FRAGMENTATION MODELS FOR HYPERVELOCITY IMPACT

Shengyu Zou - 35th Cycle

Supervisor: Prof. Alessandro Francesconi

Presentation for admission to 3nd PhD year – Jan. 11, 2022

Outline

- Research background
- SPH numerical simulation methodology
- Characterizing projectile shape effect on debris cloud
- Characterizing and modeling on fragmentation properties
- Experimental study on inclined impact effect of cylindrical projectile
- Summery

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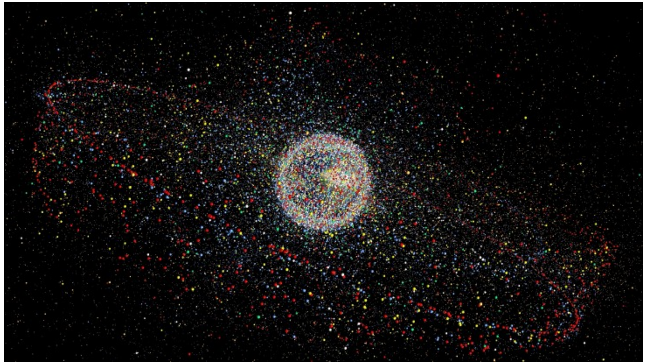
Research background

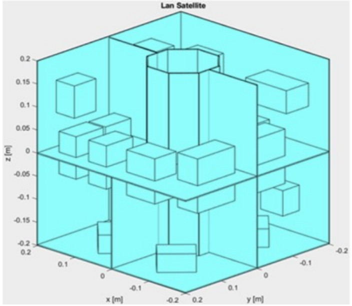
Space debris condition

- *Orbital space debris*



- *Fragmentation incidents on orbit*

- *Simulating experiment*



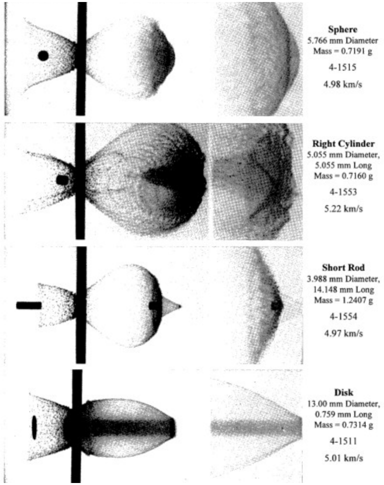
S. Lan, et al. 2014

- **One of the main causes of orbiting debris: hypervelocity impact fragmentation incident on orbit.**
- **From laboratory simulating test: a large fraction of fragmentation debris tend to be flake-like and long needle-like structures.**

Research background

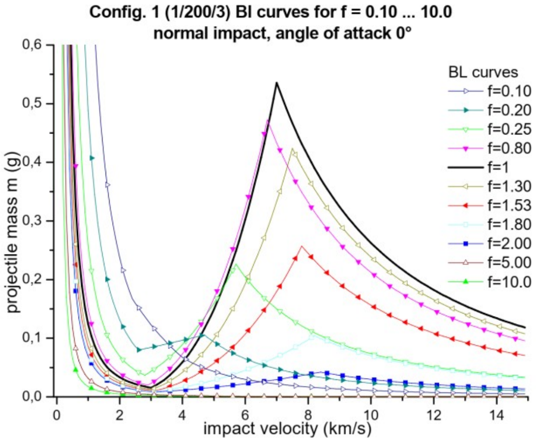
Projectile shape effect

- *Projectile shape effect on Debris cloud*



Piekutowski A.J. 1996

- *Projectile shape effect on ballistic limit curves for Whipple Shield*



F. Schafer, et al. 2003

- **Non-spherical projectiles have different characteristics in fragmentation of projectiles and shielding plates from which are generated by spherical projectiles, and consequently have different damage potential.**
- **This research aims to investigate the fragmentation models for hypervelocity impact with consideration of projectile shape effect.**

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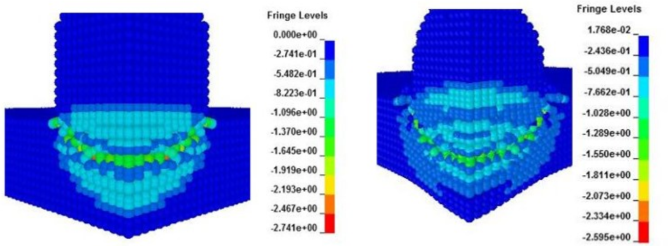
SPH simulation methodology

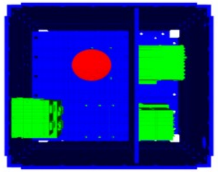
Smooth Particles Hydrodynamics - SPH

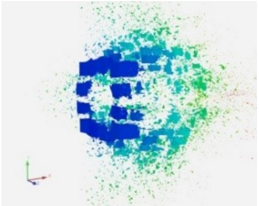


- Gridless method: filling up with particles.
- Extreme deformation and high pressure condition.

Parallel SPH simulation platform — PTS code

- PTS (Parallel Tool kit of SPH) : a parallel SPH simulation software from HIRC of CARDC.
- It can be more efficient, and of lower occupation of computational resources.
- Applications: 3D simulations of hypervelocity impact issues, and large-scale complex problems like fragmentation of orbiting satellite, simulation of asteroid impact, etc.





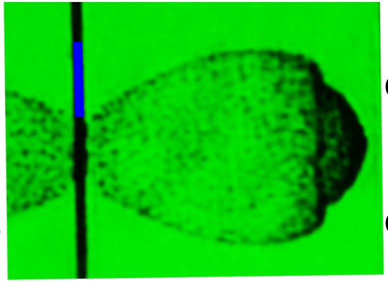
Simulation validation

Reference data of spherical projectile :

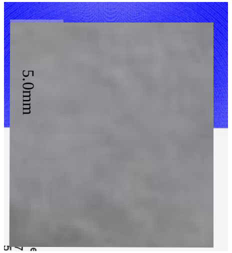
- Φ3.175mm sphere to 1mm sheet at 5.89km/s
- Projectile material: Al-2017, sheet material: Al-6061

Sim

Exp



	Length	Width		Diameter
Sim	65.7mm	41.6mm		6.95mm
Exp	66.4mm	46.7mm		7.3mm

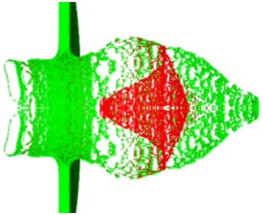


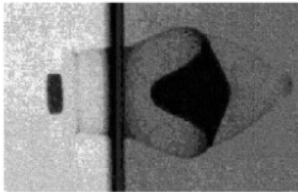
The deviation : 11% 5%

Simulation validation for shaped projectiles

Case 1:

- Cu projectile to Al sheet, at 5.55km/s
- Projectile diameter xthickness: 11.18mm3.45mm
- Sheet thickness:2.87mm

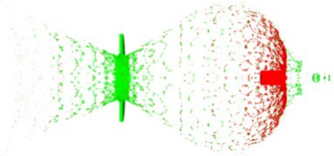


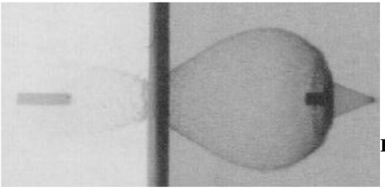


Experiment of Literature
Piekutowski A.J. 1990

Case 2:

- Zn projectile to Zn sheet, at 4.97km/s
- Projectile : 3.98mm14.15mm,
- sheet thickness: 1mm.

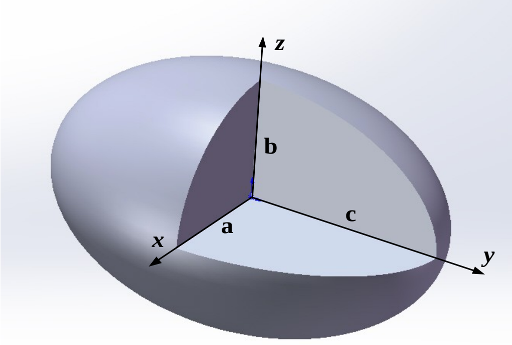


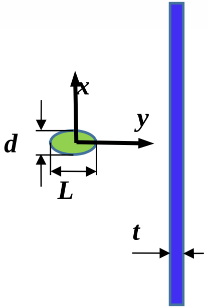


Experiment of Literature
Mullin S.A., et al. 1995

Simulation setups & cases

- **Ellipsoidal projectile: with L/d ranging 0.05~5, where *L*=2c, d=2a=2b, as shown below.**
- **Projectile material: Al-2024, sheet material: Al-6061.**
- **Collision attitude: both the ellipsoidal rotation axis and the flight direction being normal to the surface.**





L/d	*L*(mm)	*d*(mm)	Mass(mg)	Impact Velocity (km/s)	Sheet thickness (mm)
0.052	0.7	13.5	186	3.0, 5.0, 7.0	1.0, 2.0
0.103	1.1	10.7	183	3.0, 5.0, 7.0	1.0, 2.0
0.205	1.75	8.5	184	3.0, 5.0, 7.0	1.0, 2.0
0.5	3.15	6.3	182	3.0, 5.0, 7.0	1.0, 2.0
0.75	4.125	5.5	182	3.0, 5.0, 7.0	1.0, 2.0
1	5	5	183	3.0, 5.0, 7.0	1.0, 2.0
1.5	6.6	4.4	186	3.0, 5.0, 7.0	1.0, 2.0
3.043	10.5	3.45	182	3.0, 5.0, 7.0	1.0, 2.0
4.98	14.65	2.94	182	3.0, 5.0, 7.0	1.0, 2.0

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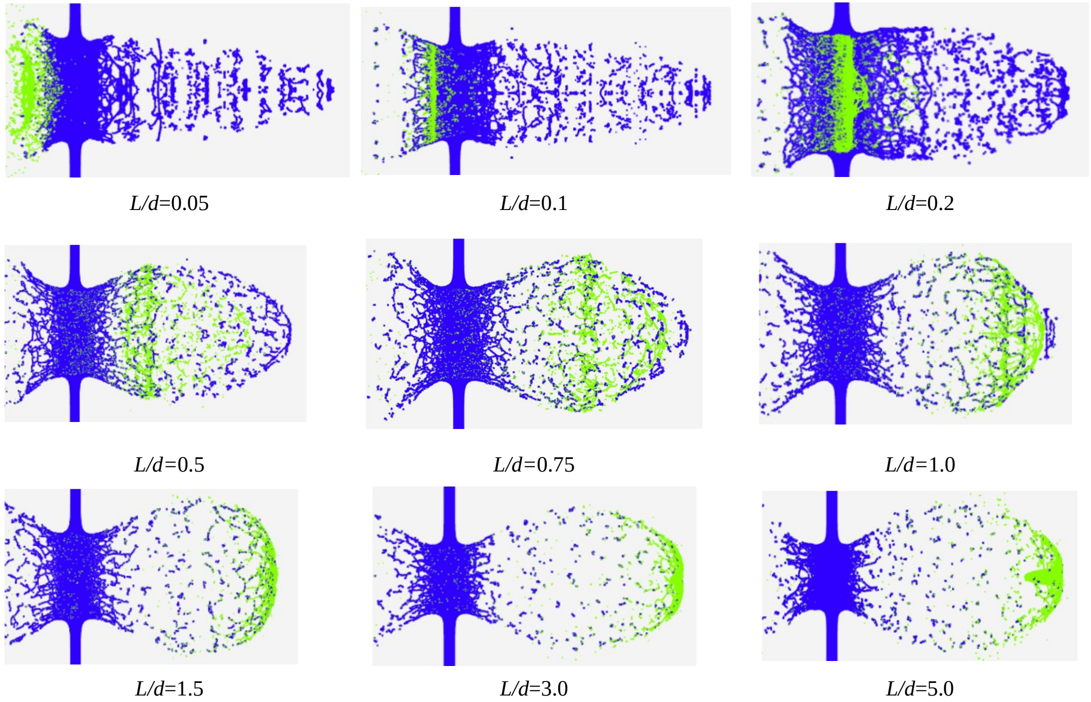
Characterization of debris cloud geometry

➢ ***For the case of 7km/s to 2mm bumper***

Projectile material

Bumper material



- Flat disk-like projectile produces a columnar debris cloud, in which the projectile material falls far behind the bumper material.

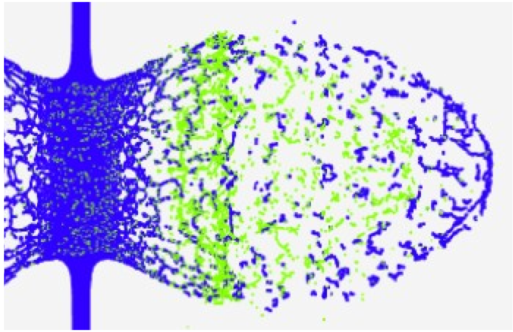
- Spherical projectile produces a more expanding debris cloud similar to spherical shell, in which the projectile material is located at the front part.

- Rod-like projectile produces a elliptical debris cloud, in which large remain of projectile is located at the leading part.

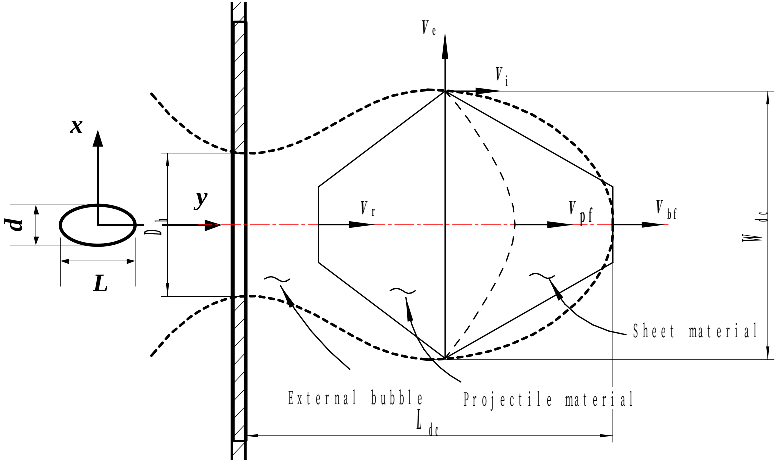
Characterization of debris cloud velocities

Debris clouds motions description

- **Axial velocities: the leading edge velocity of projectile fragment V_{pf}, the leading edge velocity of target fragment V_{bf},**
- **Radial velocity: the expanding velocity of debris cloud V_e.**



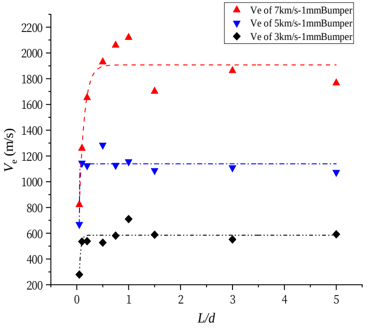
Piekutowski model



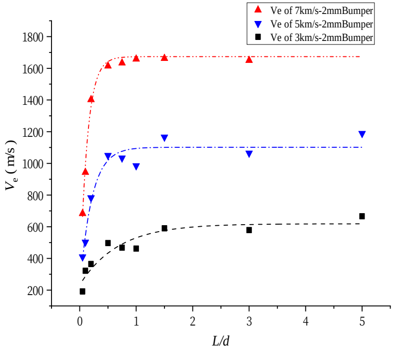
Characterization of debris cloud velocities

Fragments expanding velocity — V_e

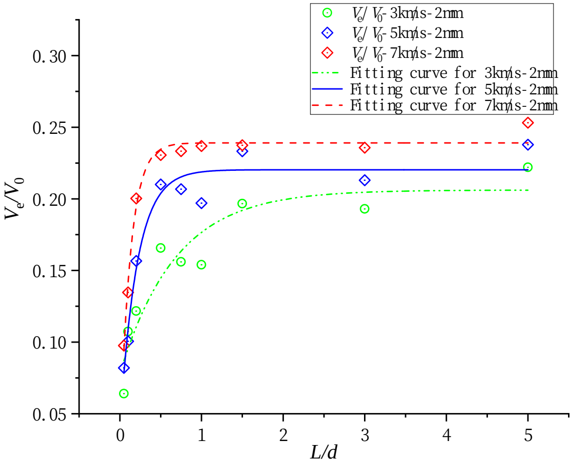
✓ **For 1mm sheet**



✓ **For 2mm sheet**



✓ **Normalized expanding velocity — V_e / V_0**

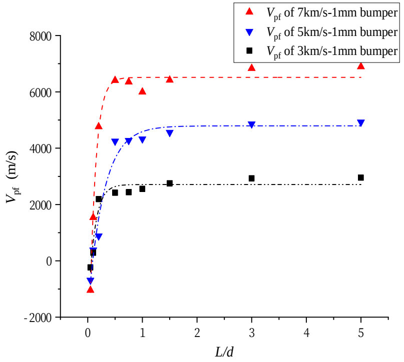


- **Disk-like projectile： lower expanding velocity.**
- **Sphere and rod-like projectile: higher expanding velocity.**
- **Thicker sheet : lower expanding velocity.**
- **Nonlinear relationship between V_e and V_0.**

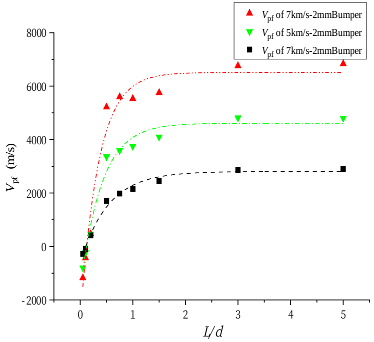
Characterization of debris cloud velocities

☐ The leading-edge velocity of projectile fragments — V_{pf}

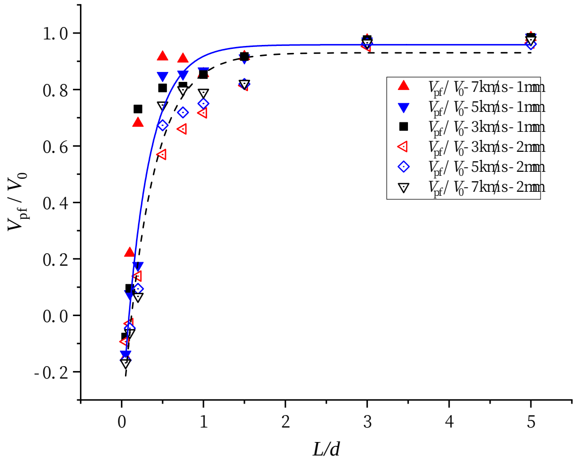
✓ **For 1mm sheet**



✓ **For 2mm sheet**



✓ **Normalized velocity — V_{pf} / V_0**

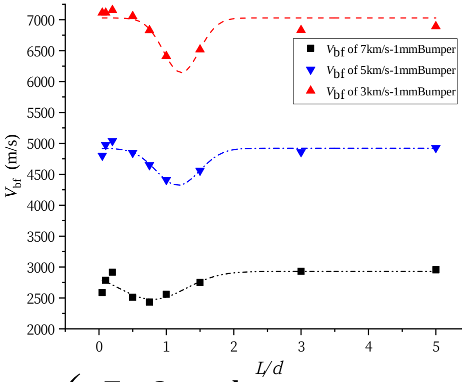


- **Disk-like projectile： lower or backward axial moving velocity.**
- **Sphere and rod-like projectile: higher projectile fragments velocity.**
- **Thicker sheet : little effect on the projectile leading-edge velocity.**
- **Nearly linear relationship between V_{pf} and V_0.**

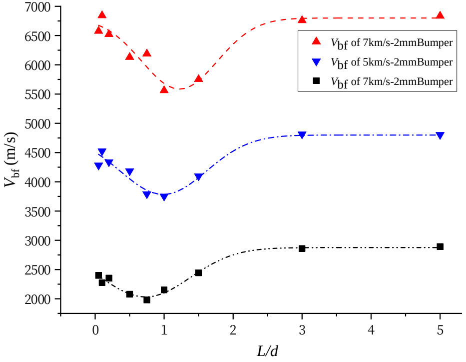
Characterization of debris cloud velocities

□ The leading-edge velocity of target fragments — V_{bf}

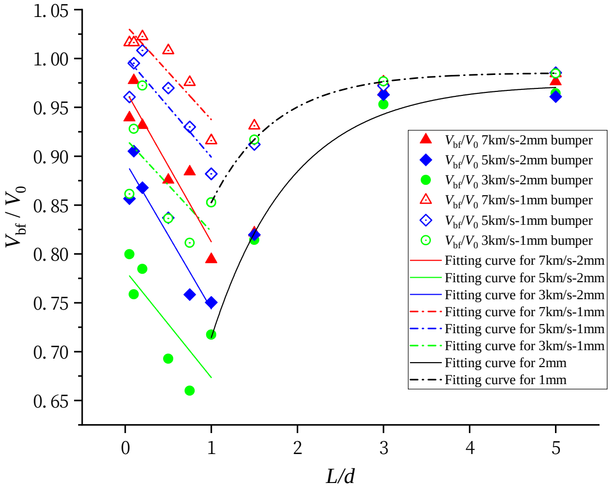
✓ **For 1mm sheet**



✓ **For 2mm sheet**



✓ **Normalized velocity — V_{bf} / V_0**



- **Sphere-like projectile: lower velocity of V_{bf} .**
- **Disk-like and rod-like projectile： higher velocity of** V_{bf} .
- **Linear relationship between V_{bf} / V_0 and *L/d* where *L/d* .**
- **Exponential relationship between V_{bf} / V_0 and *L/d* where *L/d* .**

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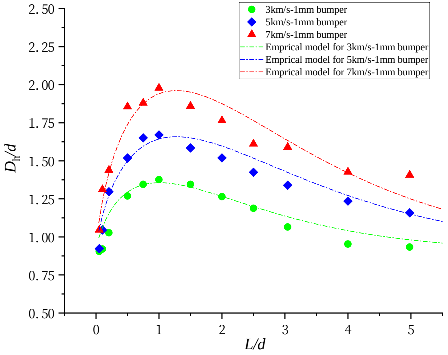
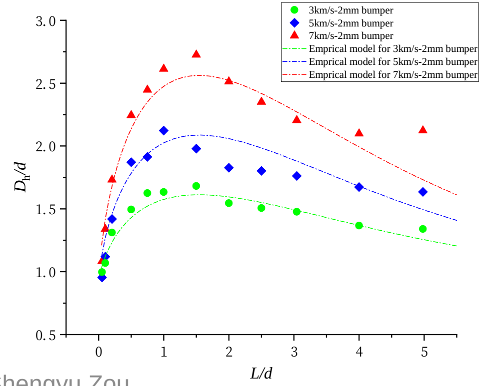
Characterizing and modeling on perforation hole

Diameter of perforated hole

For 1mm sheet



For 2mm sheet



Empirical models

- **For spherical projectile:**

Maiden CJ, McMillan AR. *AIAAJ 1964;2(11).*

$$\frac{D_h}{d} = 2.4 \cdot \frac{V_0}{c} \cdot \left(\frac{t_b}{d}\right)^{2/3} + 0.9$$

Shape effect consideration

$$f\left(\frac{L}{d}\right) = k_1 \left(\frac{L}{d}\right)^a \cdot e^{k_2 \frac{L}{d}}$$

- **For shaped projectile:**

$$\frac{D_h}{d} = 2.4 \cdot \frac{V_0}{c} \cdot \left(\frac{t_b}{d}\right)^{2/3} \cdot k_1 \left(\frac{L}{d}\right)^a \cdot e^{k_1(L/d)} + 0.9$$

✓ **For 1mm sheet**

$$f\left(\frac{L}{d}\right) = 1.6933 \left(\frac{L}{d}\right)^{0.7173} \cdot e^{-0.5620(L/d)}$$

✓ **For 2mm sheet**

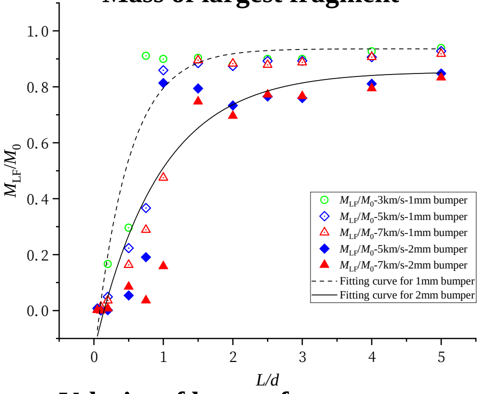
$$f\left(\frac{L}{d}\right) = 1.4069 \left(\frac{L}{d}\right)^{0.6552} \cdot e^{-0.4247(L/d)}$$

Ref: *S. Zou, L. Olivieri a, Z. Ma c, C. Giacomuzzo a,b, A. Francesconi. 72nd IAC, Oct. 2021.*

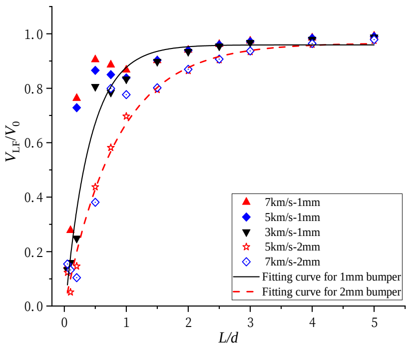
Characterizing and modeling on the largest fragment

Mass and velocity of largest fragment

Mass of largest fragment



Velocity of largest fragment



➢ ***Empirical models***

A pattern of exponential decay function was proposed.

$$\frac{M_{LF}}{M_0} = a_1 \cdot e^{-\frac{L/d}{a_2}} + C_1$$

$$\frac{V_{LF}}{V_0} = b_1 \cdot e^{-\frac{L/d}{b_2}} + C_2$$

✓ **For 1mm sheet**

$$\frac{M_{LF}}{M_0} = -1.2998 \cdot e^{-\frac{L/d}{0.6495}} + 0.9355$$

$$\frac{V_{LF}}{V_0} = -0.9735 \cdot e^{-\frac{L/d}{0.8402}} + 0.9660$$

✓ **For 2mm sheet**

$$\frac{M_{LF}}{M_0} = -0.9980 \cdot e^{-\frac{L/d}{0.9387}} + 0.8547$$

$$\frac{V_{LF}}{V_0} = -0.9986 \cdot e^{-\frac{L/d}{0.4016}} + 0.9593$$

Ref: *S. Zou, L. Olivieri a, Z. Ma c, C. Giacomuzzo a,b, A. Francesconi. 72nd IAC, Oct. 2021.*

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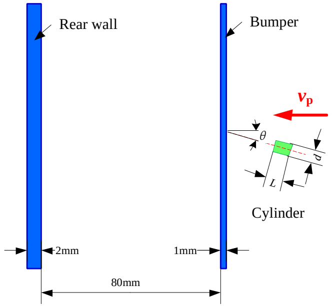
Experimental study on inclined impact effect of cylindrical projectile

Experimental work

✓ Test setup

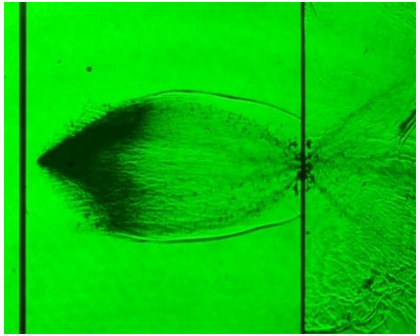
- **Test facility: Two-stage-light-gas-gun.**
- **Projectile: Cylinders of aluminum.**
- **Target: Whipple shields of aluminum.**

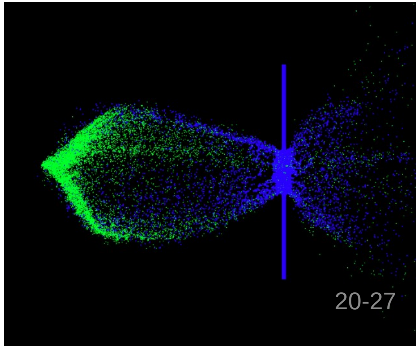
✓ Configuration of Whipple shield



✓ The Whipple shield target after experiment

✓ Debris cloud images from experiment and numerical simulation

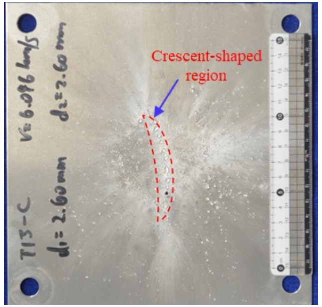




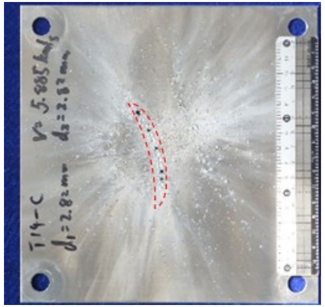
Experimental study on inclined impact effect of cylindrical projectile

Damage pattern of the rear wall

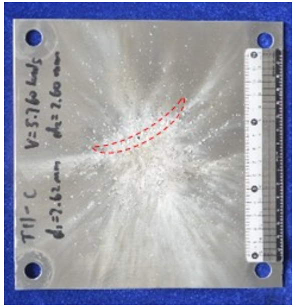
✓ **Rear wall images from experiments around 6km/s**



30° inclined

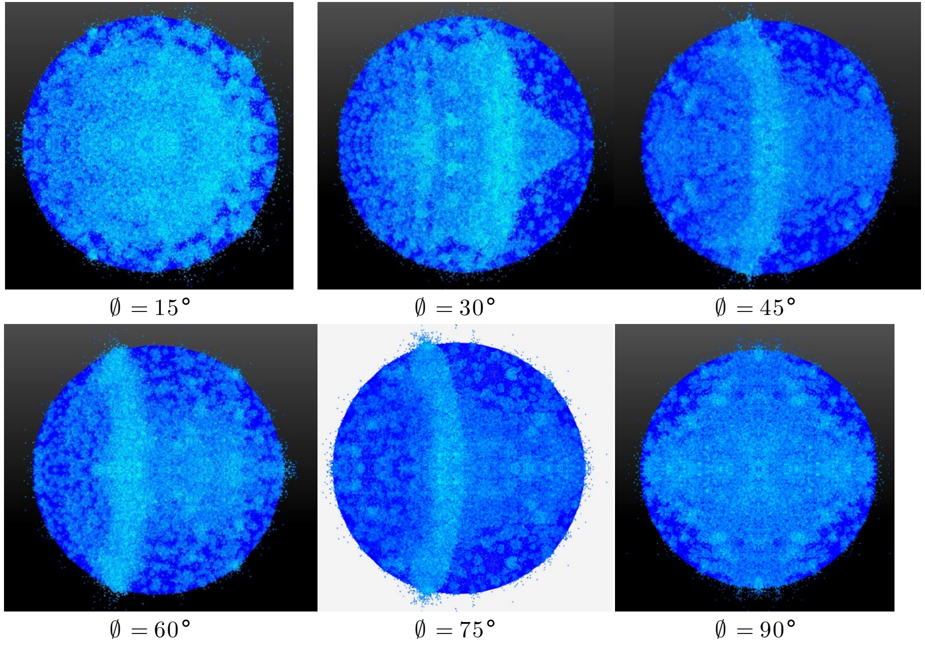


31° inclined



45° inclined

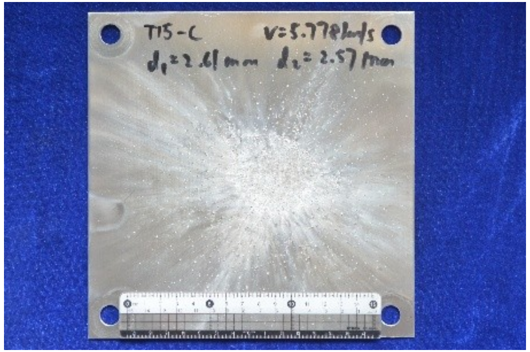
✓ **Rear wall images from simulation at 6km/s**



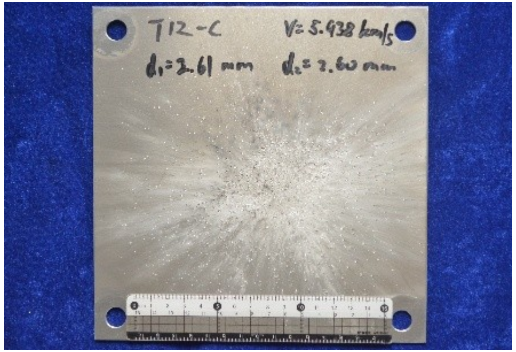
Critical inclined angle analysis

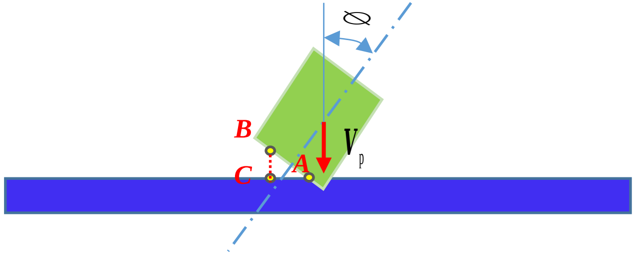
- ✓ 45° inclined cylinder of Φ2.62mm x 2.6mm at 5.760km/s

- ✓ 75° inclined cylinder of Φ2.61mm X 2.57mm at 5.778km/s



- ✓ 80° inclined cylinder of Φ2.61mm X 2.60mm at 5.938km/s





$$\frac{BC}{v_p} = \frac{AB}{U_s}$$

$$\sin \varnothing_{cr} = \frac{BC}{AB} = \frac{v_p}{U_s}$$

- ✓ If impact velocity is 6km/s, then the critical inclined angle is 40 °.

Schonberg W. etc, 1993

Summery of works done

- ***Characterizing projectile shape effect on debris cloud geometry and debris cloud motions:***
  - Flat disk-like projectile produces debris cloud with columnar geometry, in which the expansion velocity of debris cloud is lower, while the leading-edge velocity is relatively higher; the debris cloud produced by a sphere-like projectile has a higher expansion velocity but a lower leading-edge velocity, that means the debris cloud has a higher level of fragments diffusion; the fragmentation rate caused by impacting with a rod-like projectile is significantly insufficient, thus the total fragments population is significantly small, and the debris cloud includes a primary fragment with both mass and velocity close to those of projectile before collision.
- ***Characterizing and modeling projectile shape effect on perforation hole size:***
  - The sheet perforation capability of sphere-like projectile is strongest, after that, the rod-like projectile takes lower capability in sheet perforation, and the flat disk-like projectile takes the lowest capability in sheet perforation.
- ***Characterizing and modeling projectile shape effect on largest fragment:***
  - Flat disk-like projectile undergoes the most complete fragmentation because of hypervelocity impact, consequently it results in finest fragments with tiny mass and a smaller largest fragment with lower velocity. Projectiles with bigger shape factor(L/d) undergo lower level of hypervelocity impact fragmentation, thus the mass and velocity of primary fragment increase as the projectile shape transforms from disk-like one to rod-like one.
- ***Investigating the inclined impact of cylindrical projectile :***
  - For inclined impact, the most damaged area on rear wall was commonly crescent-shaped, and biased away the central craters. There is a critical inclined angle for cylindrical projectile according to shockwave propagation.

Thanks for your attention

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