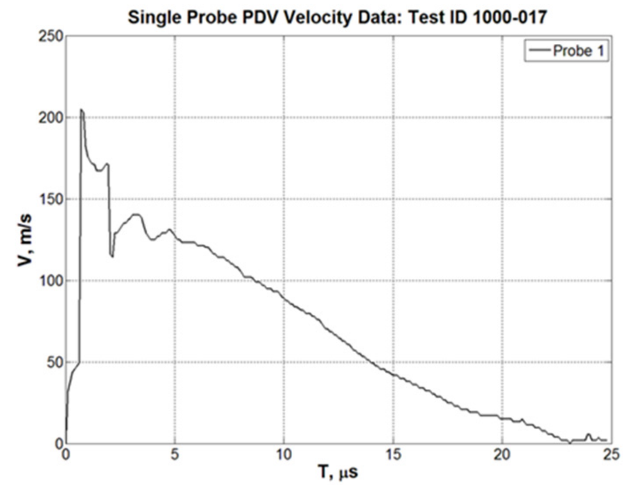
Results and Discussion

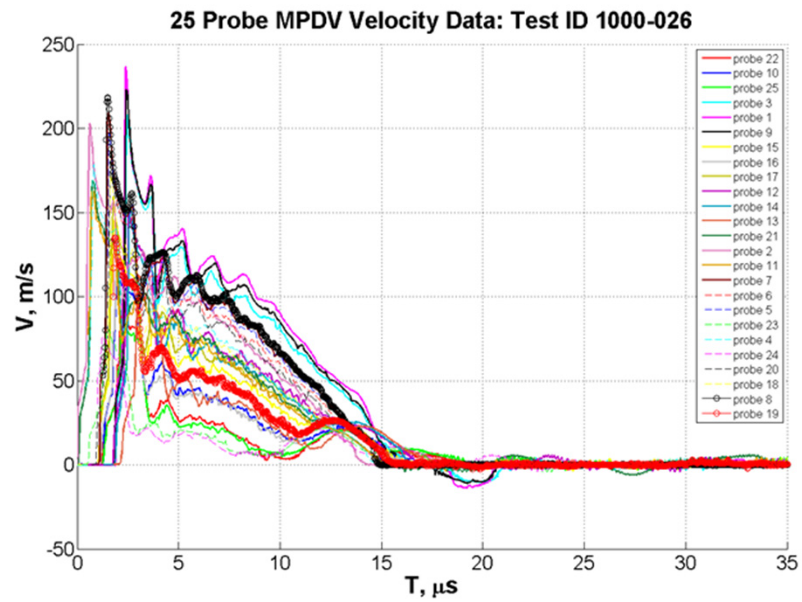
Test ID	PDV system details	Impact Velocity, km/s	Target after impact		
			Crater Diameter, mm	Penetration, mm	Bulge, mm
1000-016	single probe	5.338	17.01	6.32	2.32
1000-017		5.063	16.86	6.89	2.36
1000-024	9 probe MPDV	5.708	17.17	7.71	3.13
1000-025		4.763	15.37	6.50	1.42
1000-026	25 probe MPDV	4.823	15.14	6.51	1.48
1000-027		5.088	16.90	7.00	2.33
1000-028		5.157	15.90	6.50	1.67

- 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.

Results and Discussion

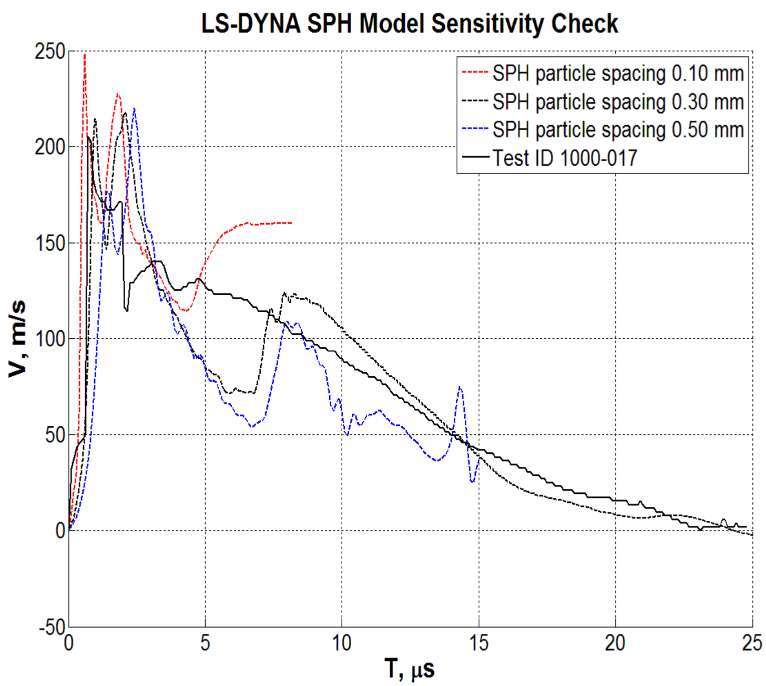
- **Free surface velocity** are measured by PDV and MPDV systems.
- Probe locations and velocity signal arrival time are very important for MPDV system.
- Typically, probe closest to the impact center should get velocity signal first and show maximum velocity profile in MPDV system. That didn't happen!
- Possible explanation for these kind of discrepancies in MPDV data may be due to causes like material defects to probe quality.
- Significant efforts are still in process to better represent and understand the MPDV data.

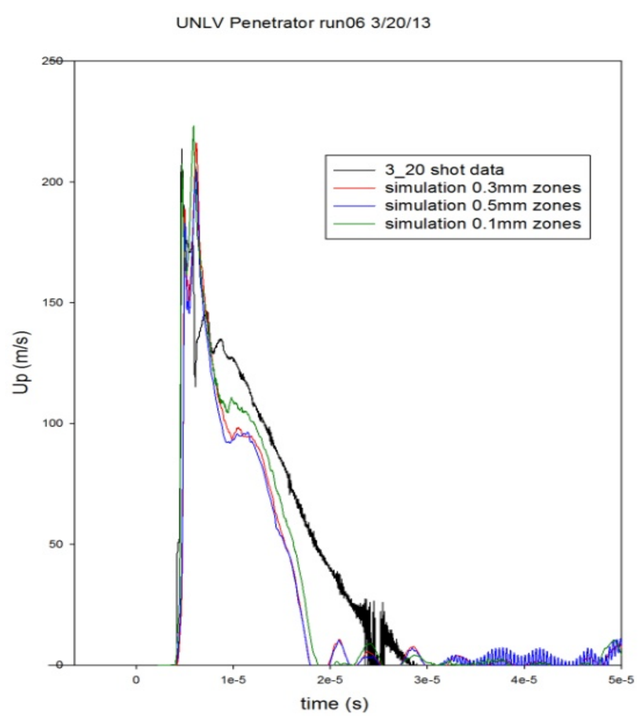




Simulation Comparison: Model Sensitivity Check

- Mesh sensitivity of both models are studied.
- The results indicate that 0.30 mm x 0.30 mm spacing (LS-DYNA)/zone size (CTH) gives the best results.





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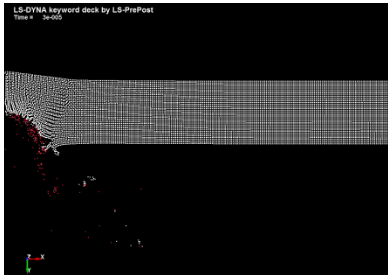
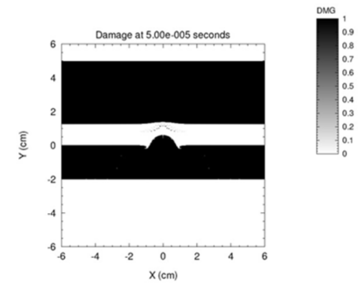
Simulation Comparison: Crater and Deformation

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



Typical LS-DYNA simulation



Typical CTH simulation

- Comparison of crater and bulge dimensions with LS-DYNA simulations are listed below

Test ID	Crater Diameter, mm		% Error	Penetration, mm		% Error	Bulge, mm		% Error
	Experimental	LS-DYNA Simulation		Experimental	LS-DYNA Simulation		Experimental	LS-DYNA Simulation	
1000-016	17.01	17.02	0.06	6.32	7.35	14.01	2.32	3.65	57.33
1000-017	16.86	15.90	5.69	5.76	5.04	14.22	2.36	2.17	8.05
1000-024	17.17	17.08	0.52	6.64	7.02	5.37	3.13	3.16	0.96
1000-025	15.37	16.20	5.40	4.83	4.14	16.75	1.42	1.39	2.11
1000-026	15.14	16.30	7.66	4.84	4.67	3.71	1.48	1.54	4.05
1000-027	16.90	16.88	0.12	5.40	4.91	9.98	2.33	1.86	20.17
1000-028	15.90	16.68	4.91	5.17	5.21	0.83	1.67	1.97	17.96
Average Error (%)			**3.48**			**9.27**			**15.81**
Standard Deviation			**3.16**			**6.07**			**19.81**

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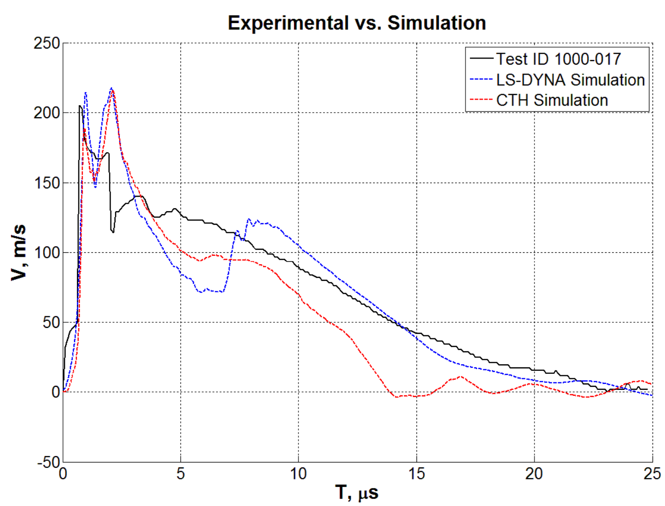
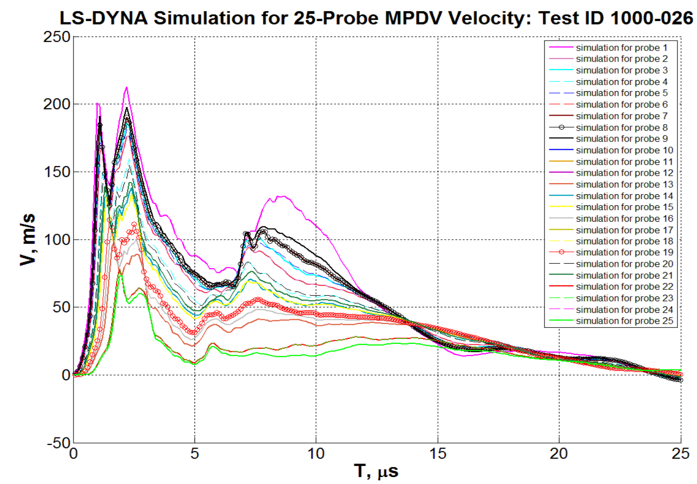
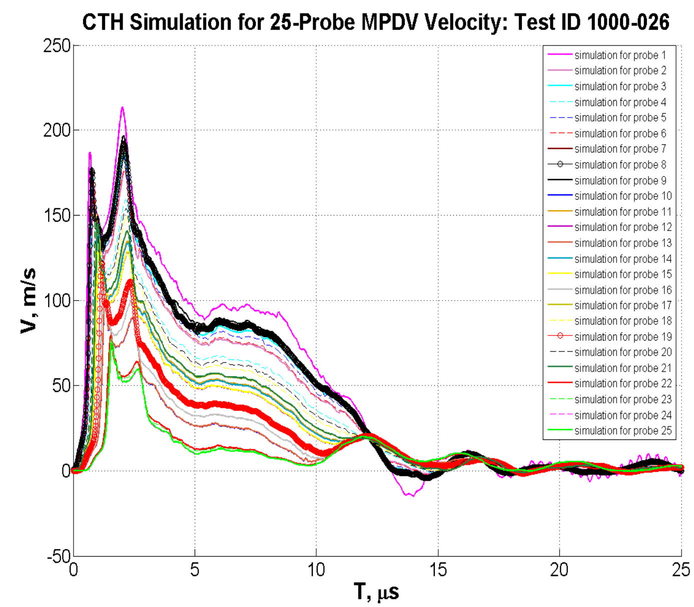
Simulation Comparison: Free Surface Velocity

- Both LS-DYNA and CTH simulations have been able to reasonably able to simulate the free surface velocity profiles.
- Further refinement of simulations are still in progress!



Typical single probe PDV data compared with CTH and LS-DYNA simulation





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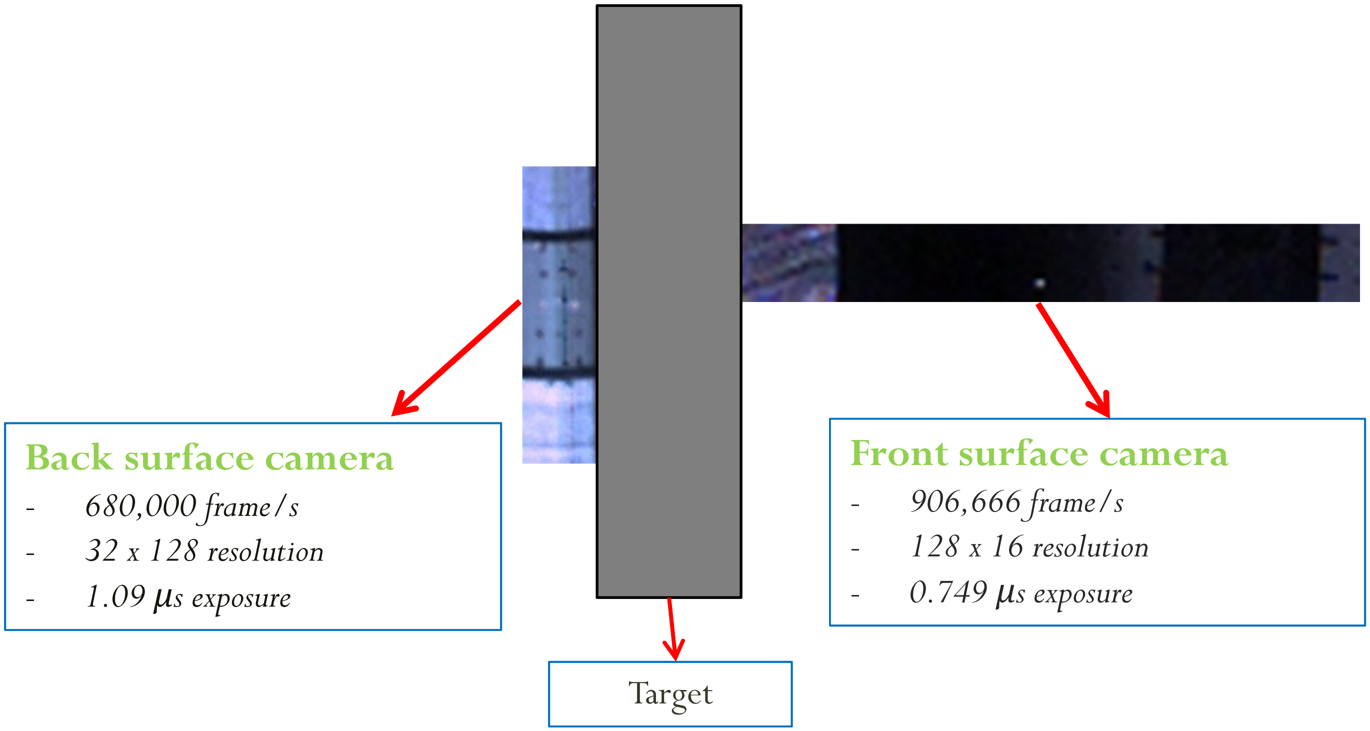
Conclusion

- Two-stage light gas gun experiments have been performed to study the plastic deformation of steel plates during high impact loading.
- Velocity of the back surface of the plate was measured using PDV and MPDV system during these experiments.
- Simulation models developed in LS-DYNA SPH solver and CTH hydrocode can reasonably simulate the experiments.
- Additional experiments and refinement of the simulation models, including the use of more accurate material models and simulation parameters are needed to further refine the simulation results.

Further Work

- Recent gas gun experiments include high speed imaging with two Phantom v710 model high speed cameras.
- Camera data will be analyzed to understand the plastic deformation behavior and will relate to PDV/MPDV data.



- Phase transition study in A36 steel due to high impact loading is in progress through electron microscopy.

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Thank You!