FRAGMENTATION MODELS FOR HYPERVELOCITY IMPACT

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

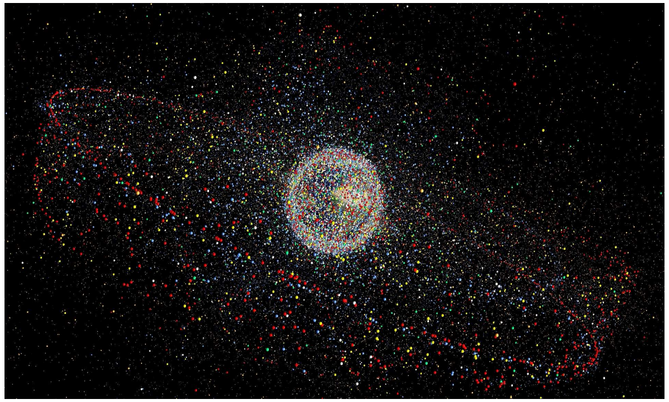
Outline

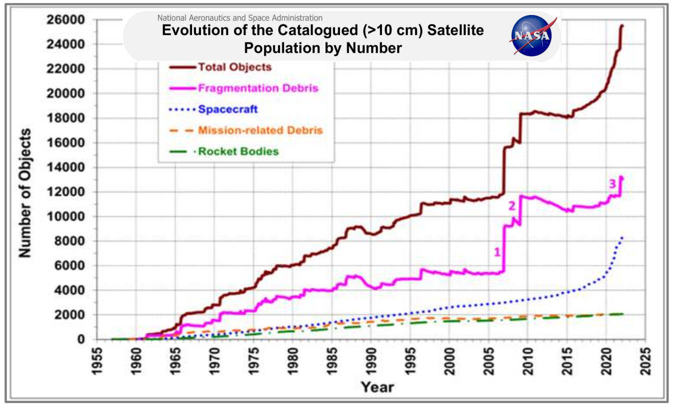
- Research background and motivations
- Research methodology
- Properties and models for hypervelocity impact fragmentation
    - Properties and models for debris-cloud velocities
    - Properties and models for perforation hole
    - Properties and models for large central fragment
- Experimental research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

Research background

☐ Space debris condition

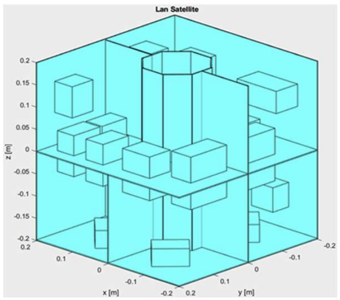
- **Orbital space debris**





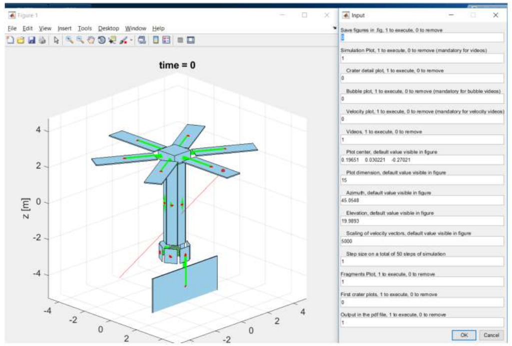
- **Fragmentation incidents on orbit**

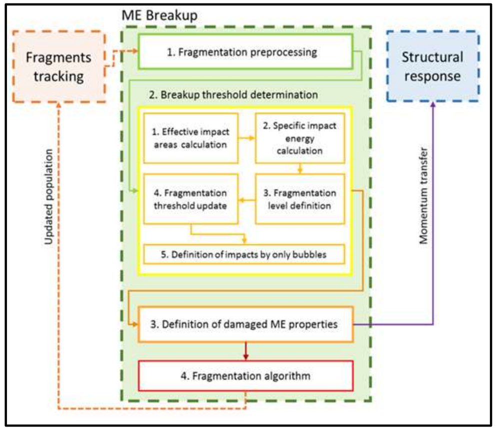
- **Laboratory tests**



S. Lan, et al. 2014

- **Semi-empirical tool in CISAS - CST**



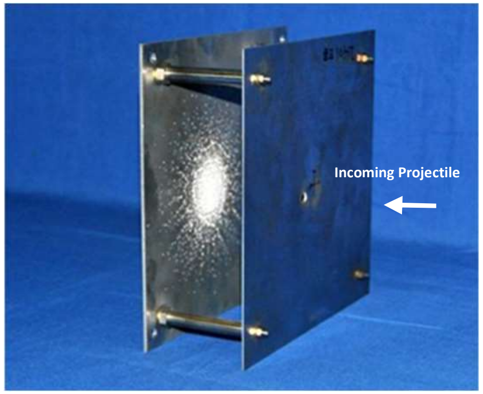


Research background

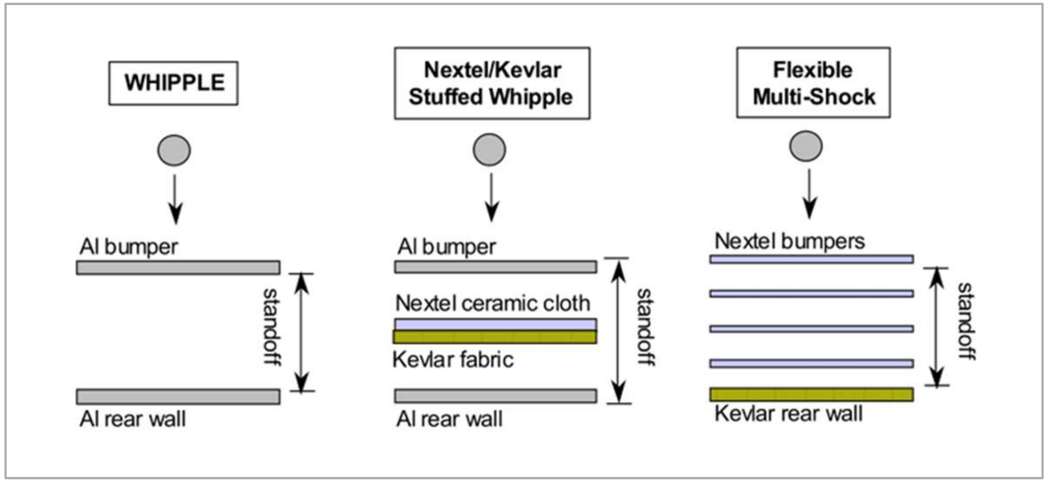
☐ Space debris shields

➢ **Whipple shield**

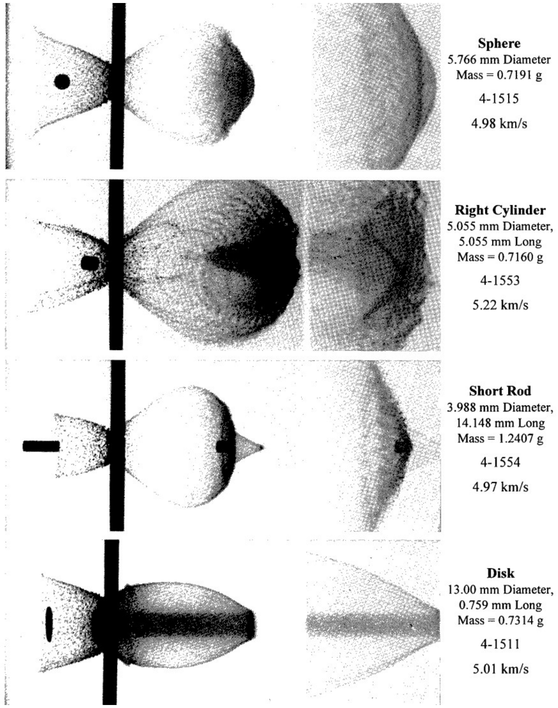
Whipple F.L in 1947



➢ **Stuffed Whipple shields & Multi-shock shields**



➢ **Thin-plate impact & shape effect**



Piekutowski A.J. 1996

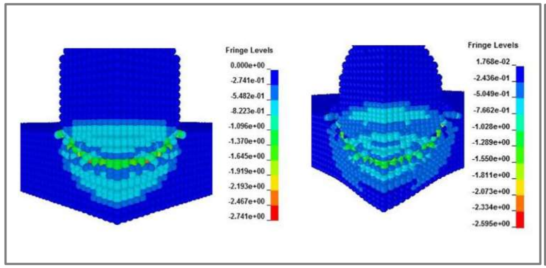
☐ Motivations

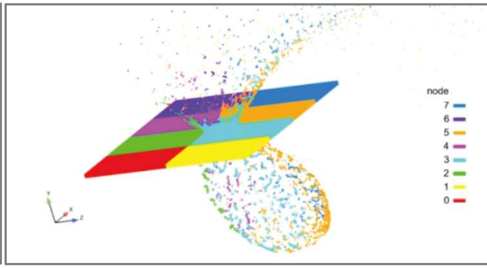
- **To study the fundamental physics of the hypervelocity impact fragmentation subjected to thin-plate impact, and to characterize the fragmentation properties.**
- **To develop semi-empirical fragmentation models for hypervelocity impact with consideration of projectile shape effect.**

Research methodology

□ Numerical simulation- Smooth Particles Hydrodynamics (SPH)

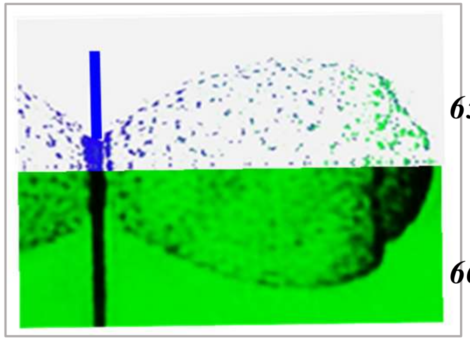
- ➢ **Meshless method: filling up with particles.**
- ➢ **Extreme deformation and high pressure condition.**
- ➢ **Parallel SPH code-PTS of HIRC/CARDC**
  - • ***more efficient & lower occupation of computation resource.***





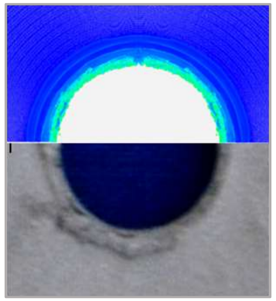
- ➢ **More than 150 simulation cases had been performed in the PhD project.**
- ➢ **Validations for simulation model**

✓ Debris cloud



	Length / Width
Sim	***65.7mm / 41.6mm***
Exp	***66.4mm / 46.7mm***

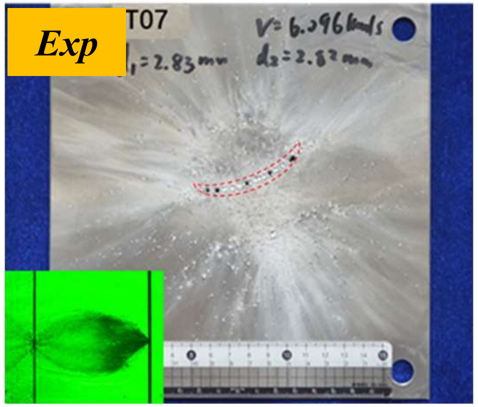
✓ Perforation hole

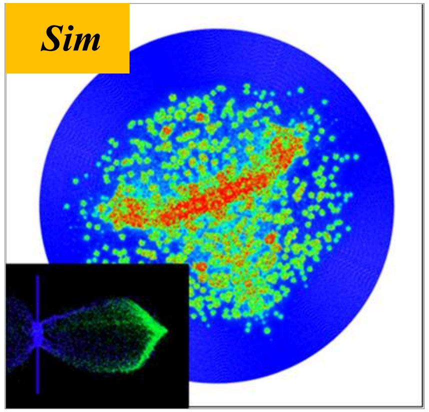


	Diameter
Sim	***Ø 6.95mm***
Exp	***Ø 7.3mm***

The deviation : ***11%*** ***5%***

✓ Backwall damage

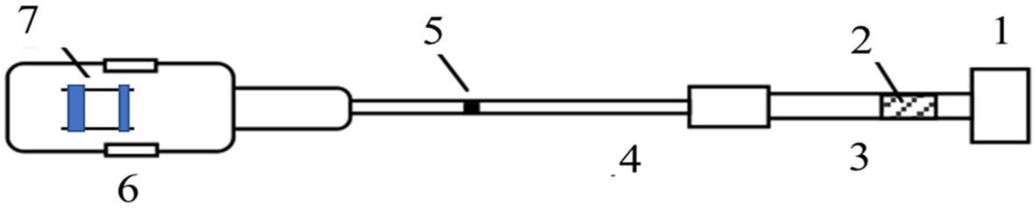




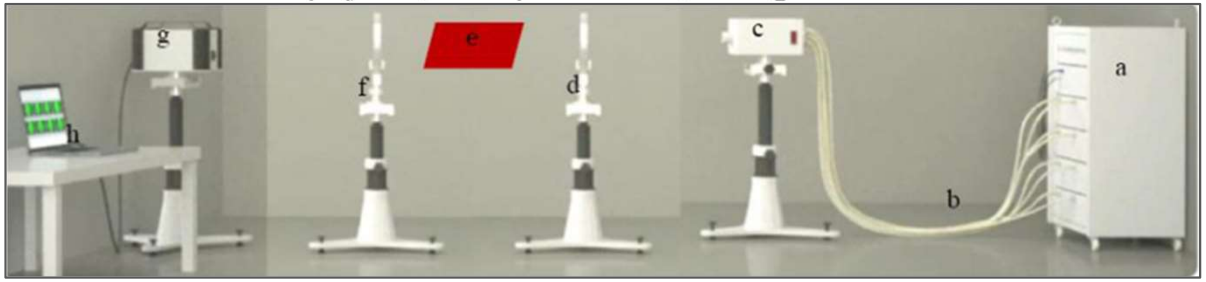
Research methodology

Hypervelocity impact tests

- A total of 20 tests had been performed in the PhD project.
- Test facilities in HIRC:
  - Two-stage-gas-gun, caliber 16mm and 7.6mm, muzzle velocity up to 9km/s.
  - Sequential laser shadowgraph instrument, $T_{interval} \geq 10ns$

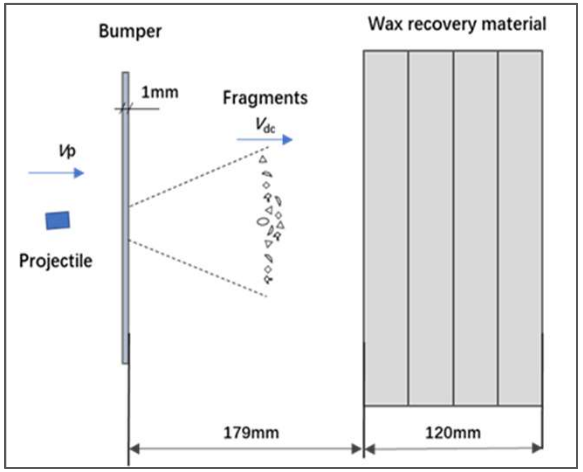


1—powder chamber; 2—piston; 3—pump tube; 4—launch tube; 5—projectile; 6—impact chamber; 7—target

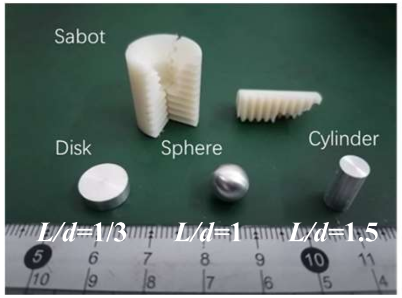


a—pulsed lasers; b—optical fiber; c—light-separating instrument; d—collimating len-1; e—measuring area; f—collimating len-2; g—image system; h—control system

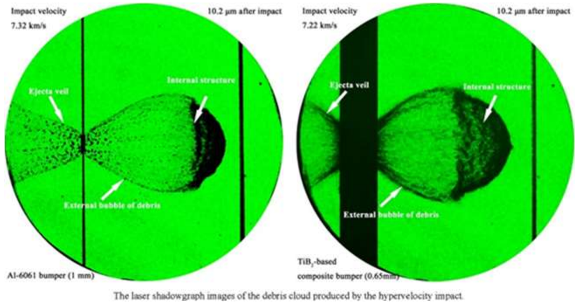
- Fragments recovery test setup



✓ *Projectiles and sabot*



✓ *Debris cloud of impact at above 7km/s*



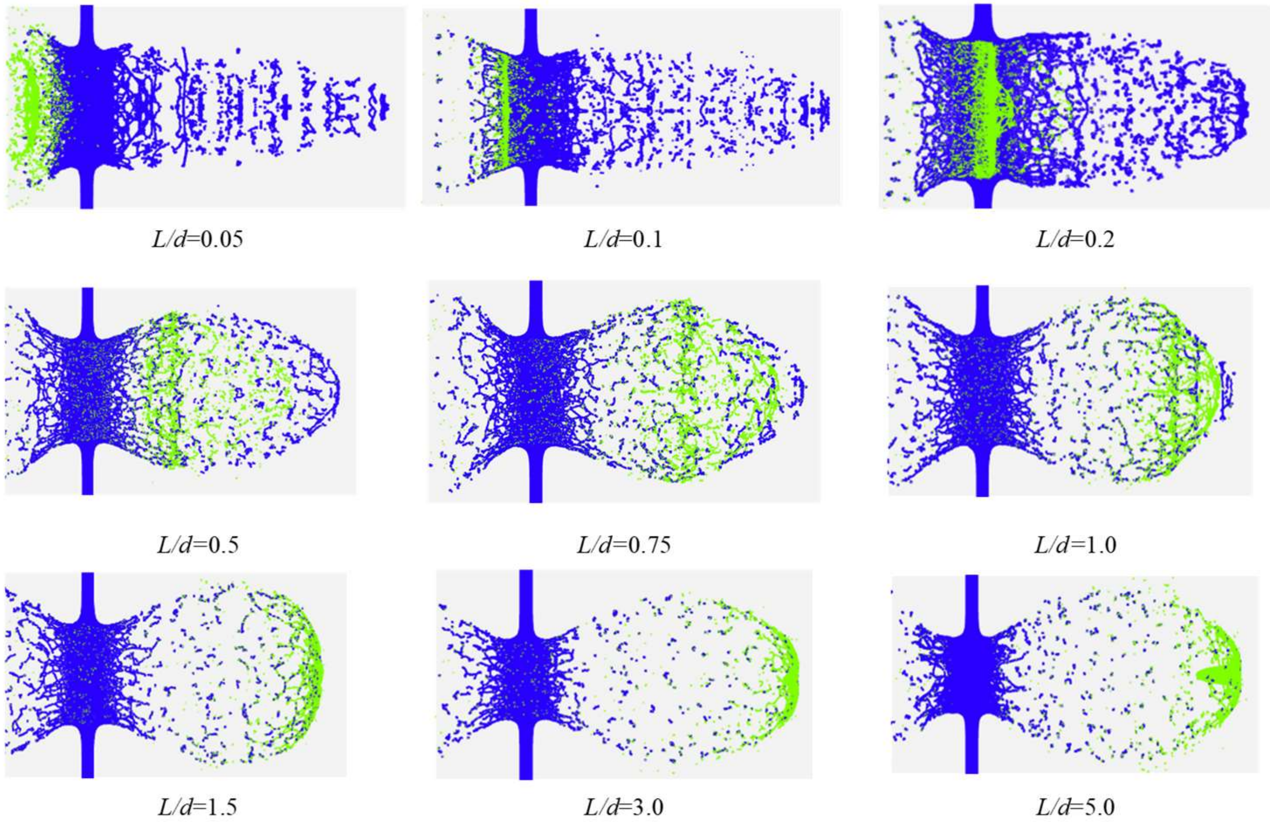
Properties and models for debris-cloud velocities

☐ Study on debris cloud geometry

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

Projectile material

Bumper material



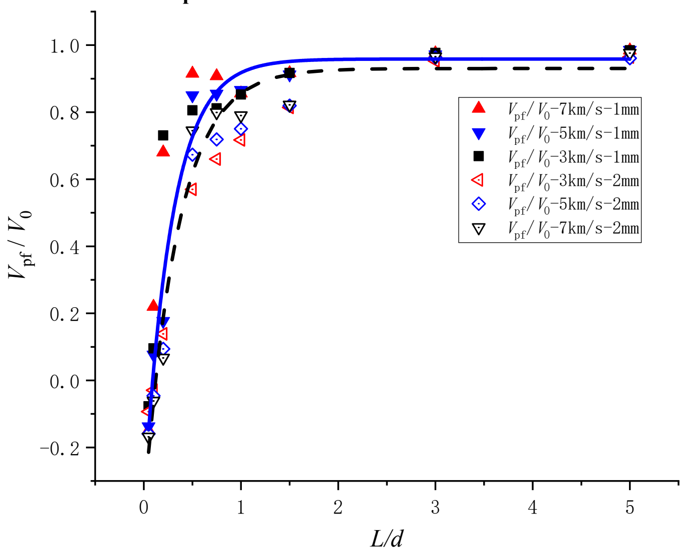
- Flat disk-like projectile produces a columnar debris cloud, in which the projectile material falls far behind the bumper material.
- Spherical projectile produces a more expanding debris cloud similar to spherical shell, in which the projectile material is located at the front part.
- Rod-like projectile produces a elliptical debris cloud, in which large remain of projectile is located at the leading part.

Properties and models for debris-cloud velocities

Characterization of debris cloud velocities

Projectile front velocity

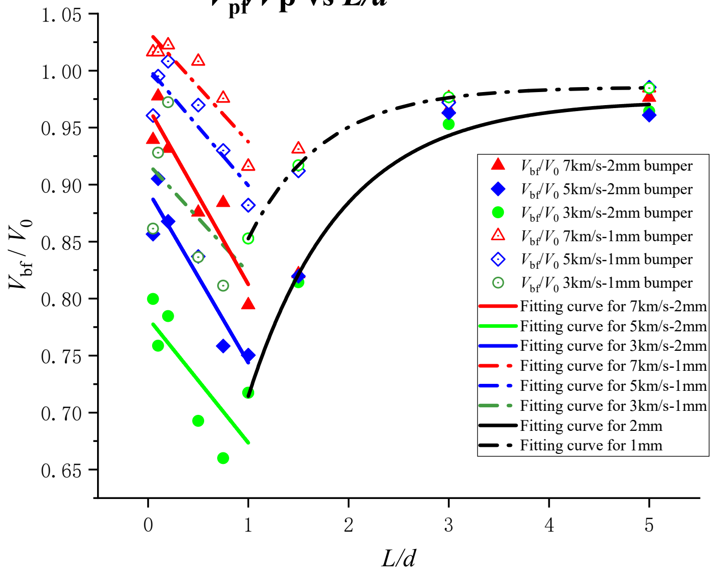
V_{pf}/Vp vs L/d



- 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 Vpf and V_0 .

Bumper front velocity

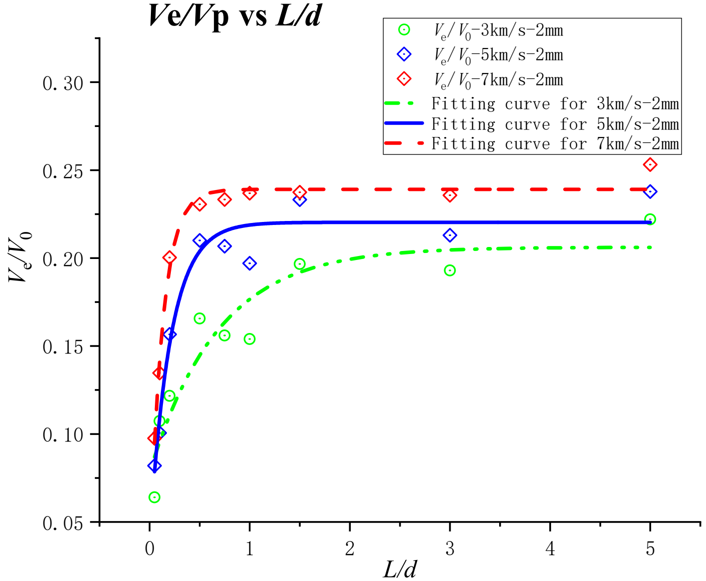
V_{pf}/Vp vs L/d



- 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 $L/d < 1$.
- Exponential relationship between V_{bf} / V_0 and L/d where $L/d \geq 1$.

Expanding velocity

Ve/Vp vs L/d



- 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 .

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

Properties and models for debris-cloud velocities

Models for Debris-cloud velocities

- **Semi-empirical dimensionless model**

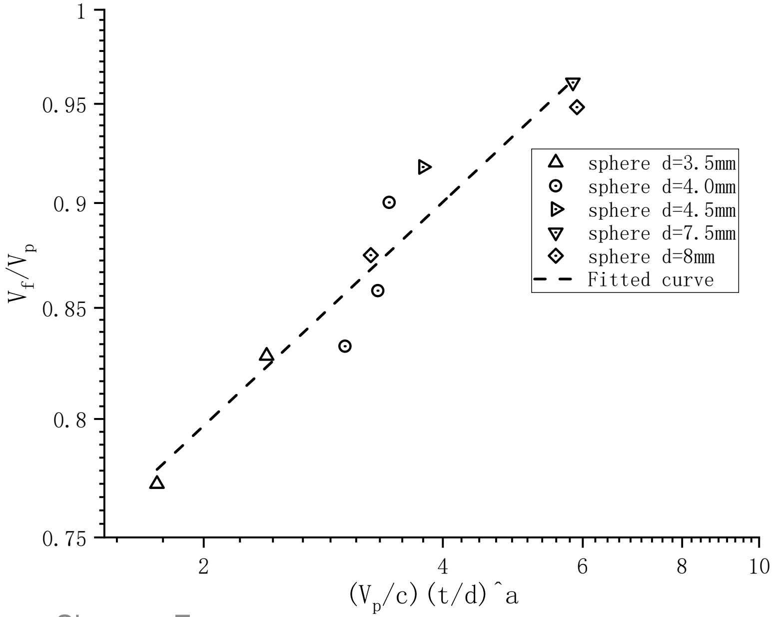
$$\frac{V_{\mathbf{dc}}}{V_{\mathrm{p}}} = C \cdot \left(\frac{t}{d}\right)^{\alpha} \cdot \left(\frac{V}{c}\right)^{\beta} \cdot \left(\frac{L}{d}\right)^{\gamma}$$

- **Calibration and validation with test data**

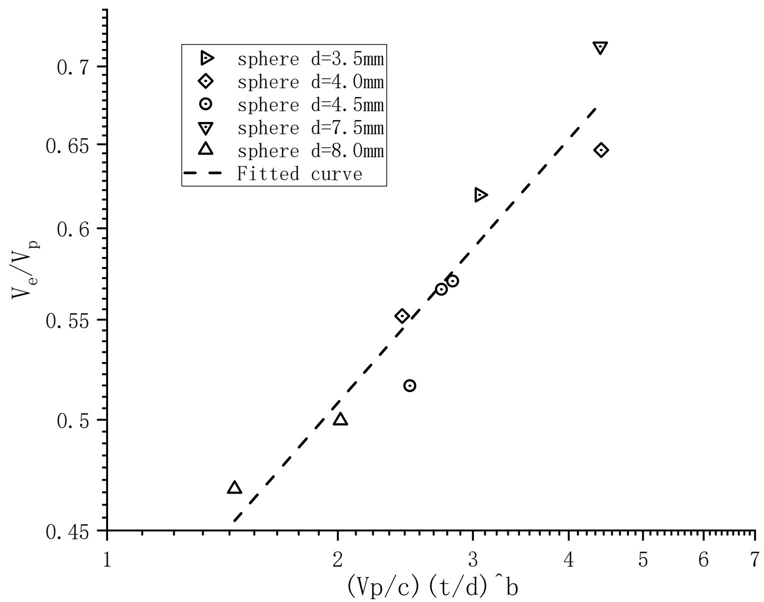
✓ ***Calibrated parameters table***

Parameters	Model for V_f	Model for V_e
C	0.7053	0.3953
α	0.1761	0.3623
β	-0.1391	-0.2355

✓ ***Validation for front velocity of spherical impact***



✓ ***Validation for expanding velocity of spherical impact***



Università degli Studi di Padova

Properties and models for perforation hole

Models for perforation hole

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

$$\frac{D_\mathrm{h}}{d} = 2.4 \cdot \frac{V_0}{c} \cdot \left(\frac{t_\mathrm{b}}{d}\right)^{2/3} + 0.9$$

Shape effect consideration $f(L/d)$

Model-1: $$\frac{D_\mathrm{h}}{d} = 2.4 \cdot \frac{V_0}{c} \cdot \left(\frac{\boldsymbol{t}}{d}\right)^{2/3} \cdot f\left(\frac{L}{d}\right) + 0.9 \quad \textbf{(1)}$$

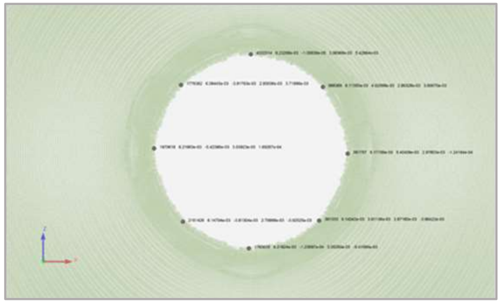
Where $$f\left(\frac{L}{d}\right) = k_1 \left(\frac{L}{d}\right)^{a} \cdot e^{k_2 \frac{L}{d}} \quad \textbf{(2)}$$

Model-2: $$\frac{D_\mathrm{h}}{d} = 2.4 \cdot \left(\frac{v}{c}\right) \cdot \left(\frac{t}{d}\right)^{f_2(L/d)} \cdot f_1\left(\frac{L}{d}\right) + 0.9 \quad \textbf{(3)}$$

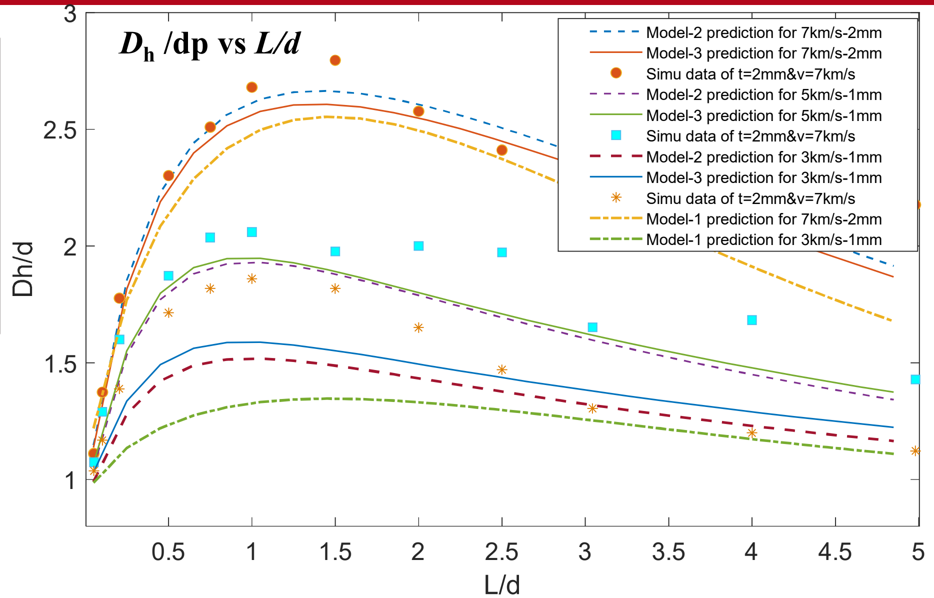
Where $$f_1\left(\frac{L}{d}\right) = q_1 \left(\frac{L}{d}\right)^{q_2} \cdot e^{q_3 \cdot \frac{L}{d}} \quad \textbf{(4)}$$

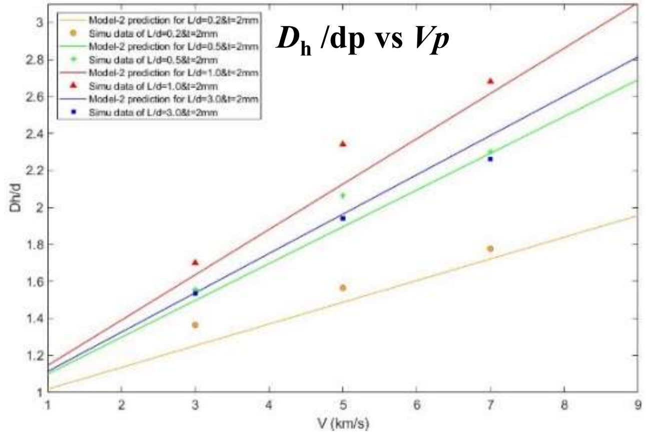
$$f_2\left(\frac{L}{d}\right) = \left(\frac{L}{d}\right)^{p_1} + p_2 e^{p_3 \cdot \frac{L}{d}} \quad \textbf{(5)}$$

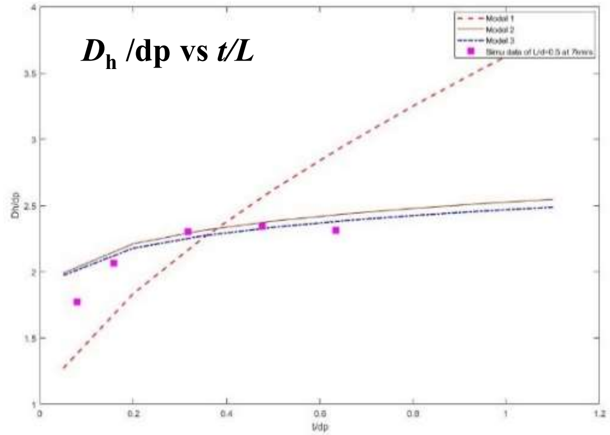
Model-3: $$\frac{D_\mathrm{h}}{d} = k_1 \cdot \left(\frac{V_0}{c}\right)^{w_1} \cdot \left(\frac{t}{d}\right)^{\left(\frac{L}{d}\right)^{w_2} + w_3 e^{w_4 \cdot \frac{L}{d}}} \cdot \left(\frac{L}{d}\right)^{w_5} \cdot e^{w_6 \frac{L}{d}} + k_2 \quad \textbf{(6)}$$



✓ ***Comparisons and Validation***







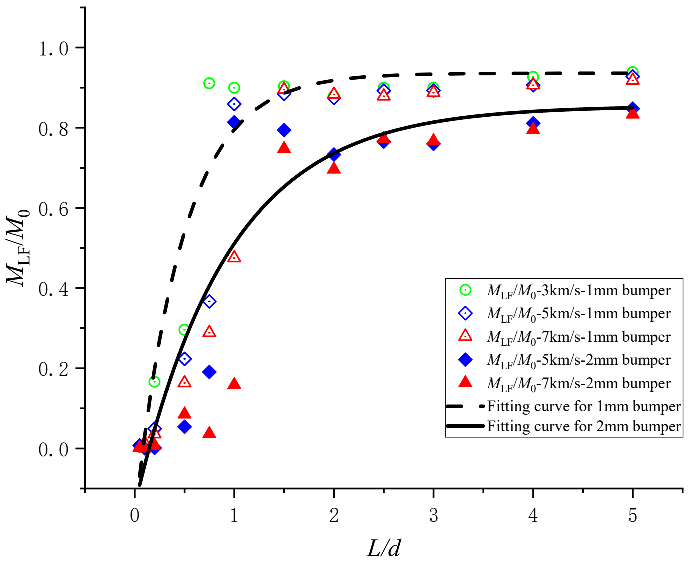
Ref: *S. Zou, L. Olivieri a, Z. Ma c, C. Giacomuzzo a,b, A. Francesconi. 72nd IAC, Oct. 2021.*

Properties and models for large central fragment

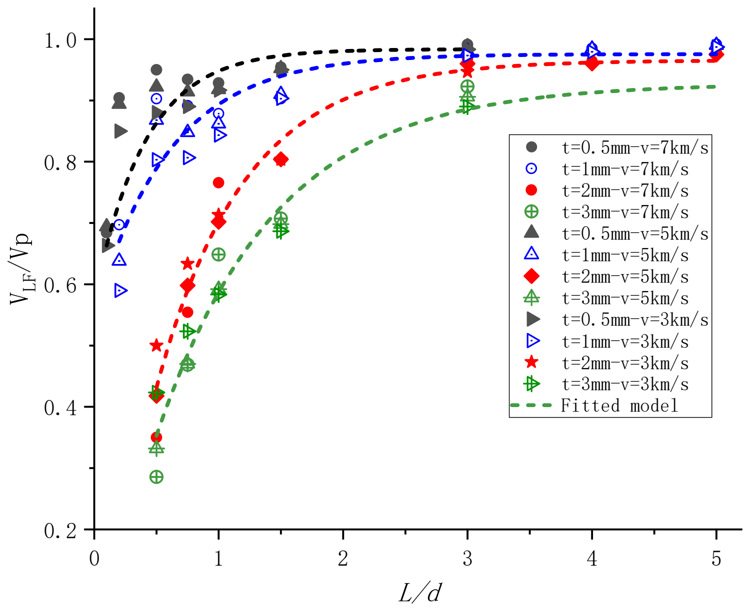
☐ The effect of projectile shape L/d

M_{LF} was normalized by dividing it by the projectile mass Mp.
V_{LF} was normalized by dividing it by the impact velocity Vp.

M_{LF} /Mp vs *L/d*



V_{LF} /Vp vs *L/d*

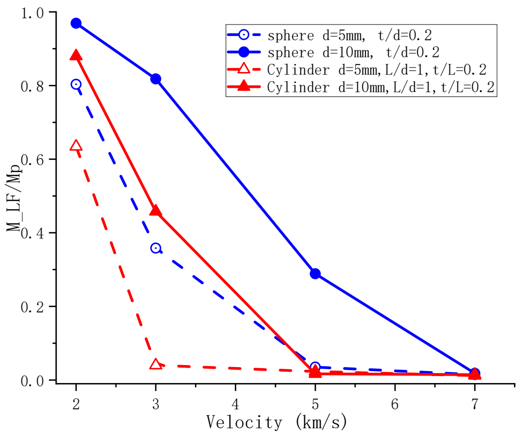


- **M_{LF} is dependent on projectile shape, target thickness and impact velocity, while V_{LF} appears to depend on projectile shape and target thickness, but only slightly depend on impact velocity.**
- **Disk-like projectiles (*L/d* ≪ 1) are easiest to be fragmented, and have relative lower velocity of the large fragment.**
- **Rod-like projectiles are usually less fragmented and less impeded by thin plate target during hypervelocity impacts.**

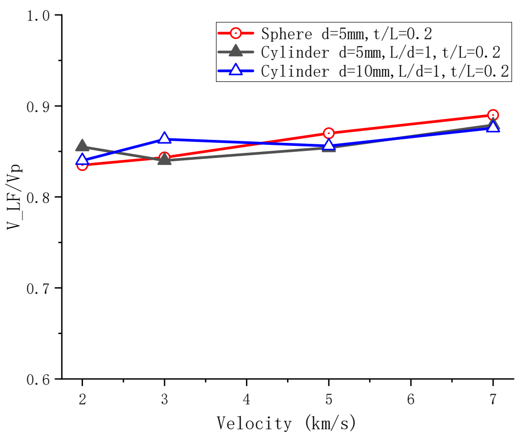
Properties and models for large central fragment

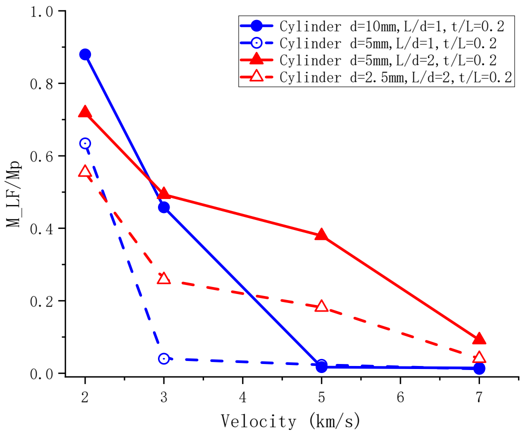
The effect of impact velocity

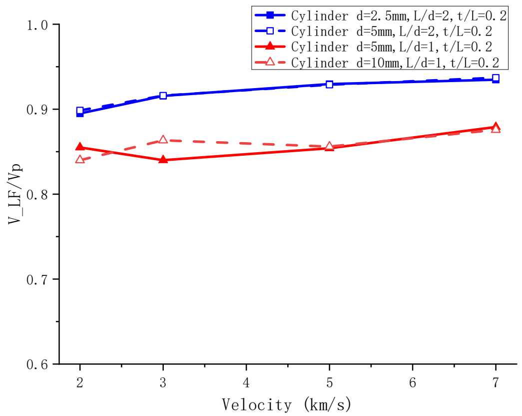
M_{LF}/Mp vs V_p



V_{LF}/Vp vs V_p





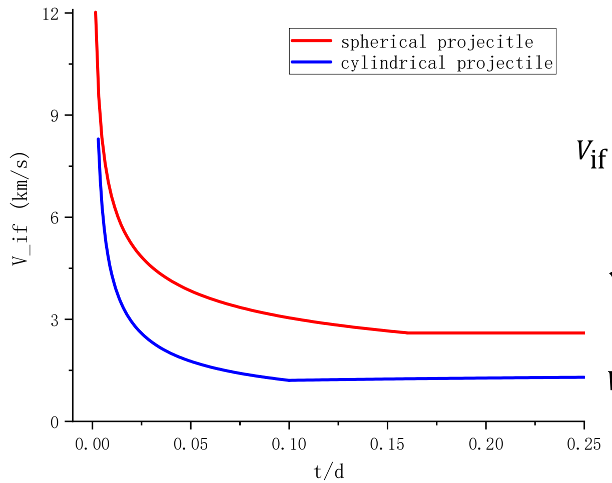


Geometrical scaling investigation

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

$$\frac{M_{LF}}{M_p} \propto \cdot \left(\frac{L}{d}\right)^{\alpha} \cdot \left(\frac{t}{L}\right)^{\beta} \cdot f\left(C\,\frac{V_p}{d}\right) \qquad \frac{V_{LF}}{V_p} \propto C \cdot \left(\frac{L}{d}\right)^{a} \cdot \left(\frac{t}{L}\right)^{b} \cdot \left(\frac{V_p}{c}\right)^{\gamma}$$

Fragmentation threshold-velocity investigation



✓ ***For sphere***

$$V_{if} = \begin{cases} 1.436\,\mathrm{km/s} \cdot \left(\frac{t}{d}\right)^{-0.333} & \text{for } \frac{t}{d} < 0.16 \\ 2.6\,\mathrm{km/s} & \text{for } \frac{t}{d} \geq 0.16 \end{cases}$$

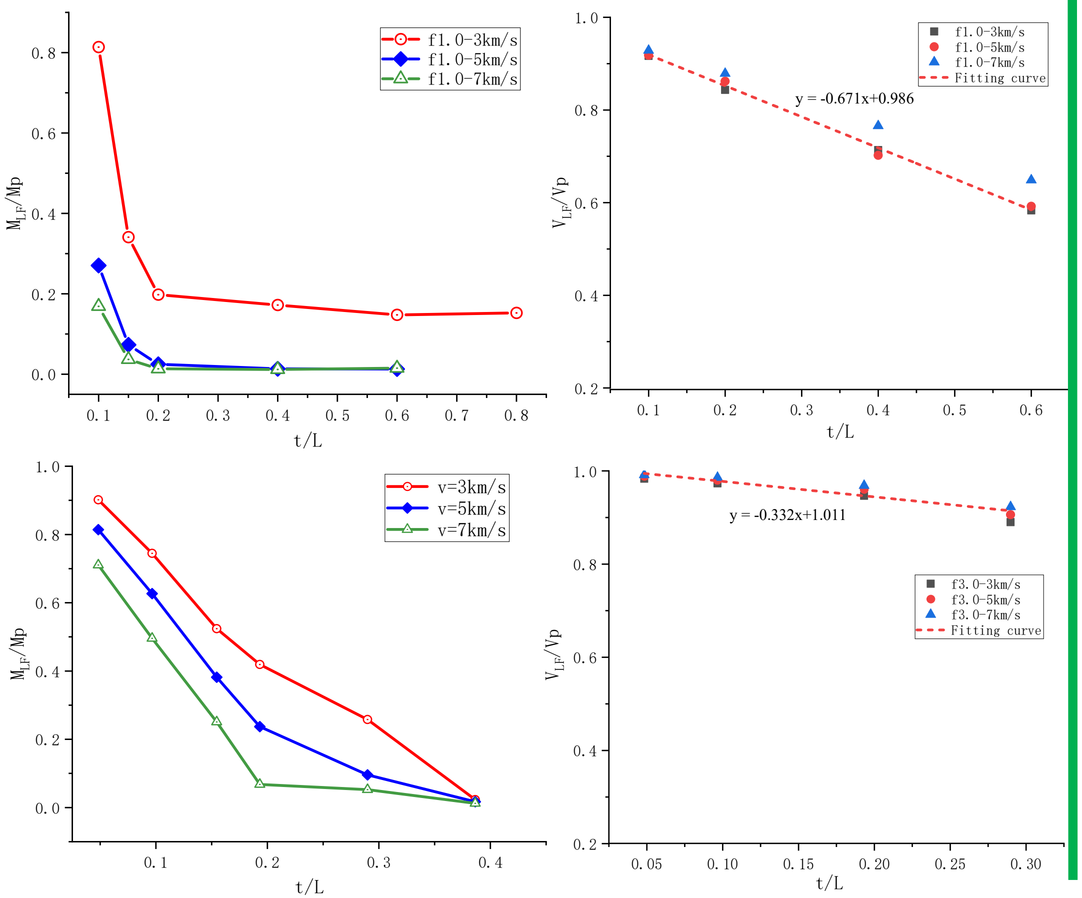
✓ ***For short-cylinder***

$$V_{if} = \begin{cases} 0.34\,\mathrm{km/s} \cdot \left(\frac{t}{d}\right)^{-0.55} & \text{for } \frac{t}{d} \leq 0.1 \\ 1.45\,\mathrm{km/s} \cdot \left(\frac{t}{d}\right)^{0.08} & \text{for } \frac{t}{d} > 0.1 \end{cases}$$

Properties and models for large central fragment

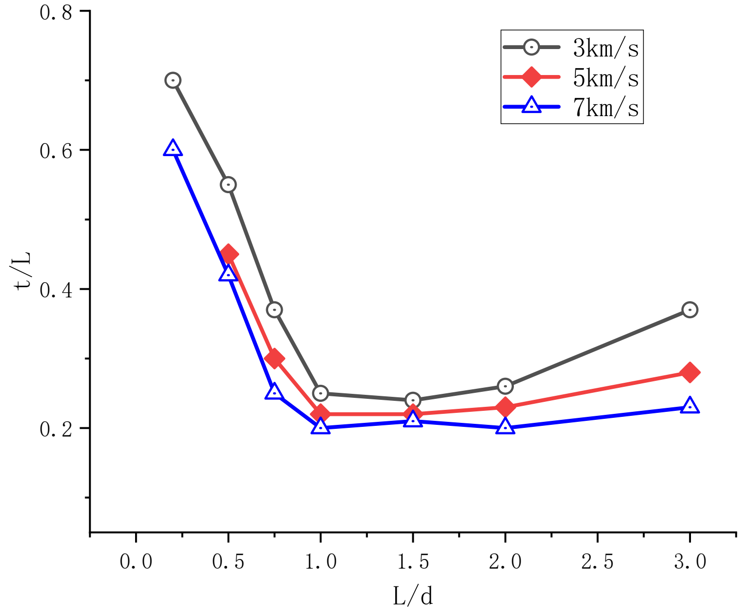
☐ The effect of target thickness ratio t/L

M_{LF}/Mp vs t/L V_{LF}/Vp vs t/L



➢ **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.**



Properties and models for large central fragment

Dimensional analysis for modelling

✓ ***The units and dimensions of the variables***

Variables	Units	Dimensions
t, L, d	m	$\hat{L}$
V_p, V_f, c	m/s	$\hat{L}\cdot\hat{T}^{-1}$
M_p, M_{LF}	kg	$\hat{M}$
ρ_p	kg/m^3	$\hat{M}\cdot\hat{L}^{-3}$
Y	N/m^2	$\hat{M}\cdot\hat{L}^{-1}\cdot\hat{T}^{-2}$
K_c	N/m$^{3/2}$	$\hat{M}\cdot\hat{L}^{-1/2}\cdot\hat{T}^{-2}$

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

- **The mass of the large central fragment**

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

Nondimensionalization

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

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

$$\frac{M_{\mathrm{LF}}}{M_{\mathrm{p}}} = C\cdot d^{-x-y}\cdot {V_{\mathrm{p}}}^{-2+y}\cdot\left(\frac{t}{L}\right)^{\alpha}\cdot\left(\frac{L}{d}\right)^{\beta}$$

The model for large-central-fragment mass

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

- **The velocity of the large central fragment**

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

Nondimensionalization

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

$$V_{\mathrm{F}} = C\cdot d^{1+x}\cdot\left(\frac{t}{L}\right)^{\alpha}\cdot\left(\frac{L}{d}\right)^{\beta}$$

The model for large-central-fragment velocity

$$\frac{V_{\mathrm{F}}}{V_{\mathrm{p}}} = C\cdot\left(\frac{t}{L}\right)^{\alpha}\cdot\left(\frac{L}{d}\right)^{\beta}\cdot\left(\frac{V_p}{c}\right)^{\gamma}$$

Properties and models for large central fragment

☐ The model for large-central-fragment mass

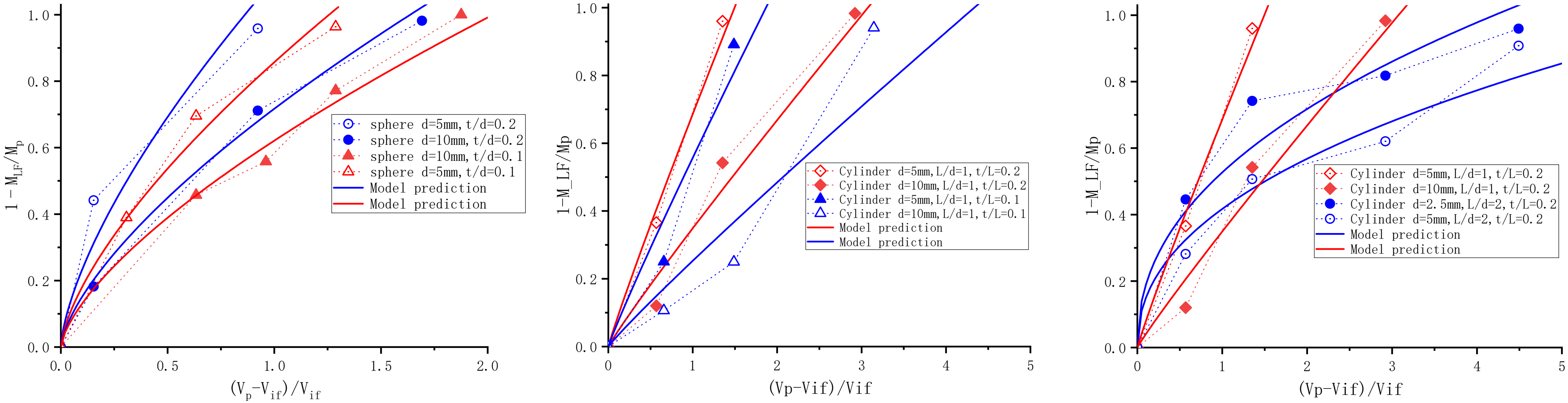
➢ ***Model formulation***

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

✓ ***Calibrated parameters table***

Parameters	Projectile type		
	Sphere	Cylinder-L/d=1	Cylinder-L/d=2
C	4.471 $\mathrm{mm}^{0.561}$	4.072 $\mathrm{mm}^{0.794}$	4.072 $\mathrm{mm}^{0.794}$
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

➢ ***Calibration and validation***



Properties and models for large central fragment

The model for large-central-fragment velocity

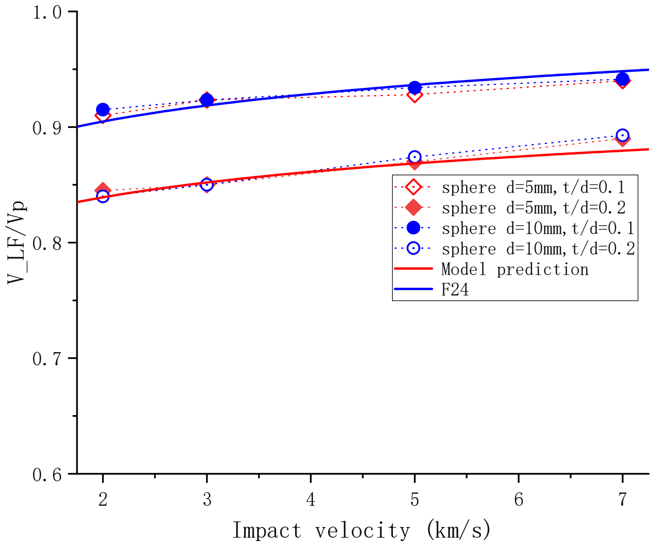
✓ ***Calibrated parameters table***

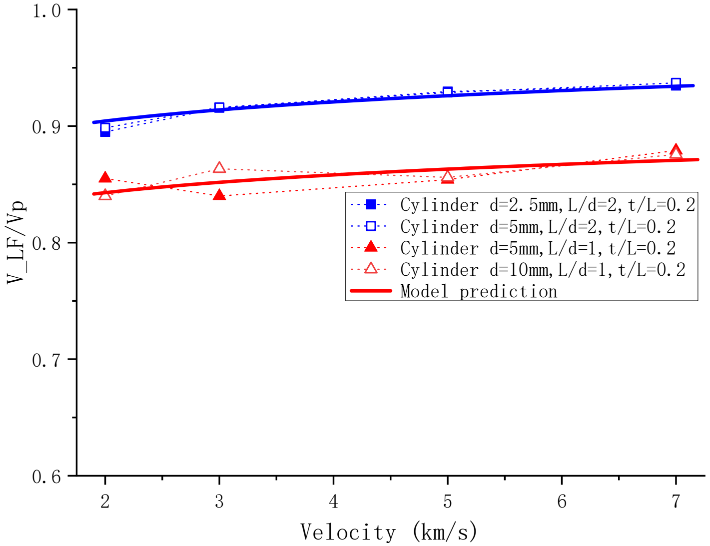
Parameters	Projectile type		
	Sphere	Cylinder or ellipsoid	
		L/d=0.2~0.75	L/d=1~2
C'	0.7306	0.7338	0.7202
α'	0.0375	0.0895	0.0259
β'	-0.1086	-0.1080	-0.1132
γ'	0	-0.0671	0.1016

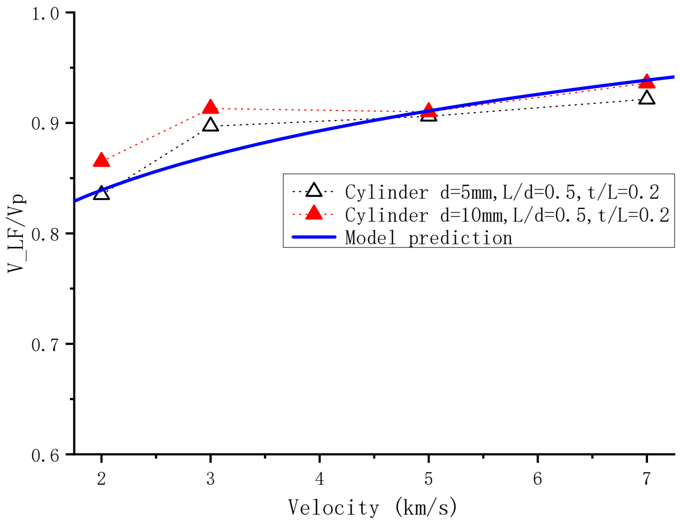
➢ ***Model formulation***

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

➢ ***Calibration and validation***





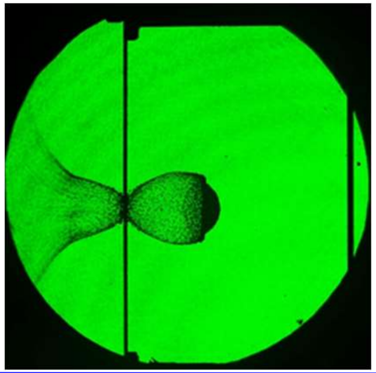


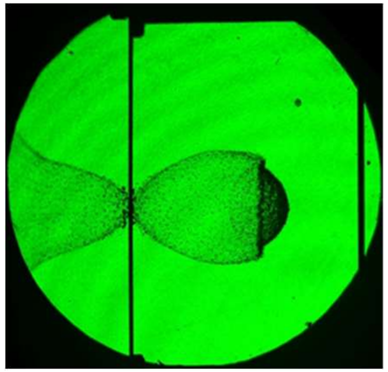
Experimental study on hypervelocity impact debris-cloud

☐ Debris cloud morphology

➢ Sphere impact

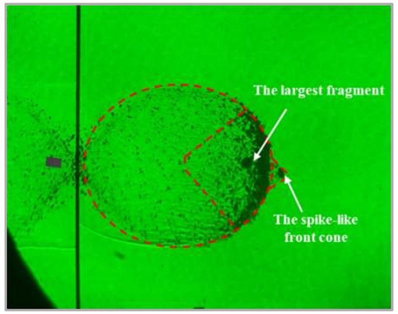
- an external bubble and an internal structure including front cap, central element and rear element.
- a hemispherical shell of fragments spalling off the rear side of the projectile .

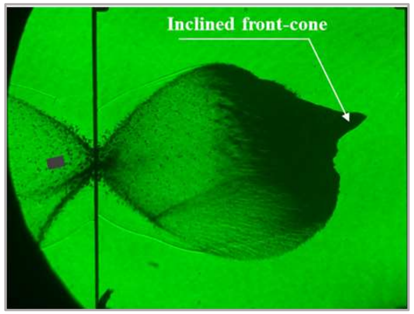




➢ Short-cylinder impact

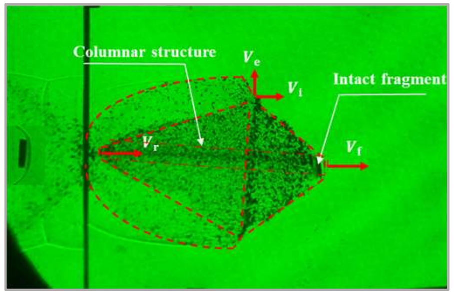
- a spike-like front cone at the leading edge with velocity of up to 4% greater than impact velocity.
- the head point of the front cone is coincident with the direction of the cylinder axis, and is dependent on the cylinder's impact inclination.

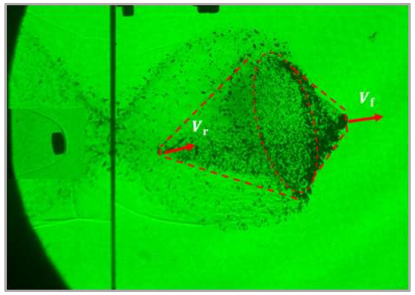




➢ Disk impact

- 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.

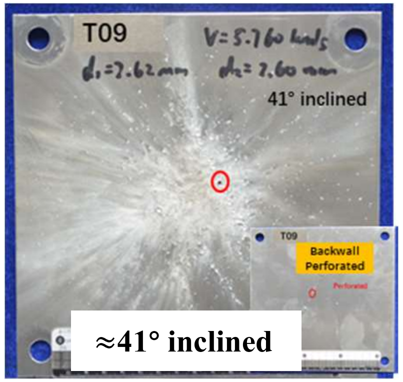




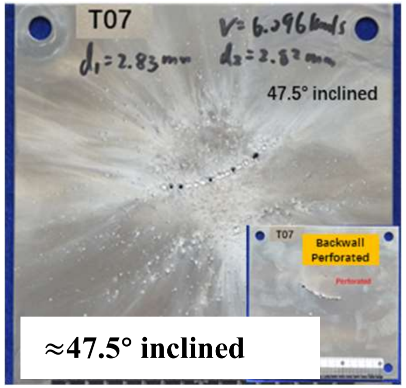
Experimental study on backwall damage response

☐ The inclination effect on backwall damage

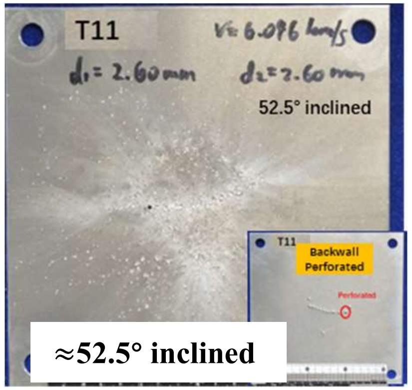
✓ *Backwall images from experiments*



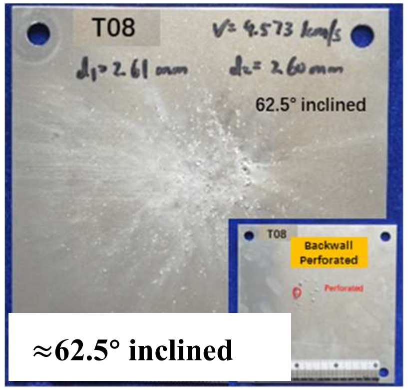
≈41° inclined



≈47.5° inclined



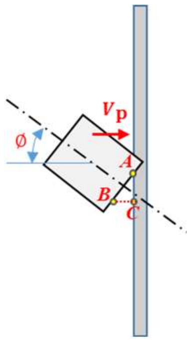
≈52.5° inclined



≈62.5° inclined

≈ 73.5° inclined

✓ *Analytic model for critical inclined angel*

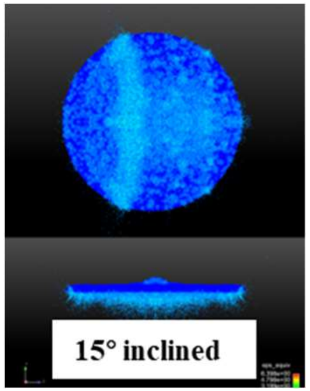


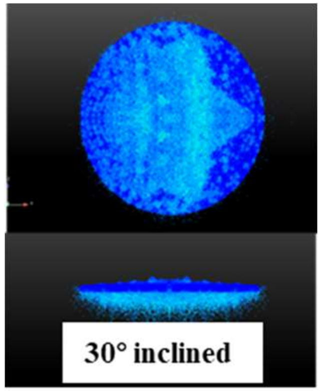
$$\sin \emptyset_{cr} = \frac{BC}{AB} = \frac{v_p}{U_s}$$

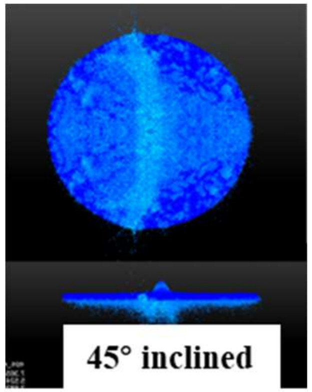
$$U_s = c_t + \frac{k v_p}{2}$$

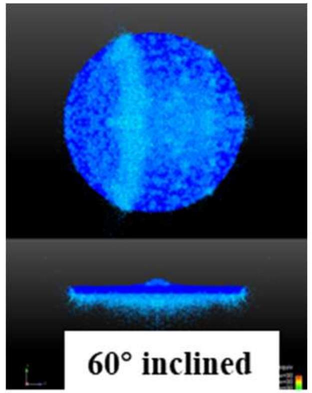
- **For Al-Al impact at about 6km/s, it is more damaging situation when the inclination is between 40° to 50°**

✓ *Backwall images from simulations*


15° inclined


30° inclined


45° inclined

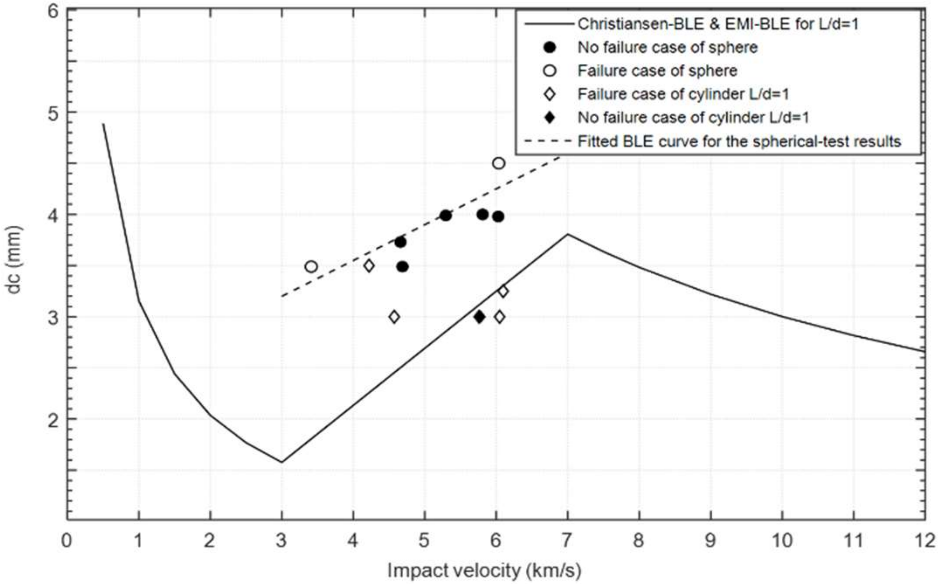

60° inclined

Experimental study on backwall damage response

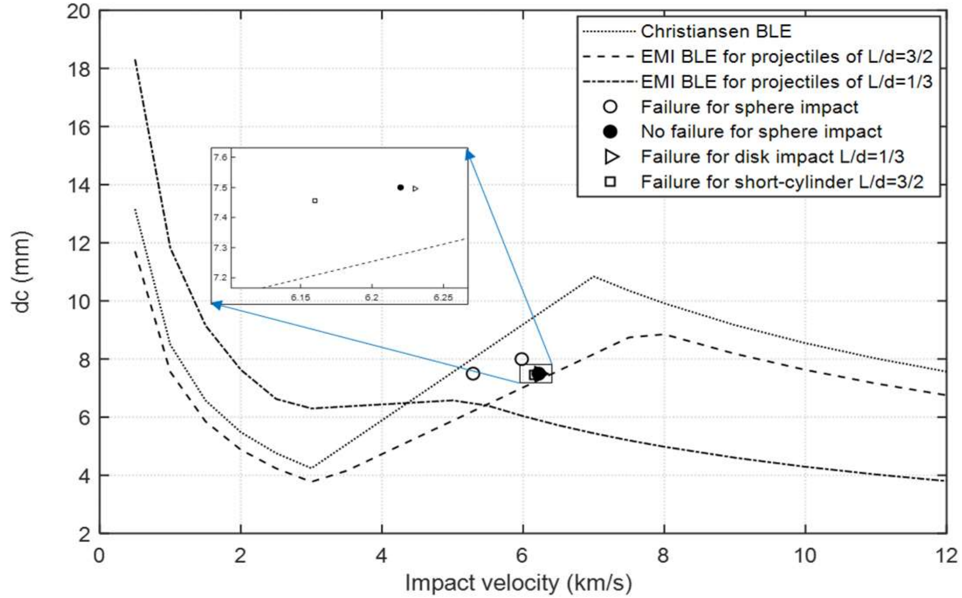
Ballistic limit equation for Whipple shields

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

WS-1: t_b-S-t_w: 1mm-80mm-2mm



WS-2: t_b-S-t_w: 1mm-129mm-7mm

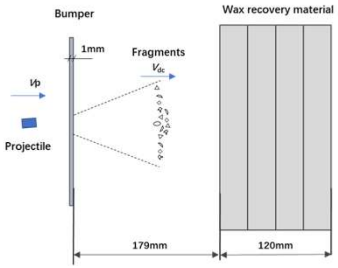


- **Christ-BLE is up to 2 times more conservative for evaluating the performance of spherical impact against WS-1, but it is dangerous when used for non-spherical impact.**
- **EMI-BLE is much more conservative than Christ-BLE, and could be applied for non-spherical impacts.**
- **Both of the two BLEs could not be applied conservatively for the impacts with inclined cylinder .**

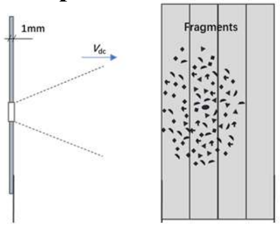
Fragments recovery experiment

☐ Fragments recovery and analysis

✓ **Before the impact**



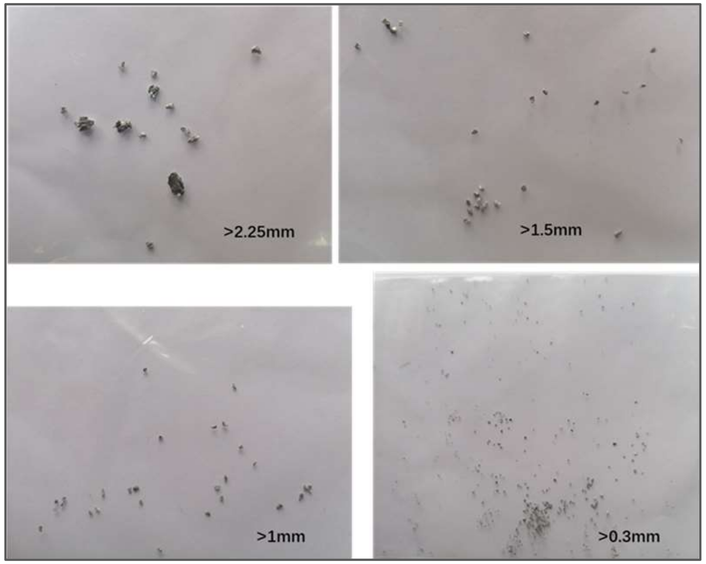
✓ **After the impact**

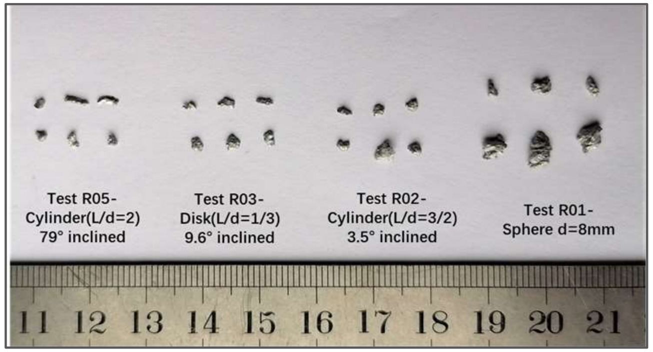


✓ **Fragments recovery procedures**

Fragments extraction
↓
Melt the wax-panels by cooking with induction cooker
↓
Heat the fragments packages with a thermal drier
↓
Classify the fragments with a serial of sieves
↓
Measure and count the fragments

✓ **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 .**

Fragments recovery experiment

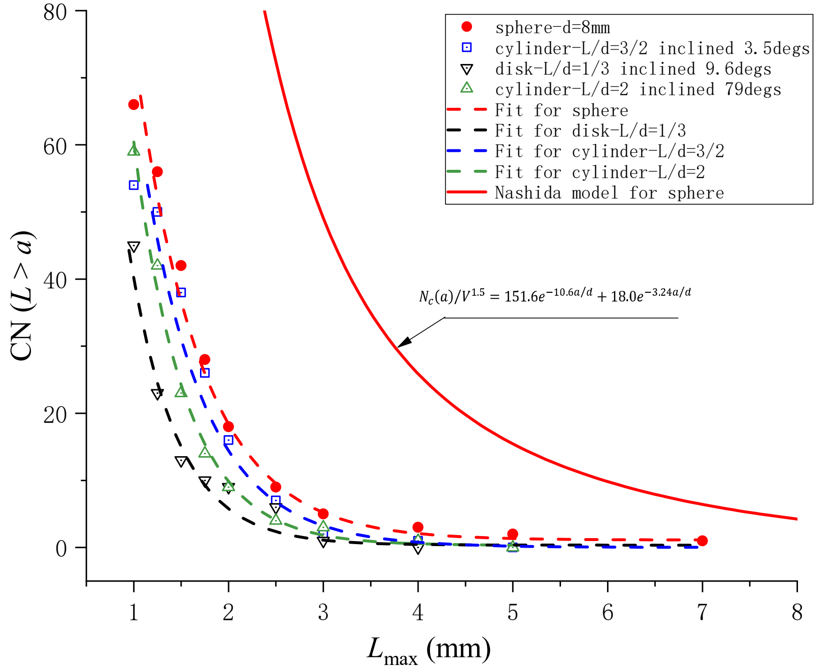
☐ Fragments distribution and model

➢ **For sphere impact**

Nashida Model:

M. Nishida, et al. 2017

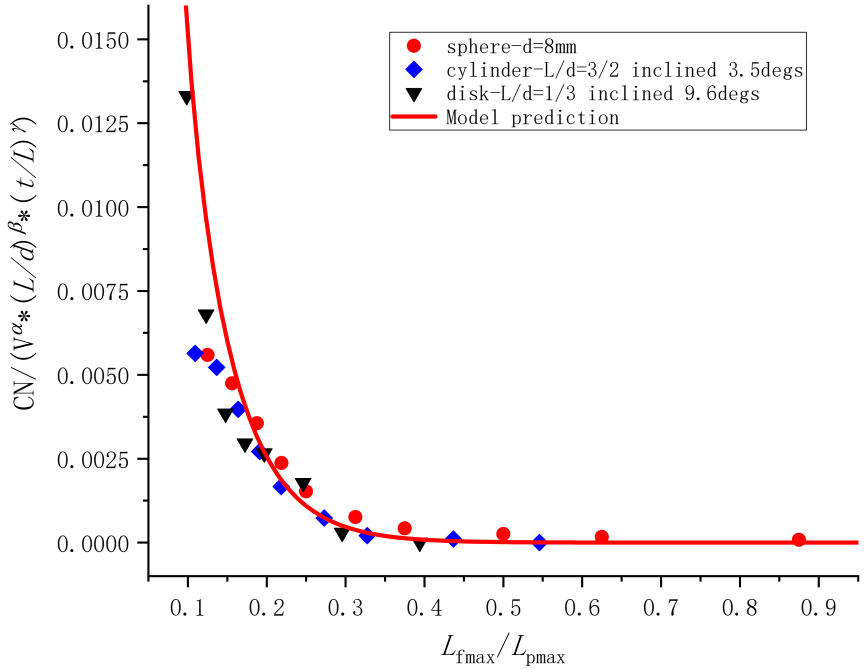
$$N_c(a)/V^{1.5} = 50.7e^{-1\ .6a/d} + 2.9e^{-4.3a/d}$$



➢ **A scaling model developed for impact with shaped projectiles**

$$\frac{N_c(a)}{V_p^{\alpha}\cdot(t/L)^{\beta}\cdot(L/d)^{\gamma}} = A_1 e^{B_1 a/L\text{pmax}} + A_2 e^{B_2 a/L\text{pmax}}$$

Parameters	α	β	γ	A_1	B_1	A_2	B_2
Values	1.5	-3.65	-1.75	1.332	-70.657	0.076	-16.975



Conclusions & training activity

- **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.

Conclusions & training activity

- **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°.

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:**

EDUCATIONAL ACTIVITIES ACTIVATED BY THE STMS PHD COURSE

Interdisciplinary Module/Activity	Lecturer	Expected credits	Frequency (YES/NO)	Exam (YES/NO)*	Date of exam	Attained credits
Space optics and detectors	Prof. G.Naletto Prof. M.-G.Pelizzo	4	YES	YES	03-04-2020	4
Exploring the solar system and its environment	Prof. G.Cremonese Prof. F.Marzari	4	YES	YES	26-06-020	4
Mechanical and thermal properties of material for aerospace constructions	Prof. U.Galvanetto Prof. M.Zaccariotto	4	YES	No exam	—	4
Space systems and their control	Prof. A.Francesconi Prof. E.Lorenzini	4	YES	YES	28-07-2020	4
Measurement techniques: fundamentals, PC based, visual and thermal image analysis based	Prof. M.Pertile Prof. G.Rossi	4	YES	NO	—	0.8
Writing a Scientific Paper / Research Project Proposal	Prof.G.Naletto	2	YES	—	——	0.4
Introduction to Computational Fluid Dynamics	Prof. F. Picano	2	YES	YES	——	2.0
Composite materials: Modeling, Processing, and Characterization (AIDAA Course)	Prof. N. Zobeiry, Prof. M. Petrolo	3	YES	No exam		0.6
An overview on space debris protection best practices (AIDAA Course)	Post Dr. L. Oliveri	1	YES	No exam		0.2
Structure dynamics: theory and practices in the space industry (AIDAA Course)	Prof. G. Kerschen Prof. G Aglietti et al	1.5	YES	No exam		0.3
Remote sensing instruments for atmospheric transparency: theory, instruments and methods	Prof. Doro - Gaug	2.0	YES	YES	04-05-2020	2.0
Durability and Ageing Organic Matrix Composites for Aircraft Applications	Prof. Marco Gigliotti	2.0	YES	YES		2.0
Safty course: GENERAL HEALTH AND SAFETY IN THE WORKPLACE	E-learning and Online test	0.78	YES	YES	01-07 -2020	0.78
PhD English Course	Prof. Gillian davies		YES	Partly yes		

Curriculum oriented seminars	Lecturer	Expected credits	Frequency (YES/NO)	Exam (YES/NO)*	Date of exam	Attained credits
Introduction to Quantum Technologies	Prof. Vallone	0.08	YES	NO	25-02-2020	0.08
Analysis of Complex Dynamics with Chaos Indicators	Prof. Guzzo	0.08	YES	NO		0.08
VUV optical anisotropy of few layers graphene: possible application for space FLY–Spec: UV-VIS-NIR reflectometry and laser-induced breakdown Spectroscopy	Prof. Zuppella	0.4	YES	YES	29-05-2020	0.4
Advanced Computational Modeling of Multiphase	Prof. F. Picano	0.4	YES	YES	11-6-2020	0.4
From Art to Science: The Flower Constellations	Prof. Mortari	0.04	YES	NO	28-01-2021	0.04
Computational modelling of strain localisation and crack initiation and propagation in multi-phase porous materials	Prof. L. Sanavia	0.4	YES	YES	01-02-2021	0.4
Space electric propulsion	Prof. Magarotto	0.08	YES	YES	18-6-2021	0.08
Characterisation of fracture resistance of interfaces in mode I,mode II and mixed mode	Prof. G. Alfano	0.08	YES	-	19-01-2022	0.08
Recent advances in numerical approach for multiphase flows	Prof. P. S. Costa Prof. F. Picano	0.08	YES	-	21-02-2022	0.08
Computational approaches for fluid-structure interaction with fracturing	Prof. F. D. Barba	0.08	YES	-	21-02-2022	0.08
Very low Earth Orbit Satellites for Earth Observations	Prof. F. Barato	0.4	YES	YES	21-02-2022	0.4
Operating a detector in space for 10 years: the case of Fermi LAT course	Prof. R. Rando	0.4	YES	YES	24-02-2022	0.4
Past and future imaging of the surface of Mars	Prof. N. Thomas	0.08	YES	-	09-03-2022	0.08
Dispersed Multiphase Flows: Physics and Modelling	Prof. F. Picano	0.08	YES	-	22-03-2022	0.08
Tethers for space applications: current developments and future perspectives	Prof. E. Lorenzini	0.08	YES	—	27-04- 2022	0.08
The OSIRIS-REx sample return mission: a journey to the origin of the Solar System	Prof. M. Pajola	0.4	YES	YES	09-05- 2022	0.4

OTHER EDUCATIONAL ACTIVITIES

Title of the activity (Date/Period/University)	Lecturer	Duration of activity	Expected credits	Frequency (YES/NO)	Exam (YES/NO)	Date of exam	Attained credits
Admission presentation	YES		0.5	YES	NO	21-02-2020	0.5
First year admission presentation	YES		0.5	YES	YES	06-11-2020	0.5
Second year admission presentation	YES		0.5	YES	YES	11-01-2022	0.5
Third year admission presentation	YES		0.5	YES	YES	15-12-2022	0.5
Dissertation defense presentation	YES		0.5				
Conferences 1 time: International Astronautics Congress 2021	YES		1.0	YES	YES		1.0
Total of expected ECTS credits attainable in educational activities (>30):			31.74	Total of credits attained in educational activities (at date 15 Dec. 2022):			31.24

Thanks for your attention

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