E5

スペースデブリの超高速衝突解析のモデル化法の諸問題について

Some Problems of Modeling Method on Hypervelocity Impact Analysis of Space Debris

○片山 雅英、竹場 敦史 (伊藤忠テクノソリューションズ株式会社（CTC）)
○Masahide KATAYAMA, Atsushi TAKEBA (ITOCHU Techno-Solutions Corporation (CTC))

現在、スペースデブリの超高速衝突問題に適用されている数値解析法に関し、それらの長所と短所について概観した後、特に、サブミリ・オーダの飛翔体（スペースデブリ）が宇宙機の各構成要素に衝突する問題に適用するに際し、問題となる点を指摘・整理する。また、有人ミッションの大型構造物で標準的に用いられる Whipple バンパー・シールド・システムを比較対象として、無人機における防護システムの特殊性という観点から、破砕・衝撃気化といった現象のメカニズムを考慮した物理モデルの問題点と、それらの現象を模擬するための数値解析手法である、数値的エロージョンを含む Lagrange の方法、Euler の方法、SPH（Smoothed Particle Hydrodynamics）法など、各数値解析手法の適用の仕方の是非について再検討を行い、今後の方向性について考える。

スペースデブリの超高速衝突解析のモデル化法の諸問題について

Some Problems of Modeling Method on Hypervelocity Impact Analysis of Space Debris

○片山 雅英 竹場 敦史
○Masahide KATAYAMA Atsushi TAKEBA

CTC
Challenging Tomorrow's Changes
伊藤忠テクノソリューションズ株式会社
ITOCHU Techno-Solutions Corporation
科学システム事業部 科学・工学技術部
Science & Engineering Systems Division
Science & Engineering Analysis Department

The 6th Workshop on Space Debris
at ARD / JAXA
17– 19 December, 2014

1

CTC
Challenging Tomorrow's Changes

Formulation on the basis of 'Continuum Mechanics'

Mixed system of three physical phases of material in a single problem

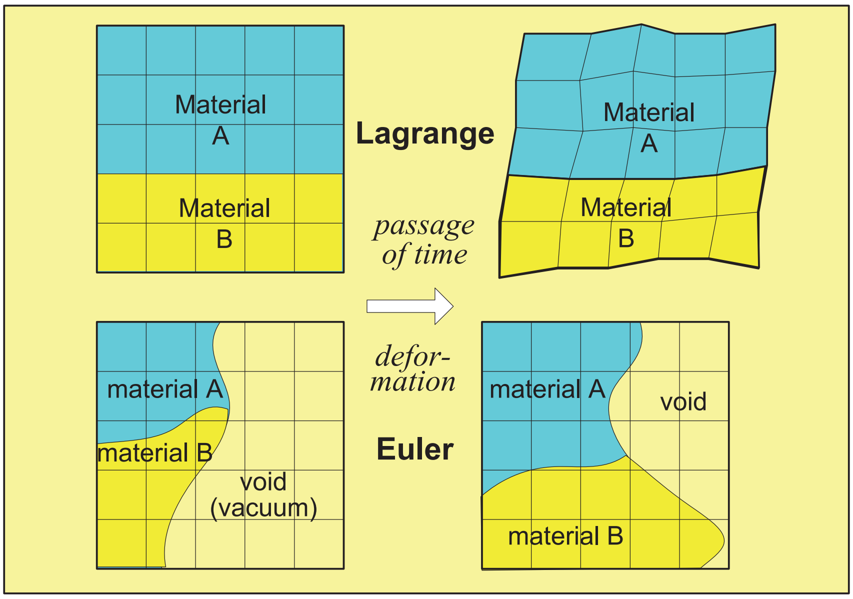
Governing Equations

1. Eq. of Continuity (Mass conservation)
2. Eq. of Motion (Momentum conservation)
3. Eq. of Energy (Energy conservation)

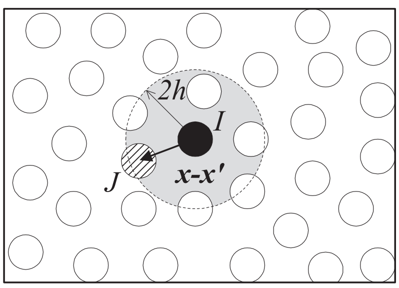
- ✓ Eq. of State (EOS)
- ✓ Constitutive Eq. (CE)
- ✓ Failure Criteria

 The 6th Space Debris Workshop 2

Lagrangian versus Eulerian Method



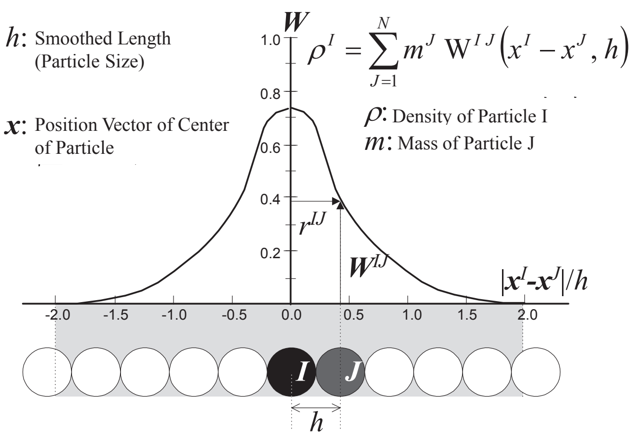
SPH (Smoothed Particle Hydrodynamics) Method



$$f(\boldsymbol{x}) \approx \int f(\boldsymbol{x}')W(\boldsymbol{x}-\boldsymbol{x}', h)d\boldsymbol{x}'$$

$$\nabla \cdot f(\boldsymbol{x}) \approx \int \nabla \cdot f(\boldsymbol{x}')W(\boldsymbol{x}-\boldsymbol{x}', h)d\boldsymbol{x}'$$

W: Weight Function (Kernel B-spline)



Schematics of SPH Method

Origin of Whipple Bumper Shield

No. 1161 **1947** THE ASTRONOMICAL JOURNAL 131

Whipple, F. L. Meteorites and space travel.

Meteorites represent a potential hazard to a pressurized space vessel. Of fundamental interest is the value of the probability that the skin of the vessel will be punctured by a meteorite. In case this probability is appreciable the problem of protection from meteorites becomes important.

We shall assume: (a) That the space vessel travels in a part of the solar system where the meteoritic frequencies and velocities approximate those at the earth.

(b) That 4.5 × 10⁷ fifth-magnitude meteors strike the earth daily and that the number increases by a factor of 2.51 per magnitude fainter (Watson).

(c) That (with Öpik) the total kinetic energy of a telescopic meteor is 1/0.0006 the energy observed in the wave length region from 4500 to 5700 angstroms.

(d) That the penetrating distance of a meteorite into a solid is equal to (extreme assumption) the length of a right circular cone of 60° total apex angle the volume of which in the solid can be heated and melted by the total kinetic energy of the meteorite.

It follows that a spherical space vessel of 12 feet diameter covered with a ¼-inch steel skin will be penetrated by a meteorite corresponding to an eighth magnitude or brighter meteor at a rate of once in 50 years. Such a meteorite weighs approximately a milligram. For thinner coverings the probability increases rapidly.

Although the probability of meteor penetration is small, a simple protection can be provided other than by the avoidance of known meteor streams. Considerations of the conservation of momentum and energy show that when a meteorite collides with a sheet of thickness comparable to the meteorite's diameter the result is an explosion in which both the meteorite and the corresponding material of the sheet are vaporized and ionized at very high temperatures. Hence a "meteor bumper" consisting perhaps of a millimeter-thick sheet of metal surrounding the ¼-inch skin of the space vessel at a distance of an inch would dissipate the penetrating power of meteorites several times larger than one corresponding to an eighth-magnitude meteor.

Harvard College Observatory,
Cambridge, Mass.

Ballistic Limit Equation (Curve)

After Apollo Program:

Modified Cour-Palais Equation → **New Cour-Palais Equation (Christiansen Equation)**

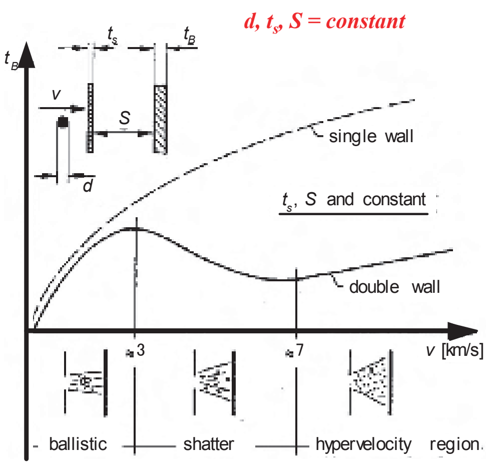


Fig. 3 Behaviour of the bumper protection concept.
(H.-G. Reimerdes et al., *Proc. 1st European Conf. on Space Debris*, ESA SD-01, Darmstadt pp.433-439, 1993.)

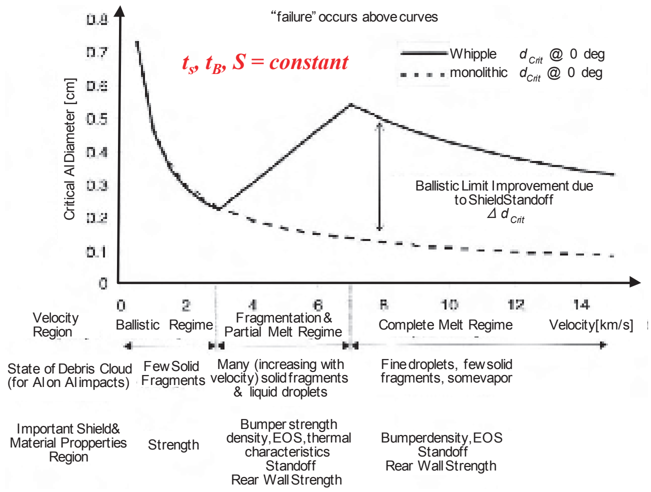
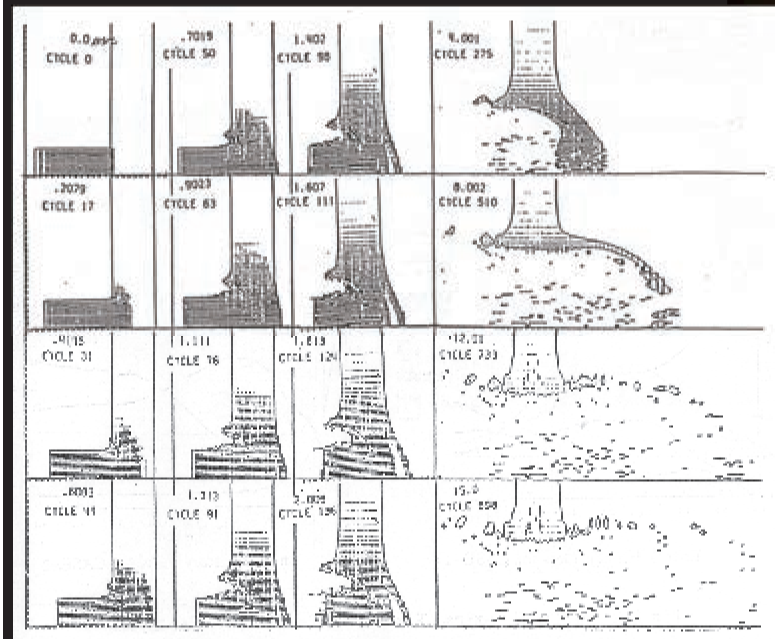


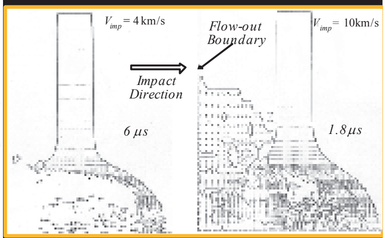
Fig.8 Ballistic limits for equal mass monolithic target and Whipple shield. (E. L. Christiansen, "Meteoroid/Debris Shielding," TP-2003-210788, NASA, 2003.)

Presented at Hypervelocity Impact Symposium in San Antonio TX, Dec.,1989



Velocity Vector Distributions

NB: Calculations were performed by using multiple-material Eulerian method of PISCES-2DELK in 1986.



Int. J. Impact Engng Vol. 10, pp. 525–534, 1990
Printed in Great Britain
0734-743X/90 $3.00 + 0.00
Pergamon Press plc

MICROMETEOROID AND DEBRIS IMPACT TEST
ON SPACE STATION BUMPER

Yasuki Adachi

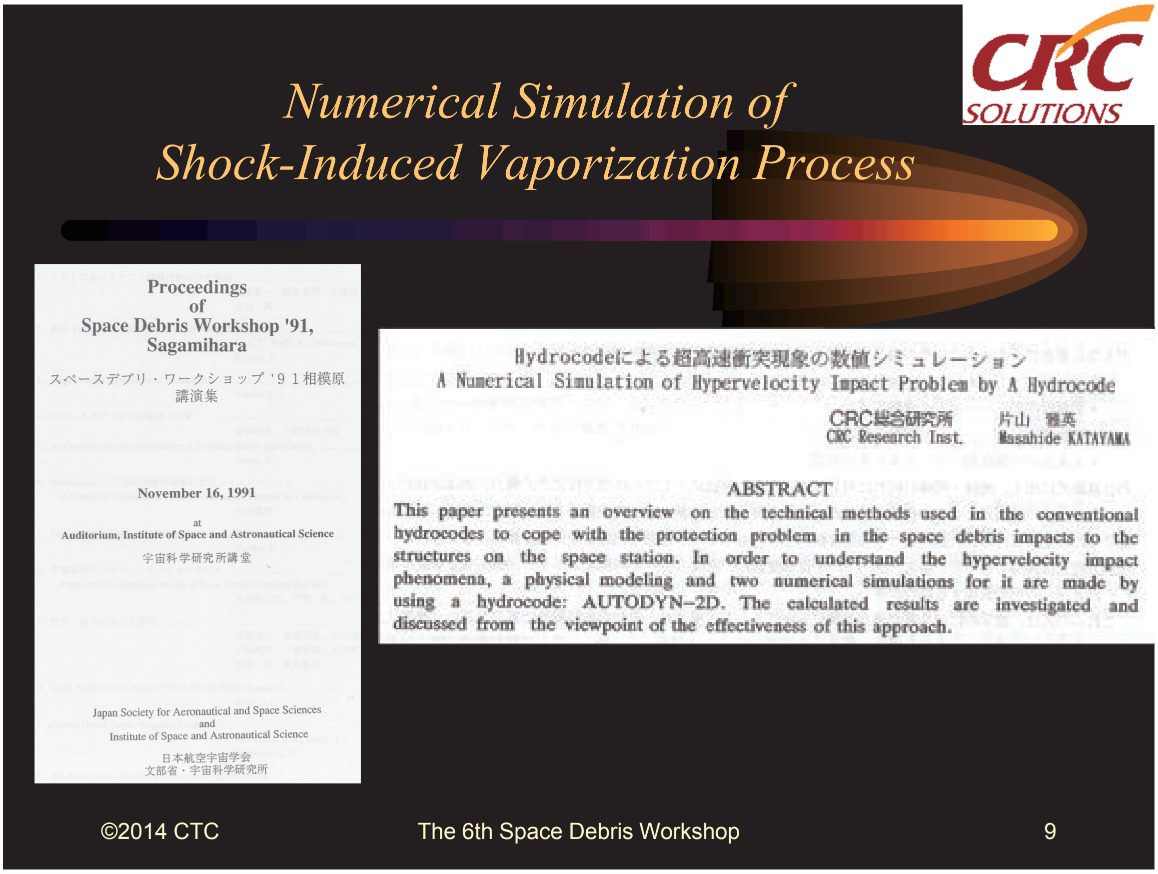
National Space Development Agency of Japan
2-4-1 Hamamatsu-cho, Minato-ku, Tokyo Japan

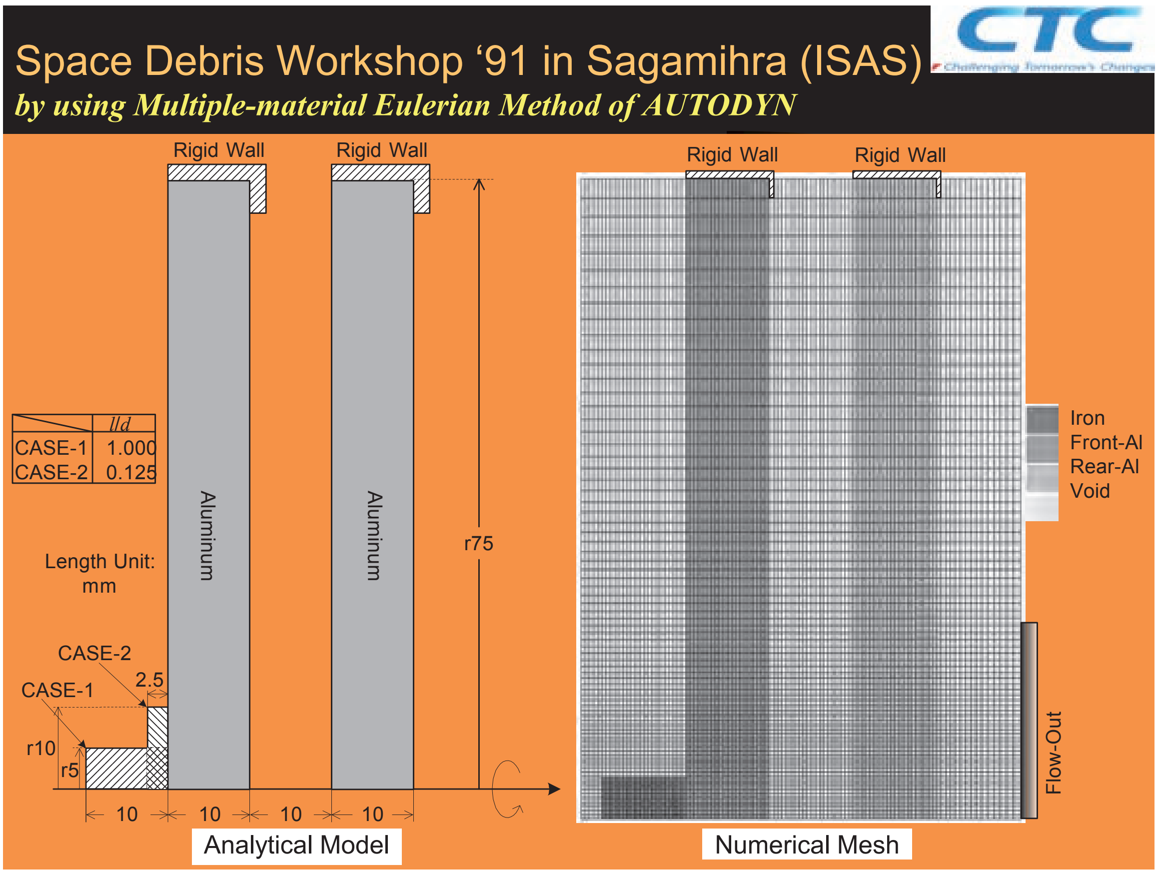
Hideshige Ohtaki, Fumio Suehiro, and Yujiro Shirai

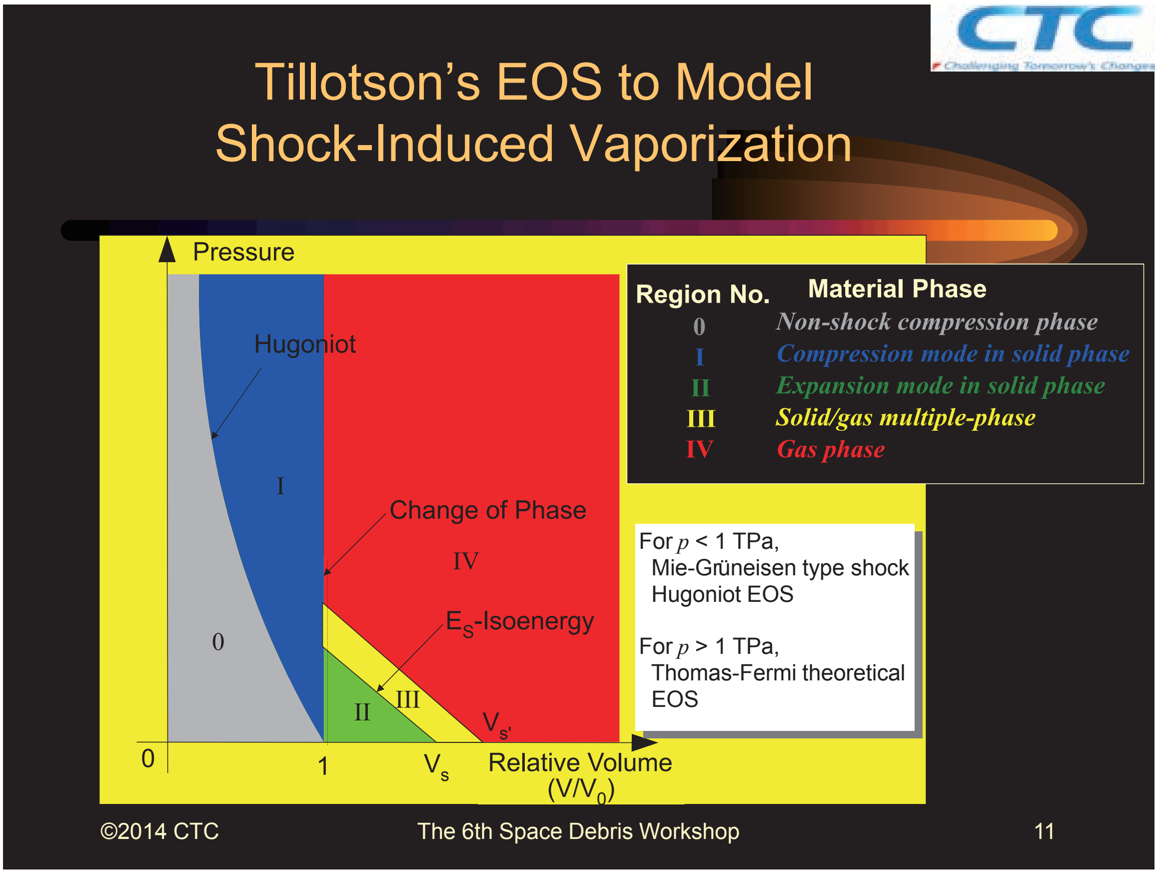
Mitsubishi Heavy Industries, Ltd.
10 Oye-cho, Minato-ku, Nagoya Japan

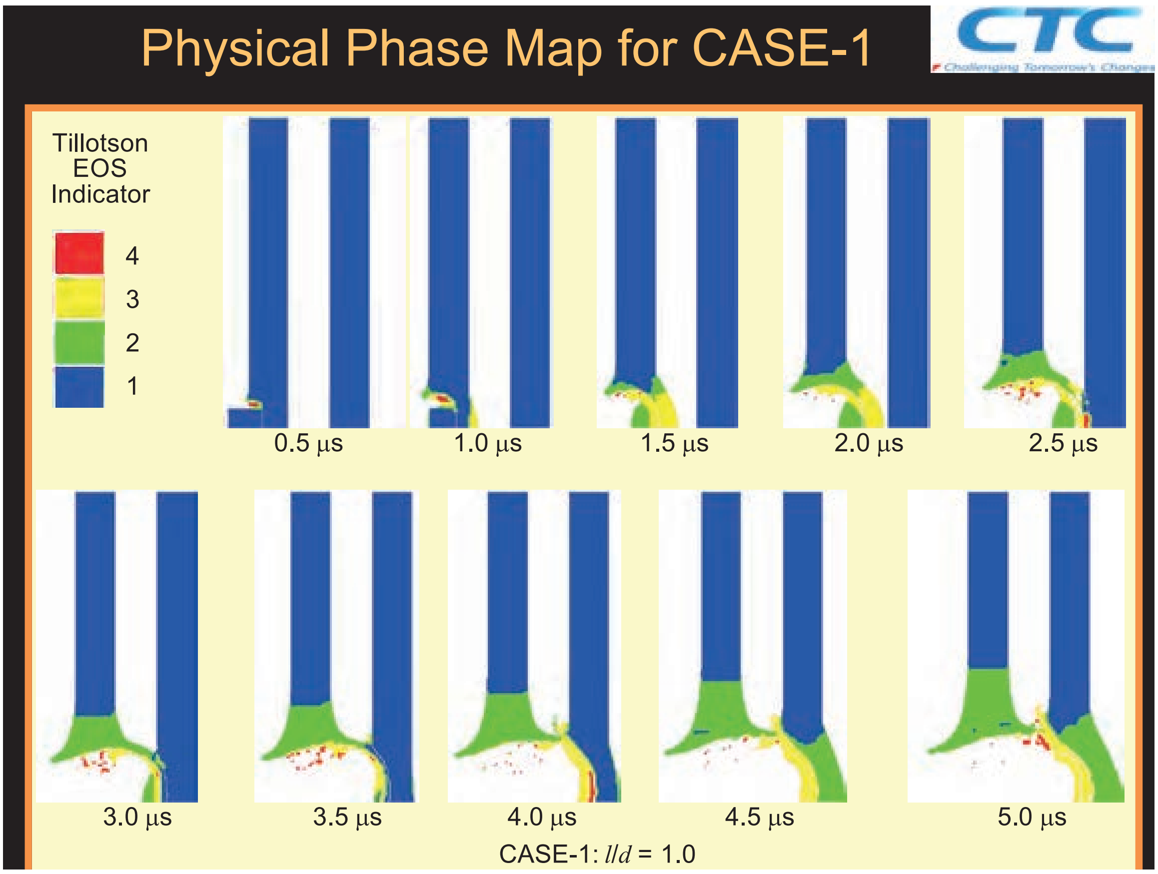
Abstract

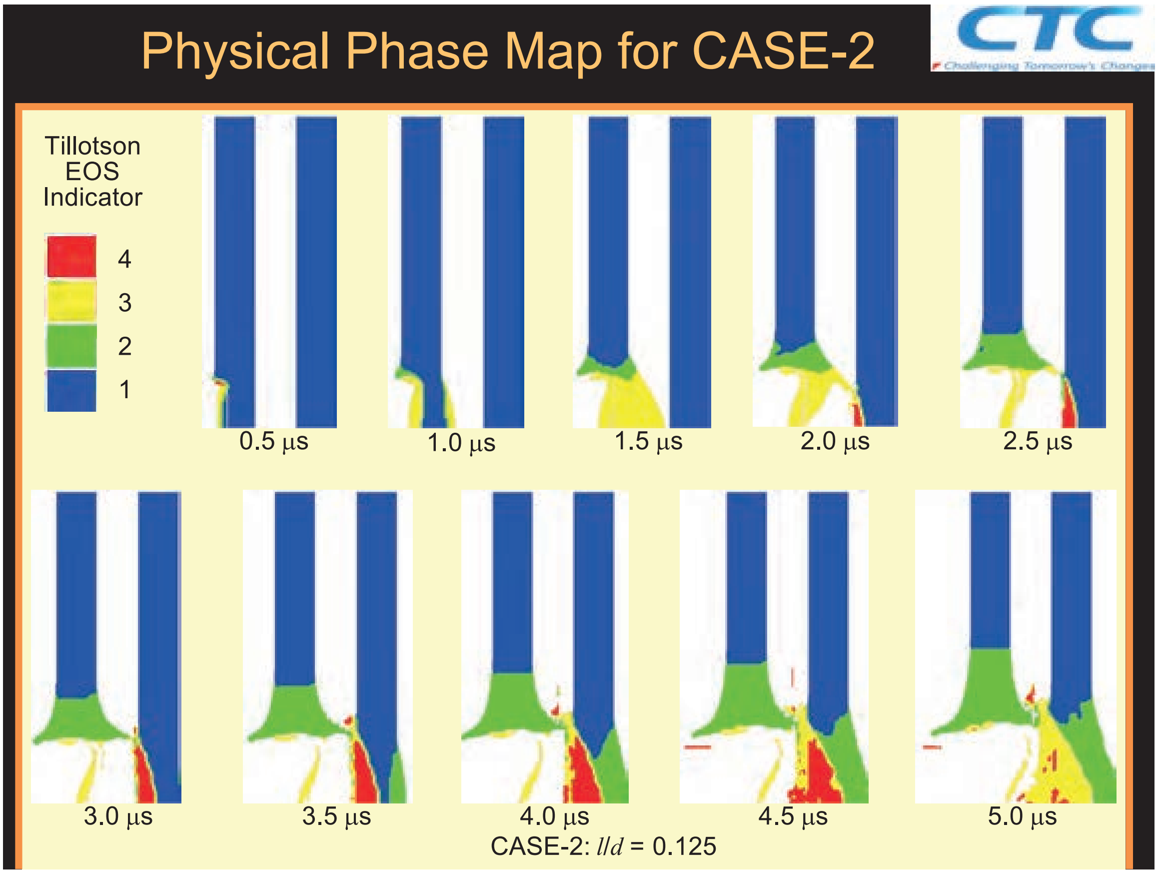
To design the micrometeoroid and debris protection bumper of the outboard structure space station module, we made a two-stage helium light gas gun and carried out hypervelocity impact tests which simulated micrometeoroid and debris impacts on space station. Fundamental characteristics of hypervelocity impact phenomena was investigated, for a projectile mass 0.45gr to 1.5gr, impact velocity about 4km/sec and aluminum-alloy bumpers. When the bumper is of double-sheet type, there exists an optimal front sheet thickness that causes melting of the front sheet. However, for thin front sheets, penetration occurs, and for thick front sheets, spall fracture occurs. In addition to the impact tests, the computational simulation of the typical test result was carried out using the PISCES code with the Tillotson constitutive equation of aluminum-alloy. The computational simulation result had a good agreement with the test result.

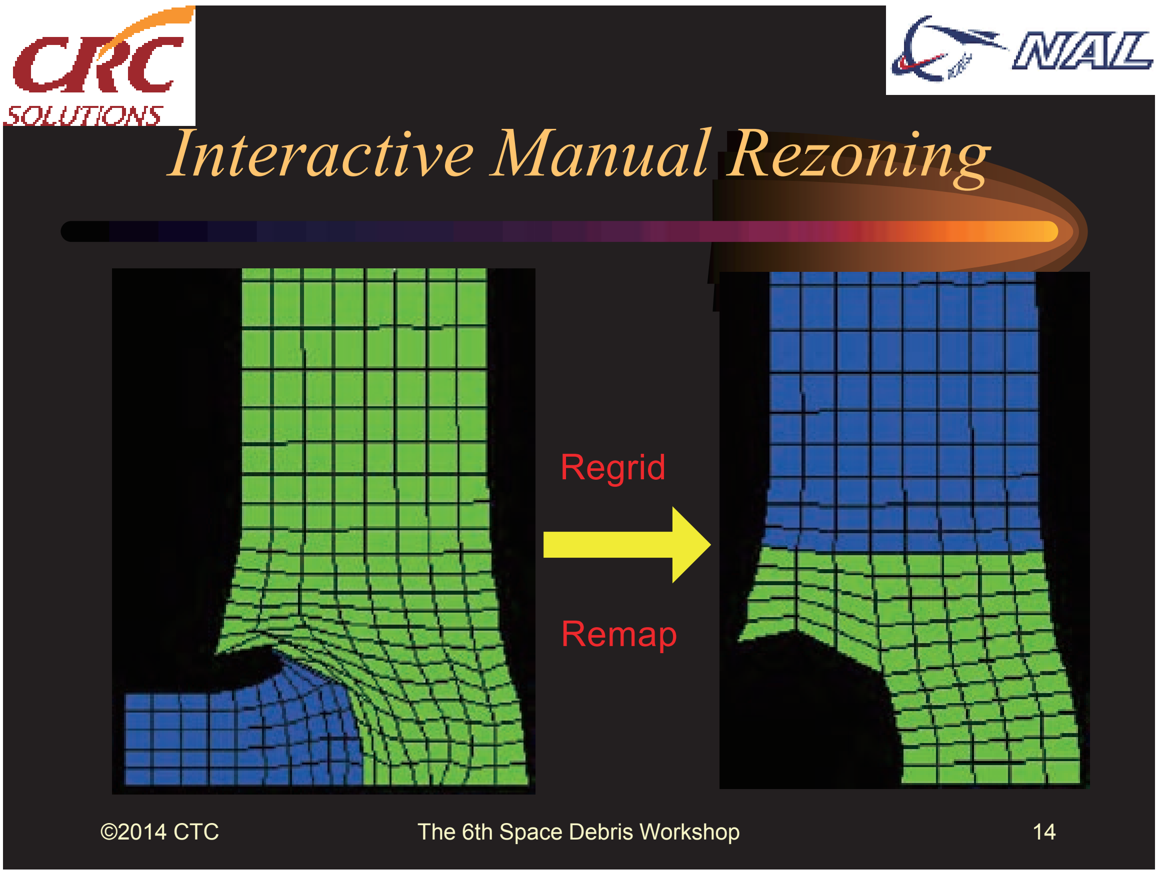

CRC SOLUTIONS
Numerical Simulation of
Shock-Induced Vaporization Process
Proceedings
of
Space Debris Workshop '91,
Sagamihara
スペースデブリ・ワークショップ '9１相模原
講演集
November 16, 1991
at
Auditorium, Institute of Space and Astronautical Science
宇宙科学研究所講堂
Japan Society for Aeronautical and Space Sciences
and
Institute of Space and Astronautical Science
日本航空宇宙学会
文部省・宇宙科学研究所
Hydrocodeによる超高速衝突現象の数値シミュレーション
A Numerical Simulation of Hypervelocity Impact Problem by A Hydrocode
CRC総合研究所 片山 雅英
CRC Research Inst. Masahide KATAYAMA
ABSTRACT
This paper presents an overview on the technical methods used in the conventional hydrocodes to cope with the protection problem in the space debris impacts to the structures on the space station. In order to understand the hypervelocity impact phenomena, a physical modeling and two numerical simulations for it are made by using a hydrocode: AUTODYN-2D. The calculated results are investigated and discussed from the viewpoint of the effectiveness of this approach.
©2014 CTC
The 6th Space Debris Workshop
9


Space Debris Workshop '91 in Sagamihra (ISAS)
by using Multiple-material Eulerian Method of AUTODYN
CTC
Rigid Wall
Rigid Wall
l/d
CASE-1 1.000
CASE-2 0.125
Aluminum
Aluminum
r75
Length Unit: mm
CASE-2
CASE-1
2.5
r10
r5
10 10 10 10
Analytical Model
Rigid Wall
Rigid Wall
Iron
Front-Al
Rear-Al
Void
Flow-Out
Numerical Mesh

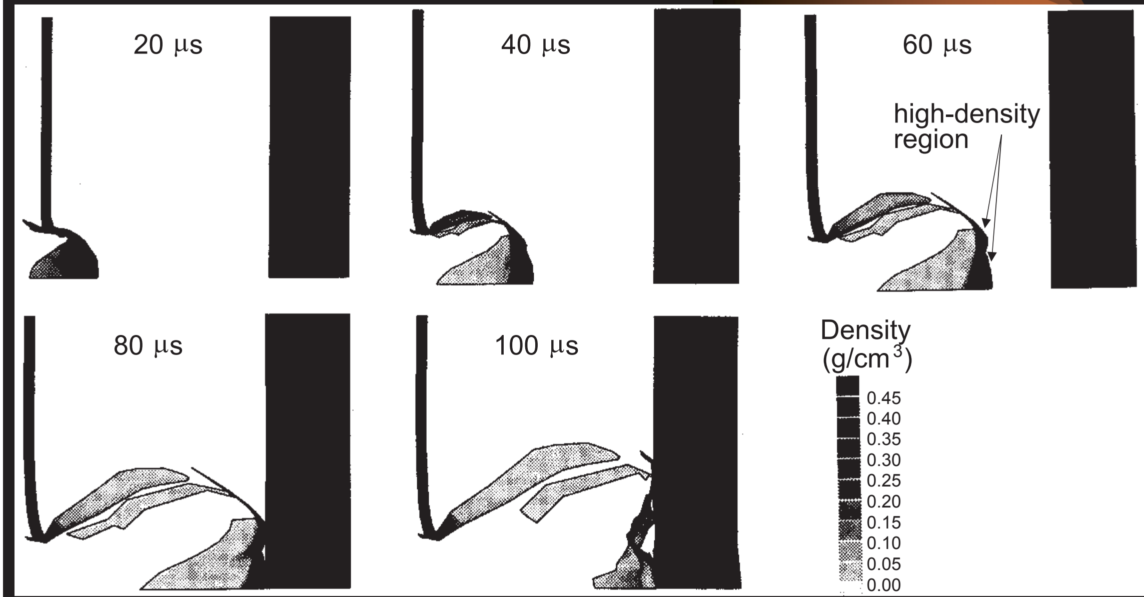

Tillotson's EOS to Model
Shock-Induced Vaporization
Pressure
Hugoniot
I
Change of Phase
IV
E_S-Isoenergy
0
II
III
$V_{s'}$
0
1
V_s
Relative Volume
(V/V_0)
Region No.
Material Phase
0 Non-shock compression phase
I Compression mode in solid phase
II Expansion mode in solid phase
III Solid/gas multiple-phase
IV Gas phase
For p < 1 TPa,
Mie-Grüneisen type shock Hugoniot EOS
For p > 1 TPa,
Thomas-Fermi theoretical EOS
©2014 CTC
The 6th Space Debris Workshop
11


Physical Phase Map for CASE-1
Tillotson EOS Indicator
4
3
2
1
0.5 μs
1.0 μs
1.5 μs
2.0 μs
2.5 μs
3.0 μs
3.5 μs
4.0 μs
4.5 μs
5.0 μs
CASE-1: l/d = 1.0

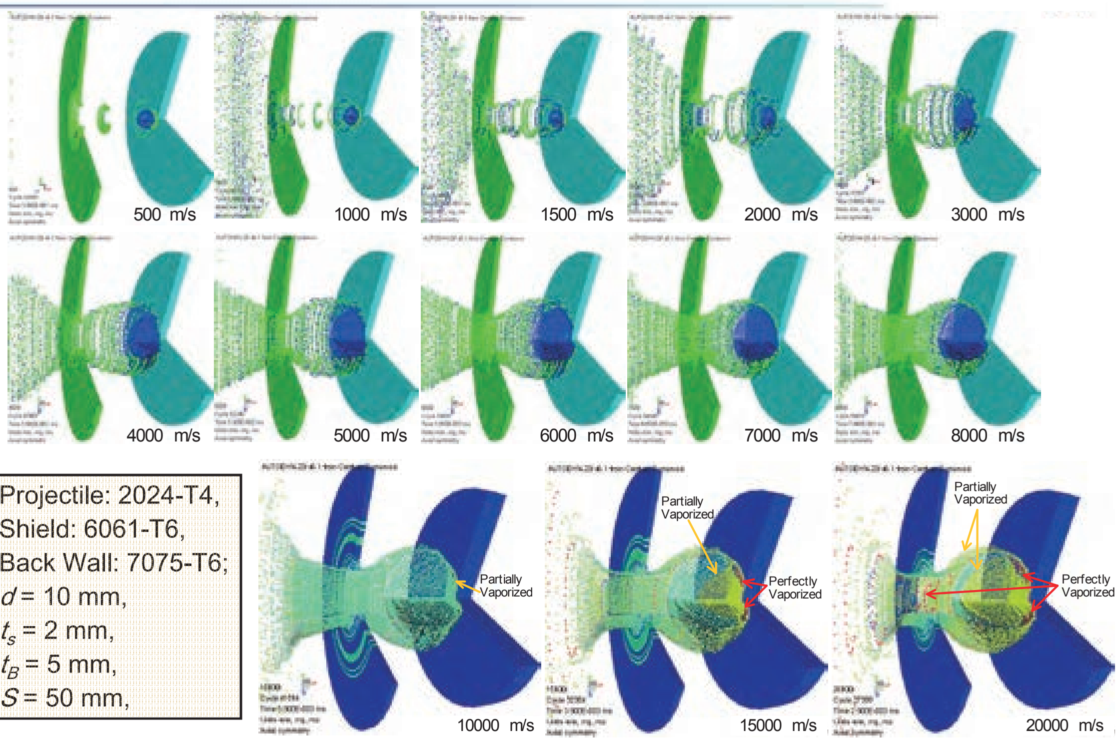

Physical Phase Map for CASE-2
CTC
Tillotson EOS Indicator
4
3
2
1
0.5 μs
1.0 μs
1.5 μs
2.0 μs
2.5 μs
3.0 μs
3.5 μs
4.0 μs
4.5 μs
5.0 μs
CASE-2: l/d = 0.125


CRC SOLUTIONS
NAL
Interactive Manual Rezoning
Regrid
Remap
©2014 CTC
The 6th Space Debris Workshop
14

Lagrange/Rezoning Method in AUTODYN Applied to Whipple Bumper Shield in 1992



Debris Cloud Formation: 500 to 20,000 m/s



Projectile: 2024-T4,
Shield: 6061-T6,
Back Wall: 7075-T6;
d = 10 mm,
t_s = 2 mm,
t_B = 5 mm,
S = 50 mm,

IAC-04-IAA.5.12.2.05

Assessment of Numerical Simulations for Hypervelocity Impacts of Space Debris

○Takeshi Kamiya*, Kuniaki Shiraki*, Masahide Katayama** and Atsushi Takeba**
*Japan Aerospace Exploration Agency (JAXA), kamiya.takeshi@jaxa.jp
**CRC Solutions Corp.

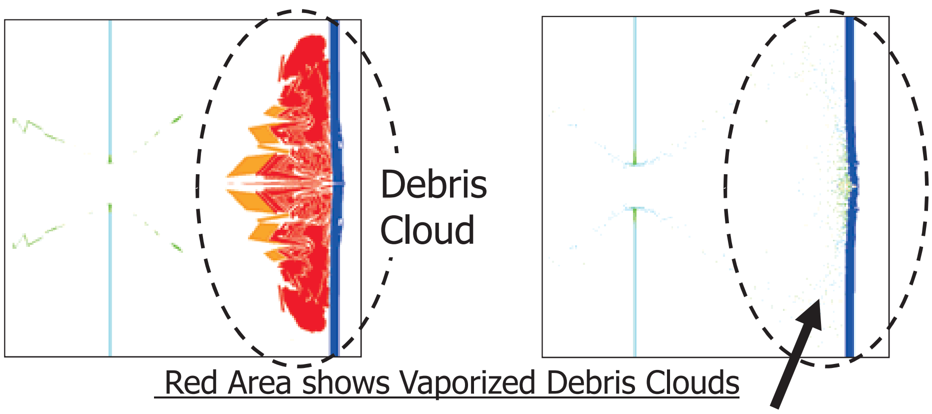
October 6th, 2004

4. Simulation Results and Assessment

IAC-04-IAA.5.12.2.05

Comparison of Vaporized Area
between Lagrange and SPH at Vi=14km/sec

2-dimensional Lagrange Method (14μsec) | 2-dimensional SPH Method (14μsec)



Red Area shows Vaporized Debris Clouds

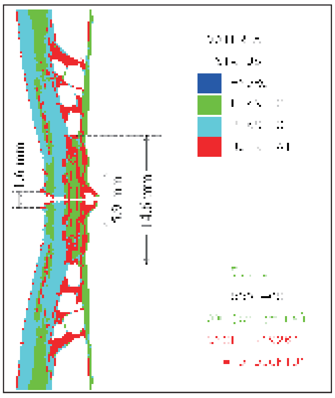
■ There is no vaporization area in SPH because Debris Cloud in the SPH cannot hold the internal energy due to the feature of the SPH method.

4. Simulation Results and Assessment

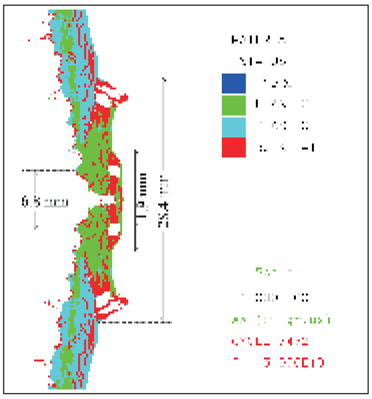
IAC-04-IAA.5.12.2.05

Comparison of Vaporized Area between Lagrange and SPH at Vi=14km/sec

2-dimensional Lagrange Method

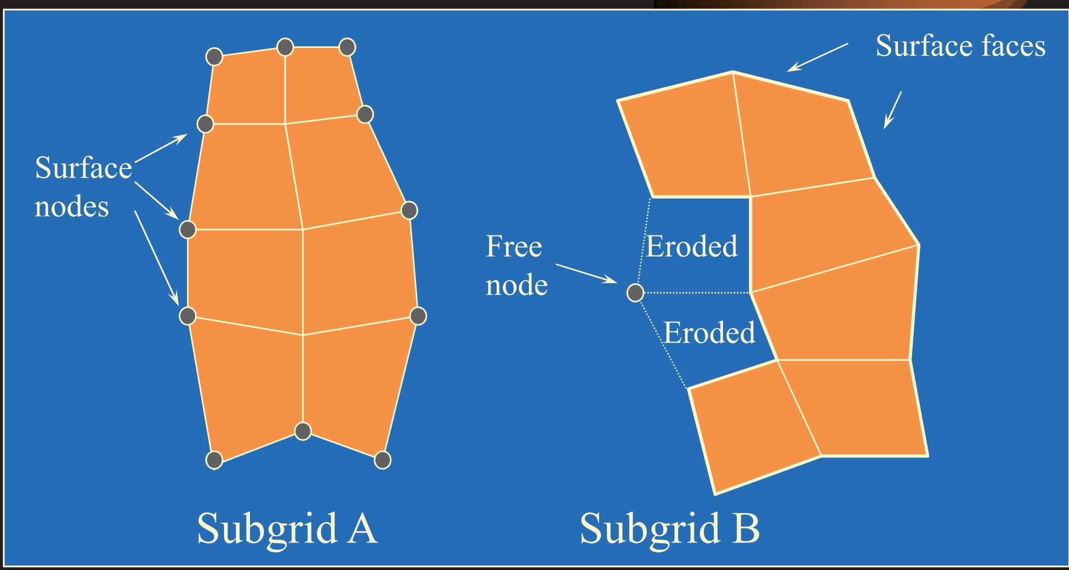


2-dimensional SPH Method



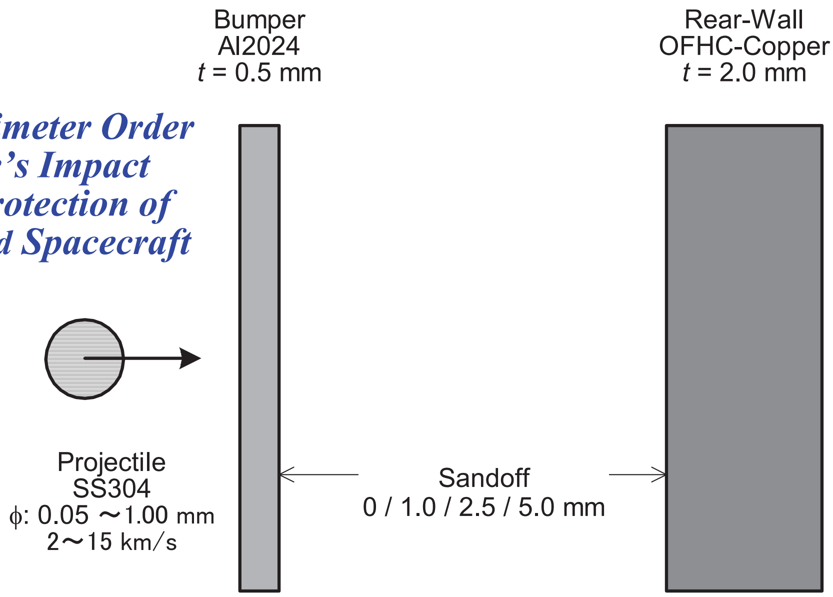
- The damage in SPH is severer than Lagrange because of less vaporization of Debris Clouds in SPH.

Numerical Erosion Option & Eroded Node Interactive with Lagrangian Grid



Ballistic Limit Curve of Double Sheet Targets Determined only by Numerical Procedures

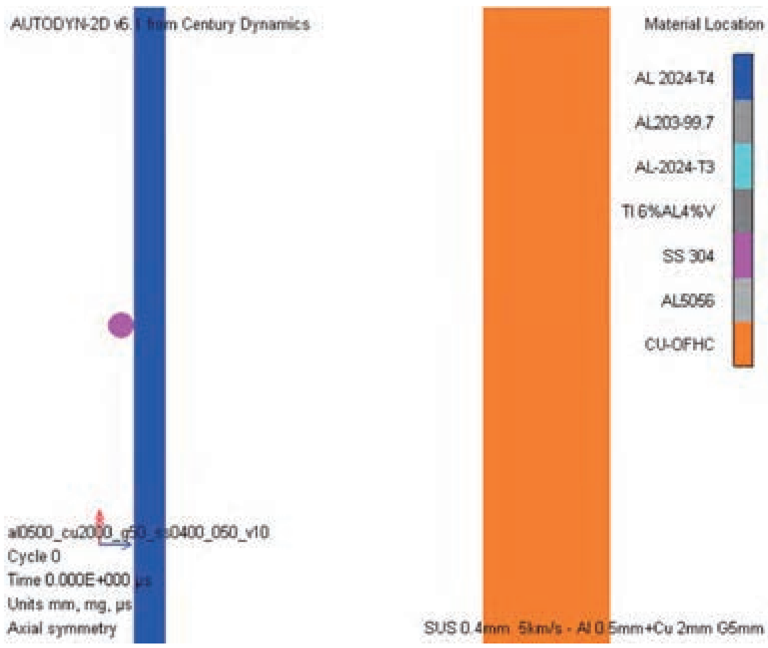
Sub-Millimeter Order Projectile's Impact for the Protection of Unmanned Spacecraft



The analytical models with different standoffs between the two sheets.

Ballistic Limit Curve of Double Sheet Targets Determined only by Numerical Procedures

Numerical Results

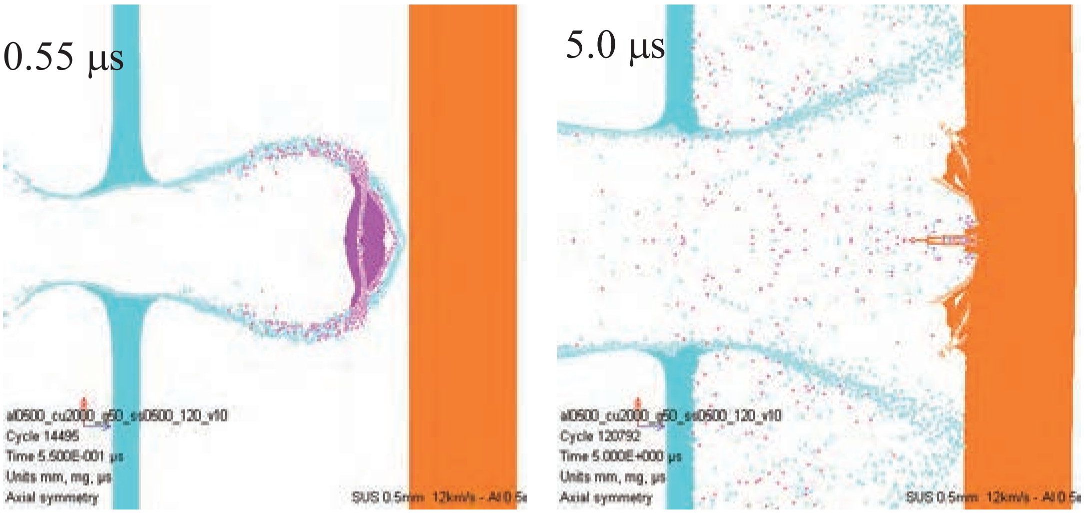


The analytical model with the standoff of 5.0 mm between the two sheets.

Ballistic Limit Curve of Double Sheet Targets Determinedbonly by Numerical Procedures

CTC

Numerical Results

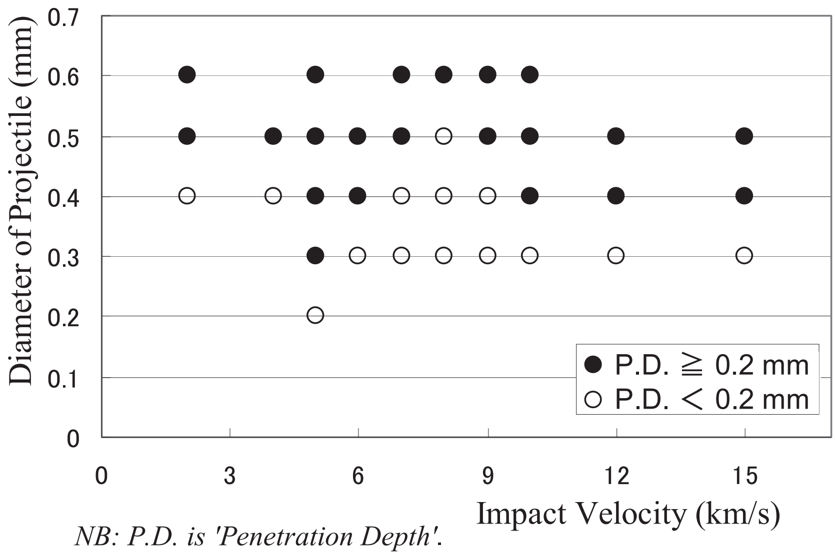


The analytical model with the standoff of 5.0 mm between the two sheets.

Ballistic Limit Curve of Double Sheet Targets Determinedbonly by Numerical Procedures

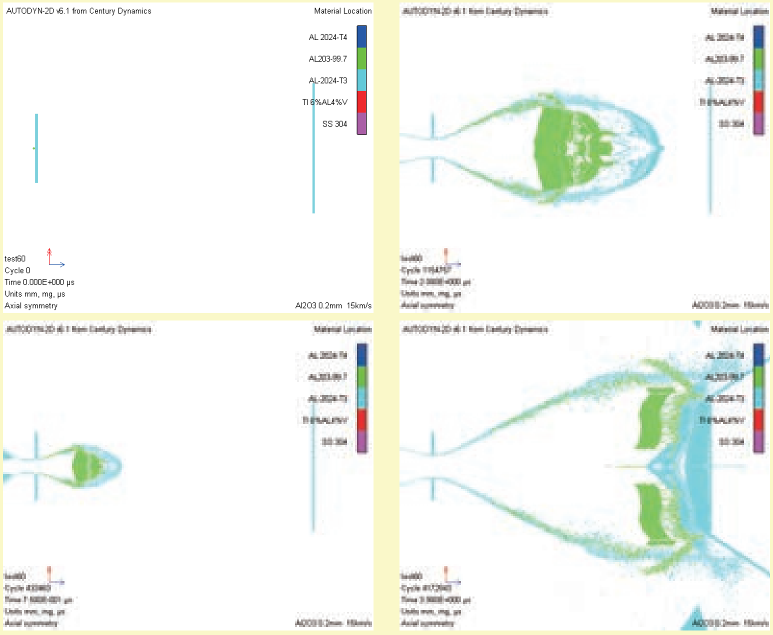
CTC

Numerical Results



The analytical model with the standoff of 5.0 mm between the two sheets.

Expansioning Debris Cloud by Lagrangian Method



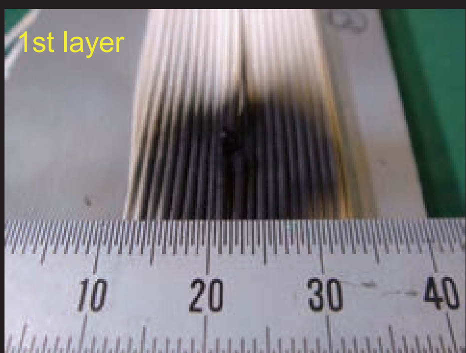
Problems

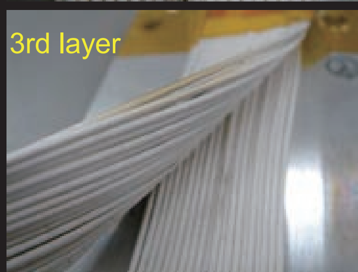
- ✓ Are there fragmentation or shattering processes actually in such a small system?
- ✓ It is difficult to be modeled by Eulerian method.

 The 6th Space Debris Workshop 25

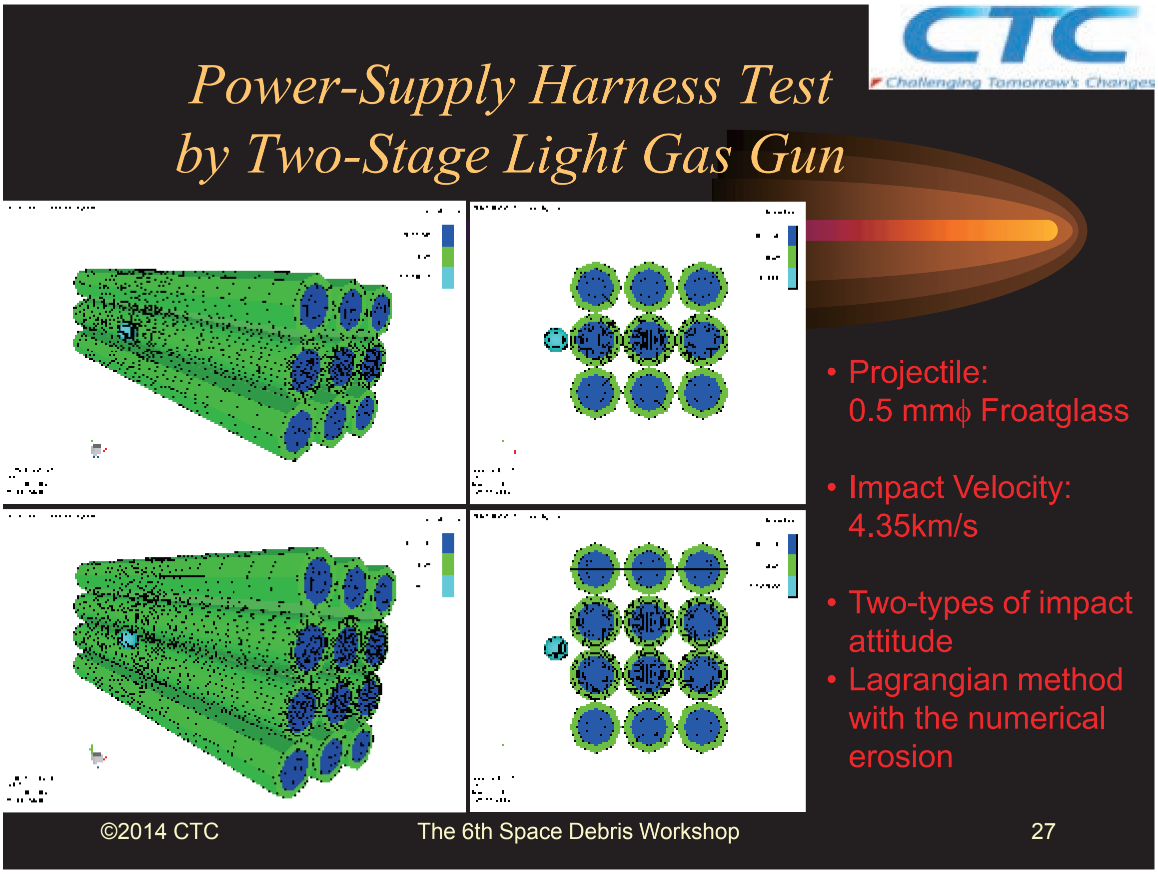
Power-Supply Harness Test by Two-Stage Light Gas Gun

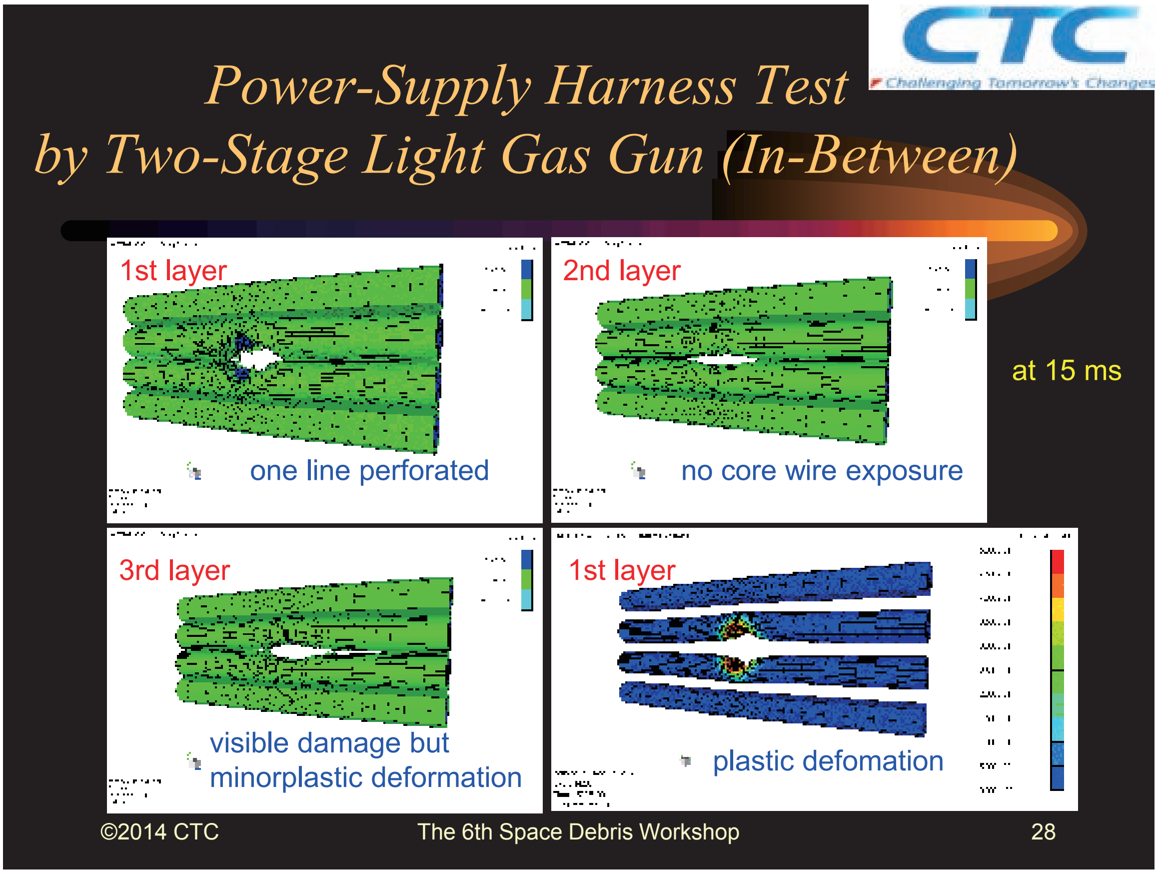
- •Projectile: 0.5 mmϕ Floatglass
- •Impact Velocity: 4.35km/s





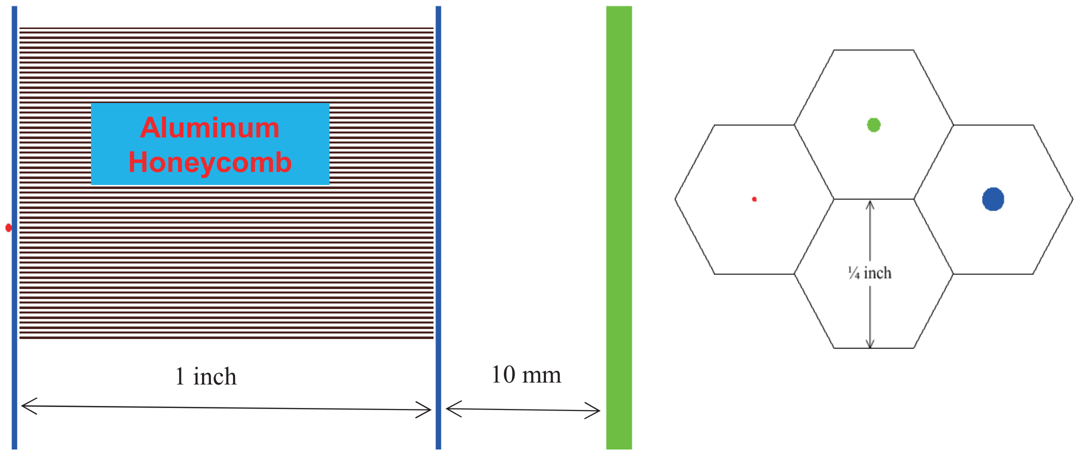
 The 6th Space Debris Workshop 26


CTC
Challenging Tomorrow's Changes
Power-Supply Harness Test
by Two-Stage Light Gas Gun
• Projectile:
0.5 mmϕ Froatglass
• Impact Velocity:
4.35km/s
• Two-types of impact attitude
• Lagrangian method with the numerical erosion
©2014 CTC
The 6th Space Debris Workshop
27

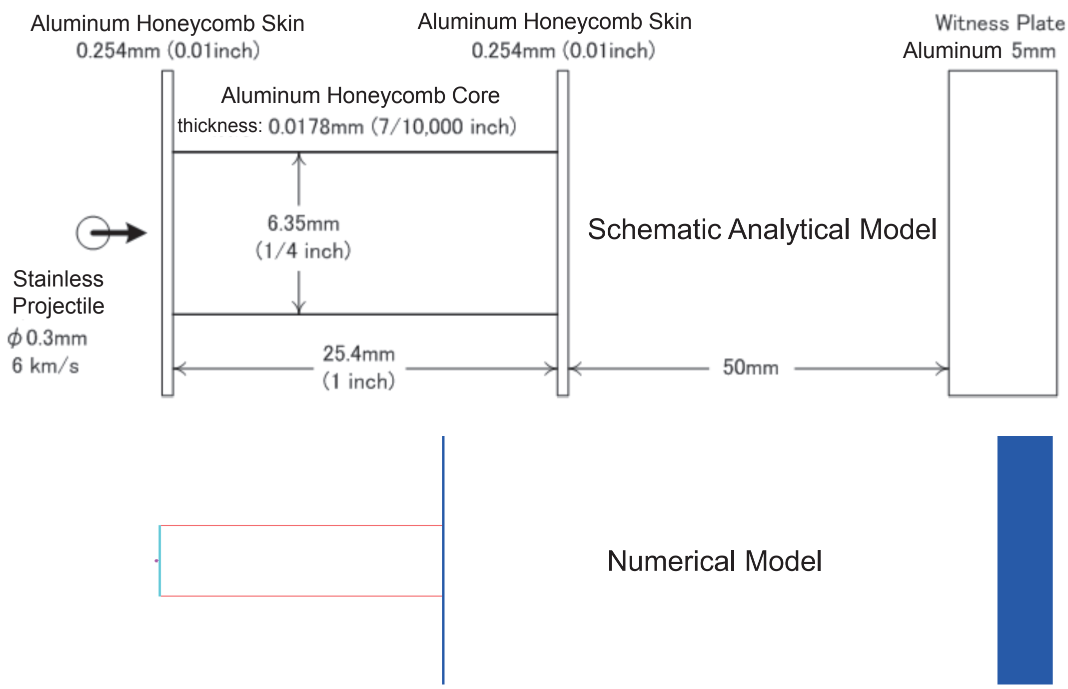

CTC
Challenging Tomorrow's Changes
Power-Supply Harness Test
by Two-Stage Light Gas Gun (In-Between)
1st layer
one line perforated
2nd layer
no core wire exposure
at 15 ms
3rd layer
visible damage but
minorplastic deformation
1st layer
plastic defomation
©2014 CTC
The 6th Space Debris Workshop
28

Analysis of Impact on Aluminum Honeycomb

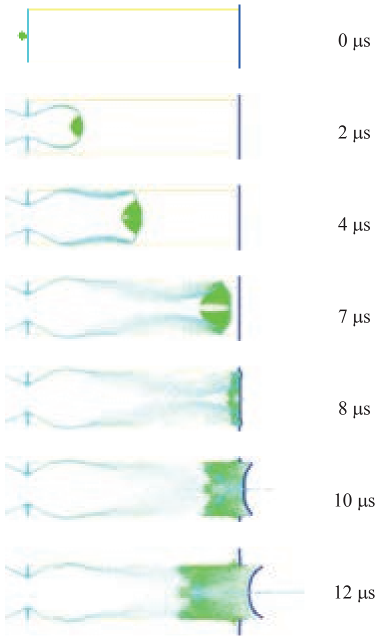
- 0.25 mm-thickness aluminum skin
- 1 inch-thickness and 1/4 inch-cell size aluminum honeycomb
- Internal component (1.6 mm-thickness aluminum, stainless steel and titanium)
- Projectiles' (aluminum or stone) diameter: 0.2 mm
- Assumed to hit on the center of cell for the conservative estimation



Analysis of Impact on Aluminum Honeycomb

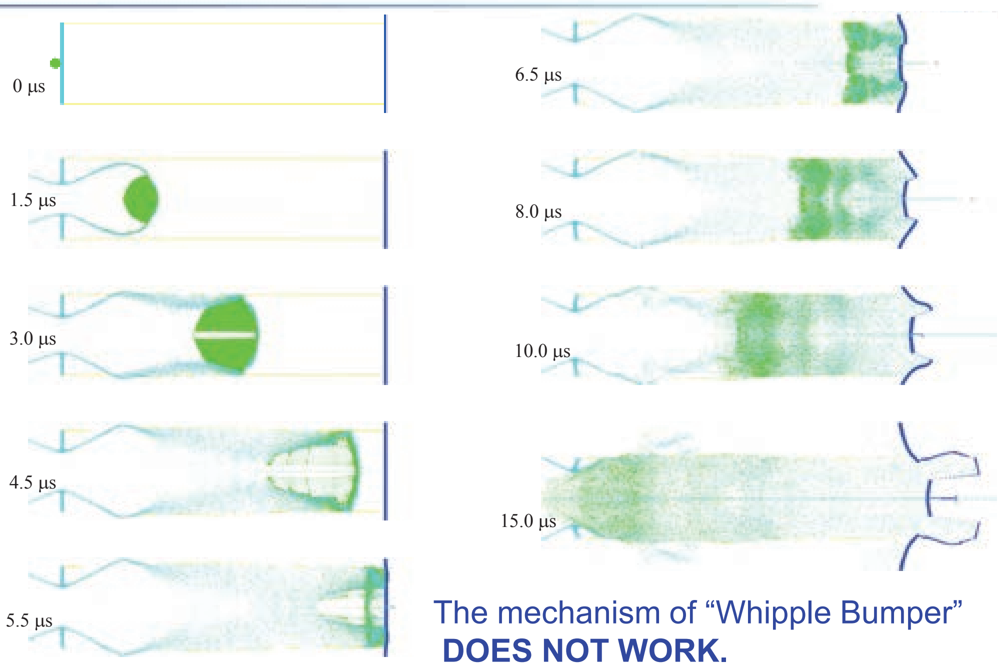


Analysis of Impact on Aluminum Honeycomb



Sequence of impact and perforation process (Alumina, 0.8 mmϕ, 4km/s)

Analysis of Impact on Aluminum Honeycomb

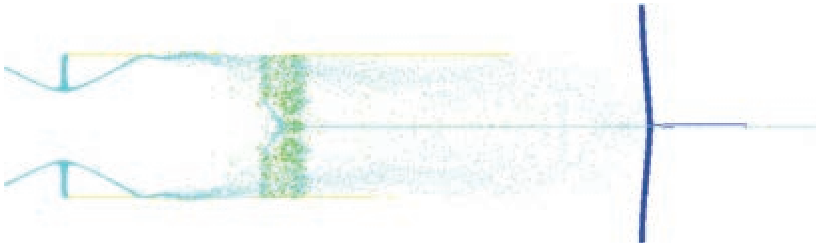


The mechanism of “Whipple Bumper”
DOES NOT WORK.

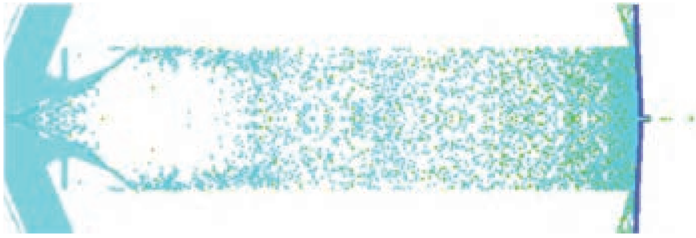
Sequence of impact and perforation process (Alumina, 0.8 mmϕ, 6 km/s)

Analysis of Impact on Aluminum Honeycomb

Another problem



Result by Lagrangian method with the numerical erosion.



Result by SPH method.

Projectile: Alumina, 0.4 mmϕ, 6 km/s

CONCLUSIONS

- There are no almighty numerical analysis methods to solve the hypervelocity impact problem for the present protection assessment of spacecraft from the space debris impact.
- It is important to comprehend adequately the feature and characteristic of each numerical method in its merits and demerits, and to apply the best method to the each component in the target problem.

Acknowledgement

This material contains a number of important numerical results obtained through the activity of preparation of “Design Manual for the Space Debris Protection” for the purpose of standardization of designing and developing satellites and probes by JAXA. Authors do specify the fact, at the same time they would like to acknowledge it gratefully.