

FRAGMENTATION MODELS FOR HYPERVELOCITY IMPACT Shengyu Zou - 35th Cycle

Supervisor: Prof. Alessandro Francesconi

Presentation for admission to the PhD thesis evaluation procedure– Dec. 15, 2022



Outline

- Research background and motivations
- Research methodology
- Properties and models for hypervelocity impact fragmentation
 - Properties and models for debris-cloud velocities
 - Properties and models for perforation hole
 - Properties and models for large central fragment
- Experimental research activities
 - Experimental study on hypervelocity impact debris-cloud
 - Experimental study on backwall damage response
 - Fragments recovery experiment

Conclusions & training activity

FRAGMENTATION MODELS FOR HYPERVELOCITY IMPACT



Space debris condition

> Orbital space debris

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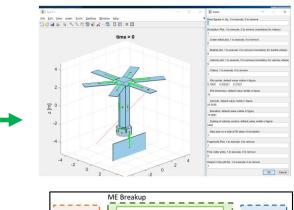
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Fragmentation incidents on orbit



Semi-empirical tool in CISAS -CST



1. Fragmentation preprocessing

2. Breakup threshold determination

5. Definition of impacts by only bubbles

3 Definition of damaged MF properties

4. Fragmentation algorithm

1. Effective impact

areas calculation

4. Fragmentation

hreshold update

2. Specific impac

energy calculation

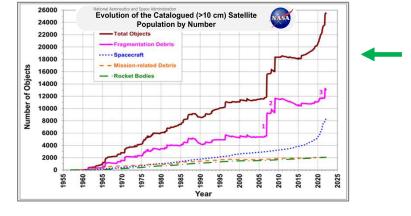
3. Fragmentation level definition

Fragments

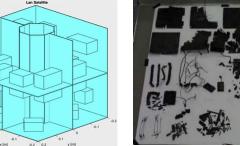
tracking

Structural

response



Laboratory tests



S. Lan, et al. 2014

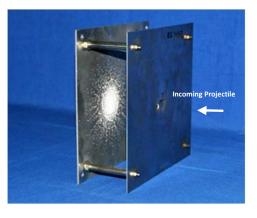


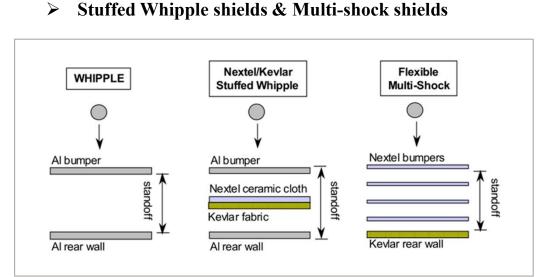


Research background

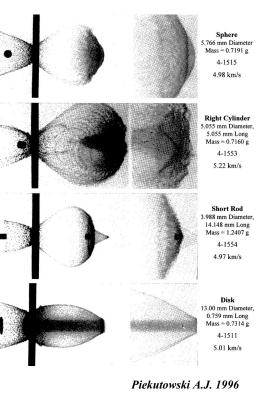
Space debris shields

Whipple shield *Whipple F.L in 1947*





> Thin-plate impact & shape effect



Motivations

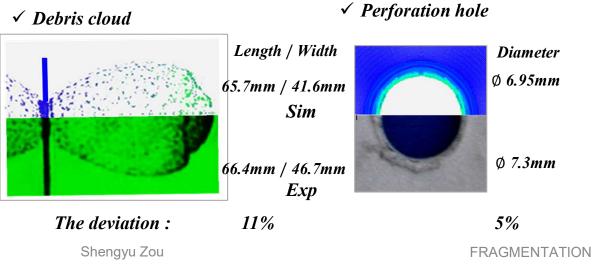
- To study the fundamental physics of the hypervelocity impact fragmentation subjected to thin-plate impact, and to characterize the fragmentation properties.
- To develop semi-empirical fragmentation models for hypervelocity impact with consideration of projectile shape effect.

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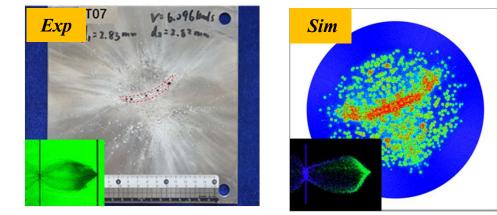
Numerical simulation- Smooth Particles Hydrodynamics (SPH)

- > Meshless method: filling up with particles.
- > Extreme deformation and high pressure condition.
- > Parallel SPH code-PTS of HIRC/CARDC
 - more efficient & lower occupation of computation resource.
- > More than 150 simulation cases had been performed in the PhD project.
- > Validations for simulation model

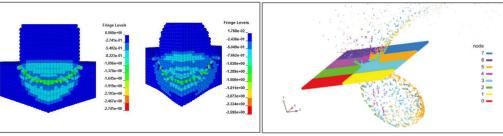
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✓ Backwall damage



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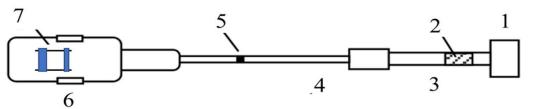
UNIVERSITÀ DECLI STUDI DI PADOVA Research methodology

Hypervelocity impact tests

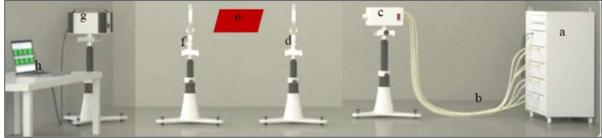
- > A total of 20 tests had been performed in the PhD project.
- > Test facilities in HIRC:

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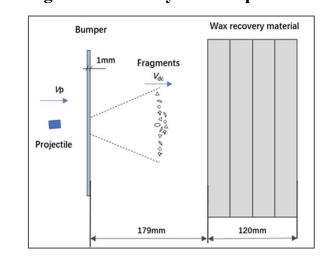
- Two-stage-gas-gun, caliber 16mm and 7.6mm, muzzle velocity up to 9km/s.
- Sequential laser shadowgraph instrument, $T_{\text{interval}} \ge 10$ ns

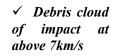


1—powder chamber; 2—piston; 3—pump tube; 4—launch tube; 5—projectile; 6—impact chamber; 7—target



Fragments recovery test setup





/3 L/d=1 L/d=1.5

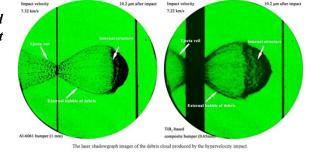
Cylinder

✓ *Projectiles and sabot*

Sphere

Sabot

Disk



a—pulsed lasers; b—optical fiber; c—light-separating instrument; d—collimating len-1; e—measuring area; f—collimating len-2; g—image system; h—control system Shengyu Zou FRAGMENTATION MODELS FOR HYPERVELOCITY IMPACT

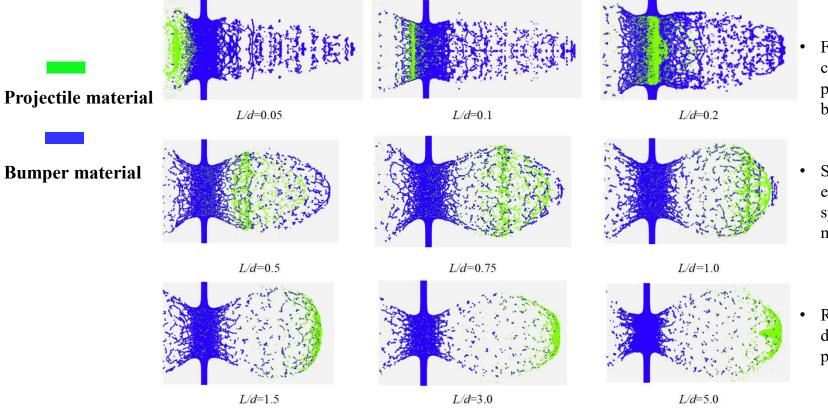
Properties and models for debris-cloud velocities

Study on debris cloud geometry

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



- 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.

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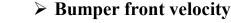
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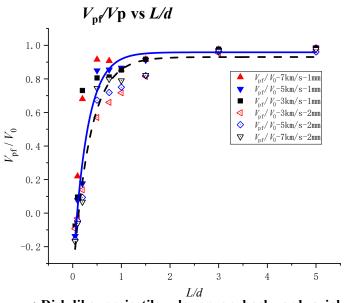
Properties and models for debris-cloud velocities

Characterization of debris cloud velocities

Projectile front velocity

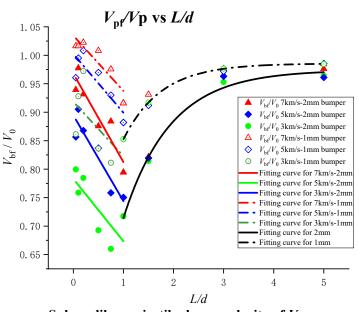
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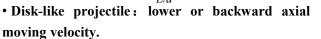




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- Sphere and rod-like projectile: higher projectile fragments velocity.
- Thicker sheet : little effect on the projectile leading-edge velocity.
- Nearly linear relationship between Vpf and $\mathbf{V}_{\mathbf{0}}$.

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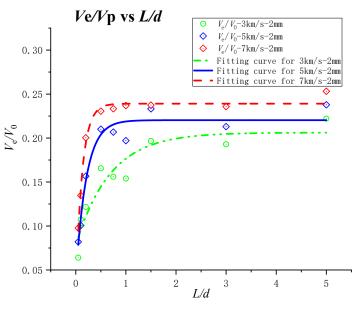
• Sphere-like projectile: lower velocity of $V_{\rm bf}$.

• Disk-like and rod-like projectile: higher velocity of $V_{\rm bf}$.

• Linear relationship between $V_{\rm bf}$ / V_0 and L/d where L/d < 1.

• Exponential relationship between $V_{\rm bf} / V_0$ and L/dwhere L/d > 1.

> Expanding velocity



- Disk-like projectile: lower expanding velocity.
- Sphere and rod-like projectile: higher expanding velocity.
- Thicker sheet : lower expanding velocity.
- Nonlinear relationship between $V_{\rm e}$ and $V_{\rm 0}$.

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

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Properties and models for debris-cloud velocities

□ Models for Debris-cloud velocities

Semi-empirical dimensionless model

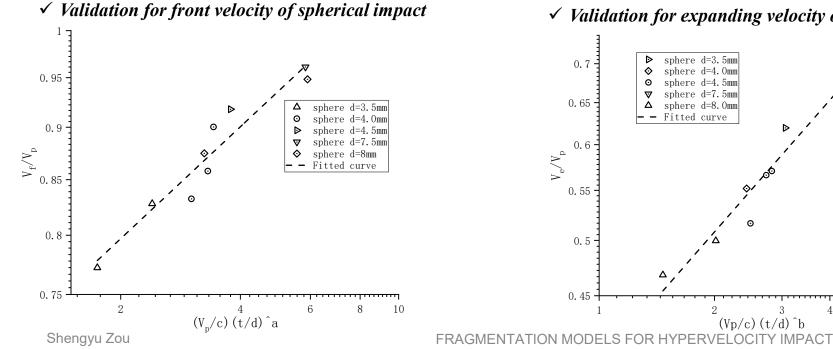
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$$\frac{V_{dc}}{V_{p}} = C \cdot \left(\frac{t}{d}\right)^{a} \cdot \left(\frac{V}{c}\right)^{\beta} \cdot \left(\frac{L}{d}\right)^{\gamma}$$

> Calibration and validation with test data



✓ *Calibrated parameters table*

Parameters	Model for V _f	Model for V _e
С	0.7053	0.3953
α	0.1761	0.3623
β	-0.1391	-0.2355

✓ Validation for expanding velocity of spherical impact

2

3

(Vp/c)(t/d) b

4

5

⊽



7

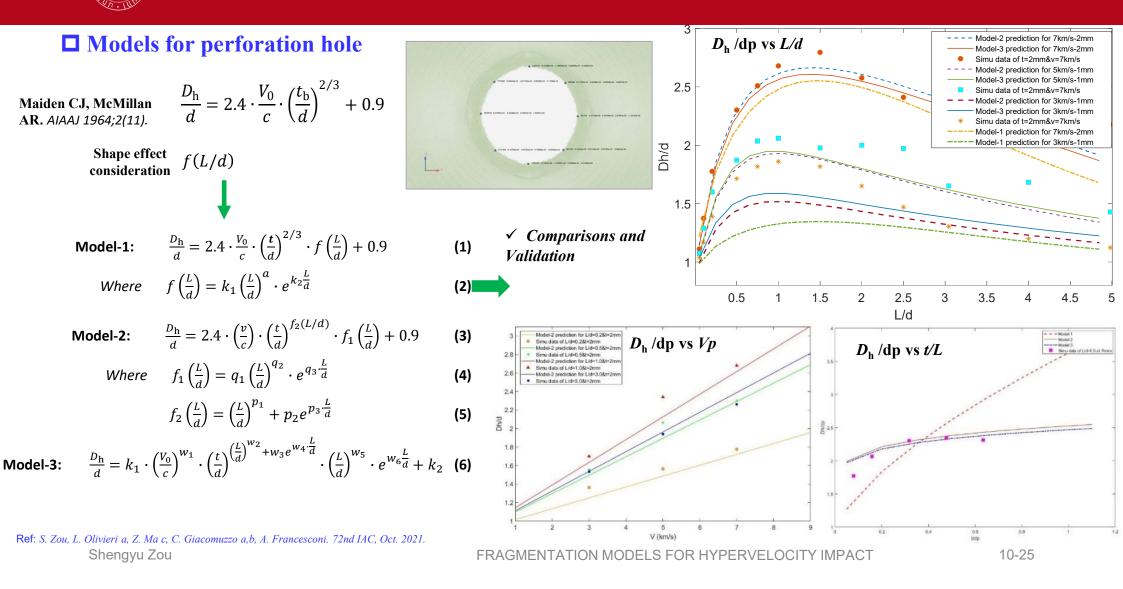
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Properties and models for perforation hole

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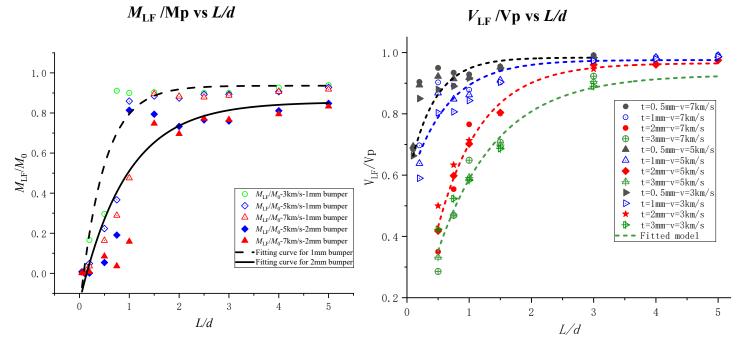
Properties and models for large central fragment

□ The effect of projectile shape L/d

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 $M_{\rm LF}$ was normalized by dividing it by the projectile mass $M_{\rm P}$. $V_{\rm LF}$ was normalized by dividing it by the impact velocity $V_{\rm P}$.



• $M_{\rm LF}$ is dependent on projectile shape, target thickness and impact velocity, while $V_{\rm LF}$ appears to depend on projectile shape and target thickness, but only slightly depend on impact velocity.

• Disk-like projectiles $(L/d \ll 1)$ are easiest to be fragmented, and have relative lower velocity of the large fragment.

• Rod-like projectiles are usually less fragmented and less impeded by thin plate target during hypervelocity impacts.

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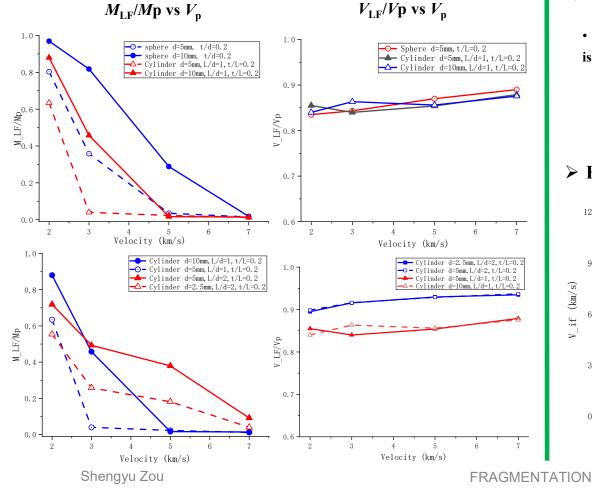
Properties and models for large central fragment

□ The effect of impact velocity

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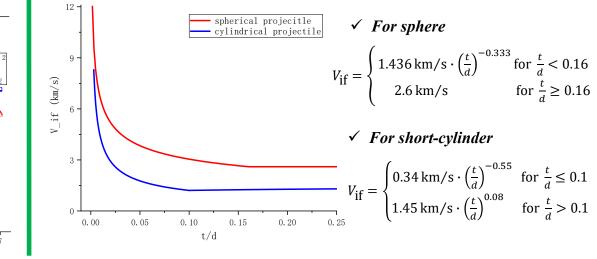


Geometrical scaling investigation

• $V_{\rm LF}$ is geometrical scaling for both spherical and non-spherical projectiles, while $M_{\rm LF}$ is not geometrical scaling but is size-dependent.

$$\frac{M_{\rm LF}}{M_{\rm p}} \propto \cdot \left(\frac{L}{d}\right)^{\alpha} \cdot \left(\frac{t}{L}\right)^{\beta} \cdot f\left(C\frac{V_{\rm p}}{d}\right) \qquad \qquad \frac{V_{\rm LF}}{V_{\rm p}} \propto C \cdot \left(\frac{L}{d}\right)^{\alpha} \cdot \left(\frac{t}{L}\right)^{b} \cdot \left(\frac{V_{\rm p}}{c}\right)^{\beta}$$

Fragmentation threshold-velocity investigation



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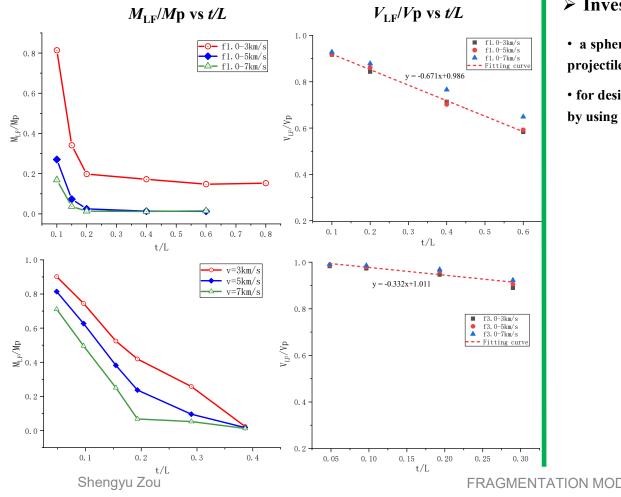
Properties and models for large central fragment

□ The effect of target thickness ratio t/L

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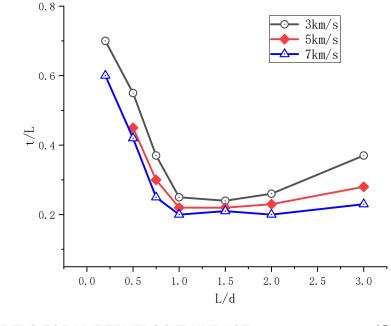
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Investigation on optimum bumper-thickness-ratio

• a sphere and a short-cylinder (L/d > 1) have a lower optimum t/L ratio than a disk-like projectile (L/d < 1) with equivalent initial mass.

• for designing a more conservative shield, it is necessary to carry out the evaluation tests by using disk-like projectiles rather than spheres or short cylinders.



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Università degli Studi di Padova **Properties and models for large central fragment**

Dimensional analysis for modelling

Based on Pi theorem, three fundamental variables: mass (\hat{M}), length (\hat{L}), time (\hat{T}).

> The mass of the large central fragment

 $M_{\rm LF} = f(t, L, d, V_{\rm p}, S, Z_{\rm p}/Z_{\rm t})$

Nondimensionalization v

$$\frac{M_{\rm LF} \cdot \rho_{\rm p} \cdot V_{\rm p}^{2-y}}{\rho_{\rm p} L d^2 \cdot S \cdot d^{-x-y}} = f\left(\frac{t}{L}, \frac{L}{d}, \frac{Z_{\rm p}}{Z_{\rm t}}\right)$$

$$\frac{M_{\rm LF}}{M_{\rm p}} = \frac{s \cdot d^{-x-y}}{\rho_{\rm p} \cdot V {\rm p}^{2-y}} \cdot f\left(\frac{t}{L}, \frac{L}{d}, \frac{z {\rm p}}{z_{\rm t}}\right) \qquad \qquad \frac{M_{\rm LF}}{M_{\rm p}} = C \cdot d^{-x-y} \cdot V {\rm p}^{-2+y} \cdot \left(\frac{t}{L}\right)^{\alpha} \cdot \left(\frac{L}{d}\right)^{\beta}$$

The model for large-central-fragment mass

$$1 - \frac{M_{\rm LF}}{M_{\rm p}} = \begin{cases} \approx 0 & \text{for } V_{\rm p} \le V_{\rm if} \\ C d^{\omega} \left(\frac{V_{\rm p} - V_{\rm if}}{V_{\rm if}}\right)^{\alpha} \left(\frac{t}{d}\right)^{\beta} \left(\frac{L}{d}\right)^{\gamma} & \text{for } V_{\rm if} \le V_{\rm p} \le V_{\rm cf} \\ \approx 1 & \text{for } V_{\rm p} > V_{\rm cf} \end{cases}$$

for
$$V_p \le V_{if}$$

for $V_{if} \le V_p \le V_{cf}$
for $V_p \ge V_{cf}$

✓ The units and dimensions of the variables

Variables	Units	Dimensions
t, L, d	m	Ĺ
V _p , V _f , c	m/s	$\hat{L} \cdot \hat{T}^{-1}$
M_{p},M_{LF}	kg	Â
$ ho_{p}$	kg/m ³	$\widehat{M}\cdot \widehat{L}^{-3}$
Y	N/m ²	$\widehat{M} \cdot \widehat{L}^{-1} \cdot \widehat{T}^{-2}$
K _c	N/m ^{3/2}	$\widehat{M}\cdot \widehat{L}^{-1/2}\cdot \widehat{T}^{-2}$

The velocity of the large central fragment

$$V_{\rm F} = f(t, d, L, K)$$

Nondimensionalization

The model for large-central-fragment velocity

$$V_{\rm F} = C \cdot d^{1+x} \cdot \left(\frac{t}{L}\right)^{\alpha} \cdot \left(\frac{L}{d}\right)^{\beta} \longrightarrow \frac{V_{\rm F}}{V_{\rm p}} = C \cdot \left(\frac{t}{L}\right)^{\alpha} \cdot \left(\frac{L}{d}\right)^{\beta} \cdot \left(\frac{V_{\rm p}}{c}\right)^{\gamma}$$

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 $\frac{V_{\mathrm{F}} \cdot K}{d^{1+x}} = f\left(\frac{t}{L}, \frac{L}{d}\right)$

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 $\leq V_{\rm cf}$

The model for large-central-fragment mass

> Model formulation

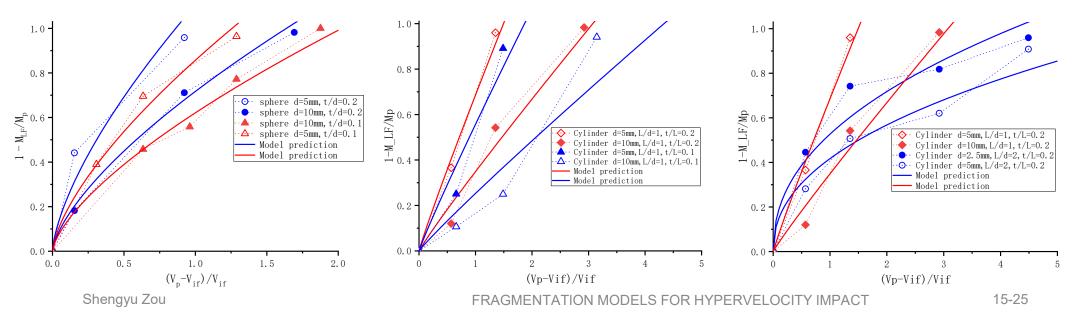
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$$1 - \frac{M_{\rm LF}}{M_{\rm p}} = \begin{cases} \approx 0 & \text{for } V_{\rm p} \le V_{\rm if} \\ C d^{\omega} \left(\frac{V_{\rm p} - V_{\rm if}}{V_{\rm if}}\right)^{\alpha} \left(\frac{t}{d}\right)^{\beta} \left(\frac{L}{d}\right)^{\gamma} & \text{for } V_{\rm if} \le V_{\rm p} \le V_{\rm cf} \\ \approx 1 & \text{for } V_{\rm p} > V_{\rm cf} \end{cases}$$

> Calibration and validation

✓ Calibrated parameters table

Deremeters		Projectile type	
Parameters	Sphere	Cylinder-L/d=1	Cylinder-L/d=2
С	4.471 mm ^{0.561}	4.072 mm ^{0.794}	4.072 mm ^{0.794}
ω	-0.561	-0.794	-0.794
α	0.675	0.937	0.577
β	0.316	0.331	0.331
γ	0	-1.003	-1.003



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□ The model for large-central-fragment velocity

> Model formulation

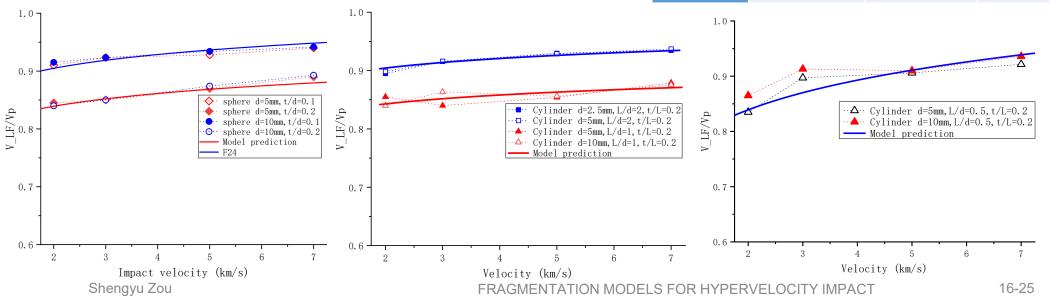
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$$\frac{V_{\rm LF}}{V_{\rm p}} = C' \cdot \left(\frac{V_{\rm p}}{c_t}\right)^{\alpha'} \cdot \left(\frac{t}{L}\right)^{\beta'} \cdot \left(\frac{L}{d}\right)^{\gamma'}$$

> Calibration and validation



		Projectile type	
Parameters	Cabara	Cylinder o	or ellipsoid
	Sphere	L/d=0.2~0.75	L/d=1~2
С′	0.7306	0.7338	0.7202
α′	0.0375	0.0895	0.0259
β′	-0.1086	-0.1080	-0.1132
γ′	0	-0.0671	0.1016



Experimental study on hypervelocity impact debris-cloud

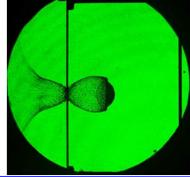
Debris cloud morphology

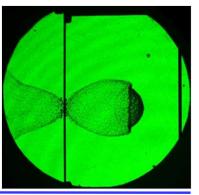
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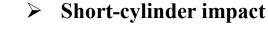
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> Sphere impact

- an external bubble and an internal structure including front cap, central element and rear element.
- a hemispherical shell of fragments spalling off the rear side of the projectile .



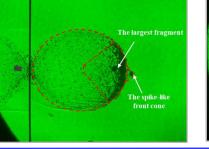


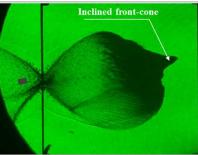


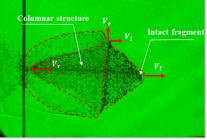
- a spike-like front cone at the leading edge with velocity of up to 4% greater than impact velocity.
- the head point of the front cone is coincident with the direction of the cylinder axis, and is dependent on the cylinder's impact inclination.

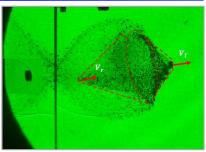


- consist of an external bubble, an internal cone and a front cone with its point aligned with the inclined direction of the disk axis.
- there is a long columnar structure in the middle, a fast-moving head at about 3% higher than Vp, and a very slow-moving end at only 6% of Vp.
- the columnar structure doesn't show any tendency to disperse.
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Experimental study on backwall damage response

✓ Analytic model for critical inclined angel

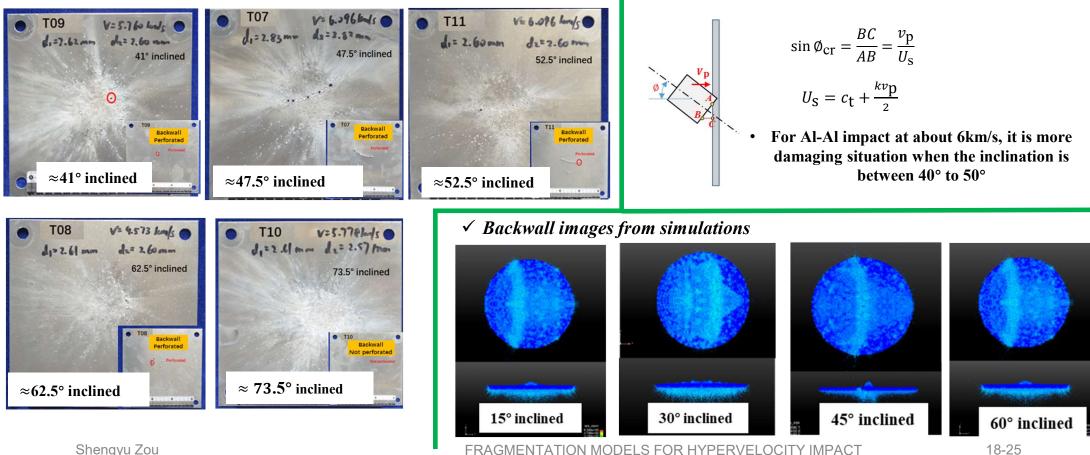
□ The inclination effect on backwall damage

✓ Backwall images from experiments

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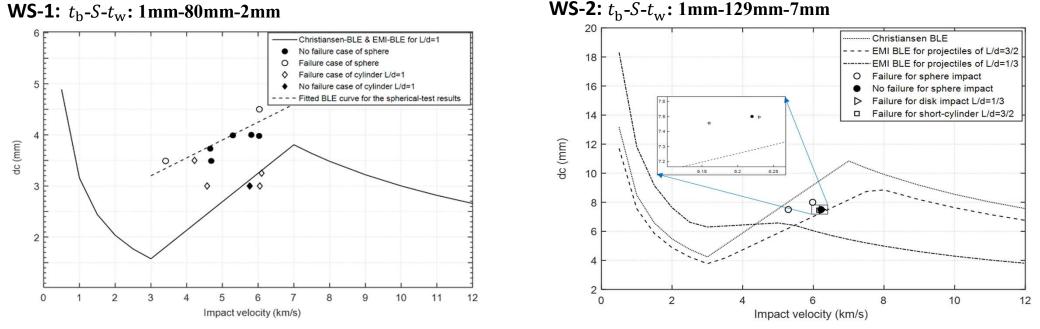
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Ballistic limit equation for Whipple shields

Examination and comparison of two BLE models: Christ-BLE and EMI-BLE.

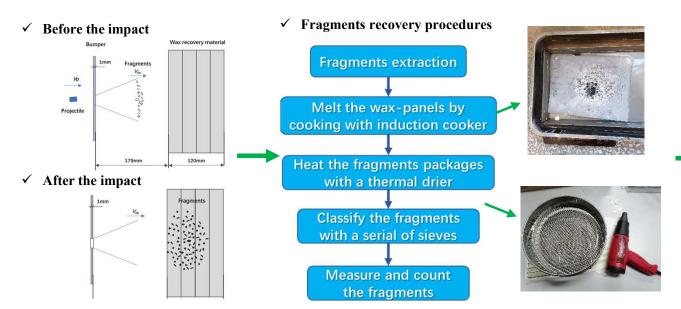


• Christ-BLE is up to 2 times more conservative for evaluating the performance of spherical impact against WS-1, but it is dangerous when used for non-spherical impact.

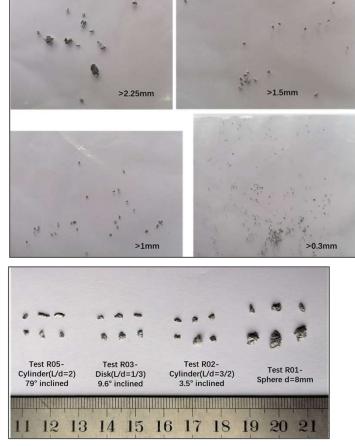
- EMI-BLE is much more conservative than Christ-BLE, and could be applied for non-spherical impacts.
- Both of the two BLEs could not be applied conservatively for the impacts with inclined cylinder .
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Fragments recovery and analysis



✓ Fragments collected from spherical impact



Comparisons of large fragments for impacts with different shaped projectiles

- The disk-like projectile is easiest to be fragmented, sphere is harder to be fragmented than short-cylinder.
- Impact of short-cylinder with large inclination undergoes a complete fragmentation like a disk projectile .

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Fragments distribution and model

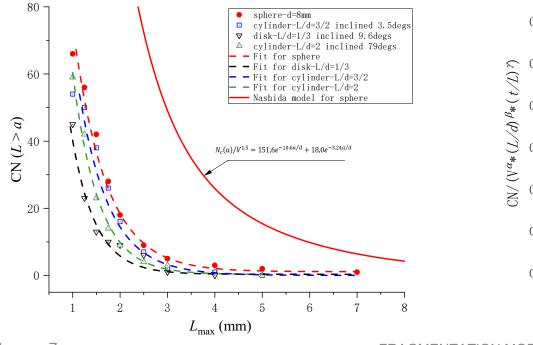
> For sphere impact

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Nashida Model:

M. Nishida, et al. 2017

$$N_c(a)/V^{1.5} = 50.7e^{-1.6a/d} + 2.9e^{-4.3a/d}$$



> A scaling model developed for impact with shaped projectiles

-

$$\frac{N_{c}(a)}{V_{p}^{\alpha} \cdot (t/L)^{\beta} \cdot (L/d)^{\gamma}} = A_{1}e^{B_{1}a/L}pmax + A_{2}e^{B_{2}a/L}pmax$$

$$\frac{Parameters}{V_{p}^{\alpha} \cdot (t/L)^{\beta} \cdot (L/d)^{\gamma}} = A_{1}e^{B_{1}a/L}pmax + A_{2}e^{B_{2}a/L}pmax$$

$$\frac{Parameters}{V_{p}^{\alpha} \cdot (t/L)^{\beta} \cdot (L/d)^{\gamma}} = A_{1}e^{B_{1}a/L}pmax + A_{2}e^{B_{2}a/L}pmax$$

$$\frac{Parameters}{V_{alues}} \frac{\alpha}{1.5} - 3.65 - 1.75 + 1.332 - 70.657 + 0.076 + 16.975$$

$$0.0150 + 0.0150 + 0.0125 +$$

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• 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.

• Properties study and model development for debris-cloud velocities:

- Debris cloud structure for different projectile shape were studied from the debris-cloud morphology based on simulation and experiments. The debris-cloud velocities were characterized and semi-empirical models for spherical impact have been developed.

• Properties study and model development for perforation hole :

- Based on simulation data, the sphere or short-cylinder is strongest in the enlargement capability of the perforation hole, while the rod-like projectile takes lower capability, and the flat disk-like projectile takes the lowest capability. Three semi-empirical models were proposed and compared.

• Properties study and model development for large central fragment:

The effects of shape ratio, target thickness ratio and impact velocity on the mass and the velocity of large central fragment were characterized, and semi-empirical models for the mass and the velocity of large central fragment were developed based on dimensional analysis, and were calibrated and validated with simulation data.
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• Investigated on fragmentation threshold velocity :

- There existed two threshold-velocities for judging the fragmentation intensity, one is the threshold-velocity of initiation fragmentation V_{if} , and another is the threshold-velocity of catastrophic fragmentation V_{cf} . Disk-like projectile has the lowest fragmentation threshold velocity, rod-like projectile has the largest fragmentation threshold velocity, and sphere or short-cylinder have moderate fragmentation threshold velocity. Short cylinder can be fragmented more easily than sphere at fixed t/d ratio.

• Investigated on optimum bumper-to-projectile thickness ratio:

- A sphere and a short-cylinder (L/d > 1) have a lower optimum t/L ratio than a disk-like projectile (L/d < 1). Such that it appears to be not conservative when sphere or short-cylinder is used to evaluate the effectiveness of a shield against space debris impacts. Thus for designing a more conservative shield, it is necessary to carry out the evaluation tests by using disk-like projectiles rather than spheres or short cylinders.

• Investigated on geometrical scaling of large-central-fragment:

- The velocity of the large central fragment is geometrical scaling for both spherical and non-spherical projectiles, while the mass of the large central fragment is not geometrical scaling but is size-dependent.

• Investigated on the inclination effect on cylindrical impact :

- The work of simulation, experiment and analytic model had performed. The investigation indicates: for inclined impact, the most damaged area on rear wall was commonly crescent-shaped, and biased away the central craters. For Al-to-Al impact, there is a more damaging situation when the inclination is between 40° to 50°.

Shengyu Zou

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Conclusions & training activity

• Investigated on BLE models for damage evaluation:

- Christ-BLE is up to 2 times more conservative in spherical impact for evaluating the performance Whipple shield-1 employed in our tests, but it is dangerous when used for non-spherical impact. Another observation is that Christ-BLE is not applicable for evaluating the shielding configuration with lower t/d ratio under the impact velocity higher than 6km/s; It is observed that it is rather conservative with respective to Christ-BLE, and it is applicable for evaluating the non-spherical impacts against Whipple shield-2, but it is not applicable for an inclined impact of right-cylinder.

Investigated on fragments distribution:

- The projectile shape as well as the impact inclination are effective on fragments distribution. The mass of the largest-fragment for the spherical impact is 4 times larger than that of the short-cylinder (L/d=3/2) impact, and is 10 times larger than that of the disk(L/d=1/3). This indicates the disk-like projectile is easiest to be fragmented, and a short-cylinder is easier to be fragmented than a sphere. An scaling model on the fragments distribution has been developed.
- Educational activities during PhD study:

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FRAGMENTATION MODELS FOR HYPERVELOCITY IMPACT

24-25

Thanks for your attention





Università degli Studi di Padova





