Orbital Debris: Effect on Spacecraft Pressurized Structures
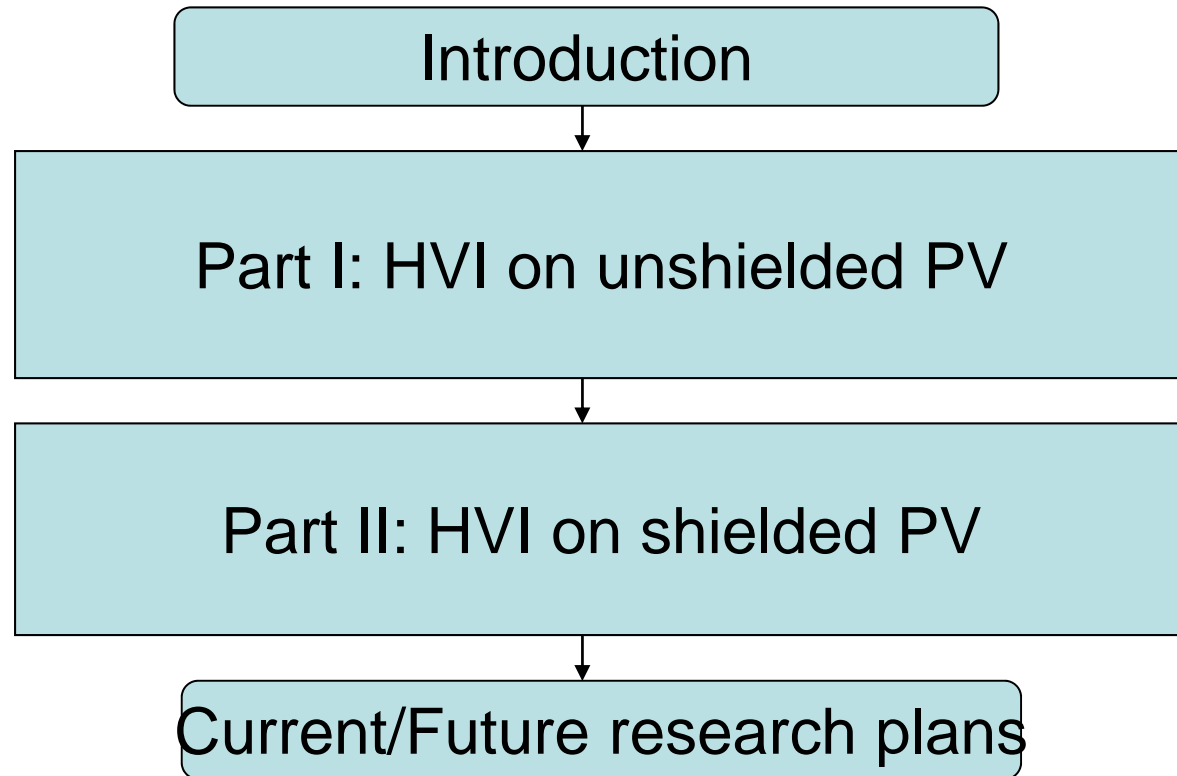
Igor Telichev

University of Manitoba

Presentation outline

Introduction

Part I: HVI on unshielded PV

Part II: HVI on shielded PV

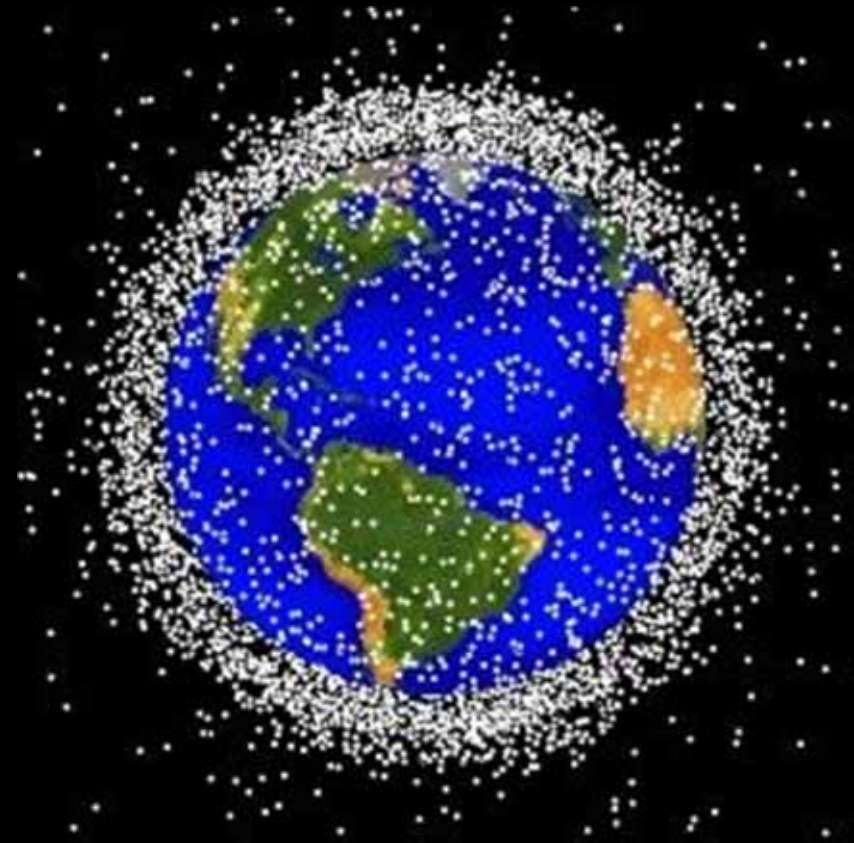Current/Future research plans

MANITOBA AEROSPACE

- University of Manitoba

- Bristol Aerospace (Magellan), Winnipeg
- Boeing, Winnipeg
- Standard Aero, Winnipeg

- Canadian Space Agency

Space Debris Population

- 17,300 objects
  size > 10 cm
  – detectable

- 300,000 objects,
  size 1-10 cm
  – non-detectable

- Millions objects,
  size < 1 cm
  – non-detectable

(by Secure World Foundation)

Av. V=11 km/s

Space debris distribution in Low Earth Orbit
© NASA

Debris Source

- Rocket bodies
- mission related debris
- fragmentation debris
- dysfunctional spacecraft

Debris Source

- Trackable
- Non-trackable

- Orbital debris impacts are random events, and for the untrackable objects it is not possible to precisely determine exactly when or where an impact will occur on a spacecraft.

- The untrackable orbital debris has become a major design consideration in the development of spacecraft and vulnerability/survivability analysis.

- Spacecraft pressurized structures are identified as the most critical components exposed directly to the orbital debris environment
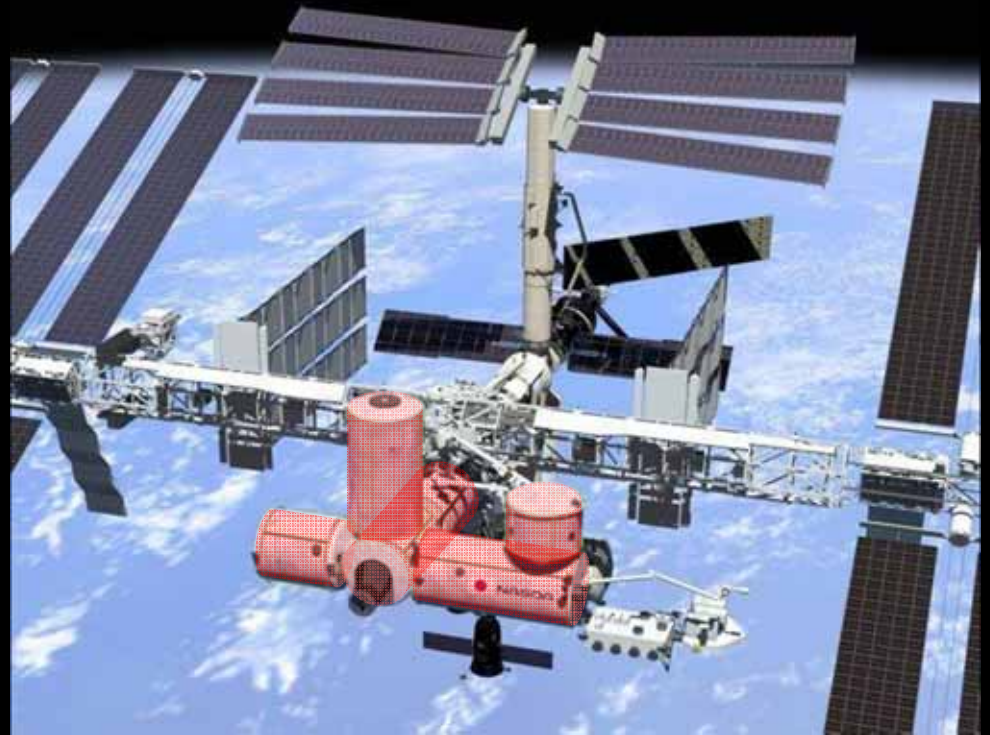
Types of Pressure Vessels

- Spacecraft pressurized modules (low pressure)

- Onboard system pressure vessels (high pressure)
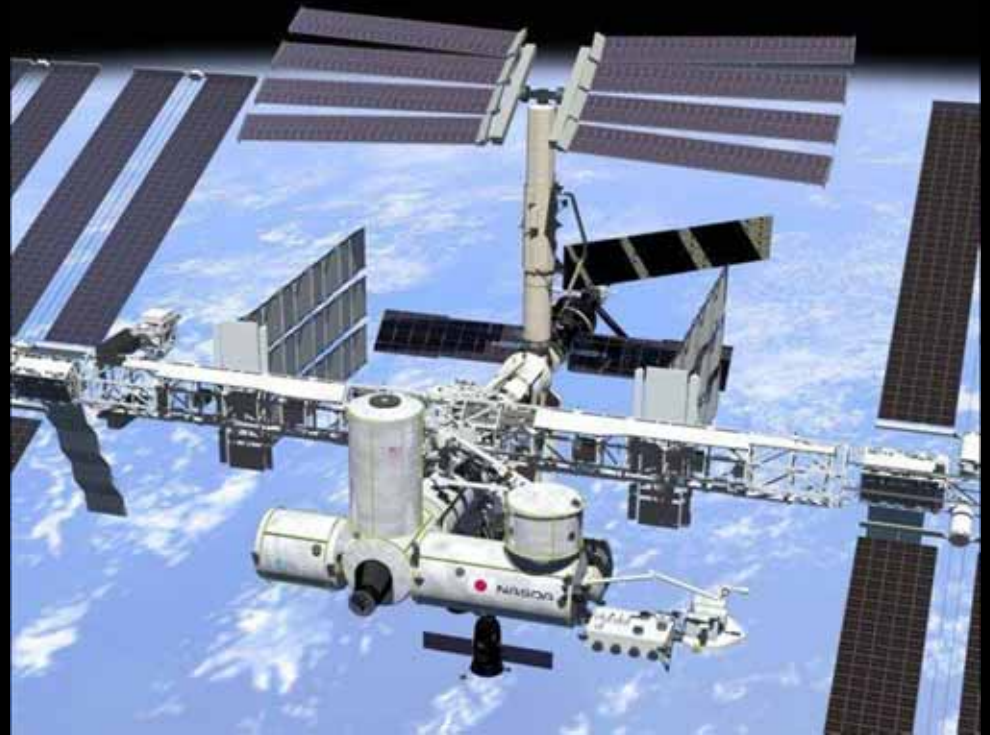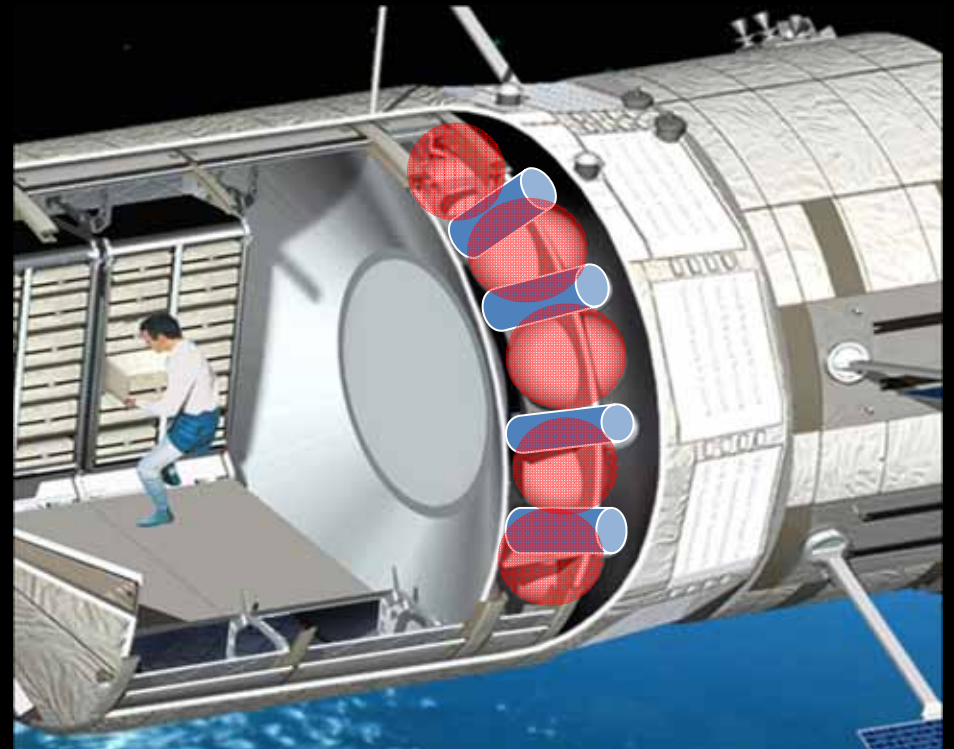
Types of Pressure Vessels

- Spacecraft pressurized modules (low pressure)

- Onboard system pressure vessels (high pressure)

Low internal pressure (~0.1 MPa) and a relatively large size (~4 x 7 m)

Types of Pressure Vessels

- Spacecraft pressurized modules (low pressure)

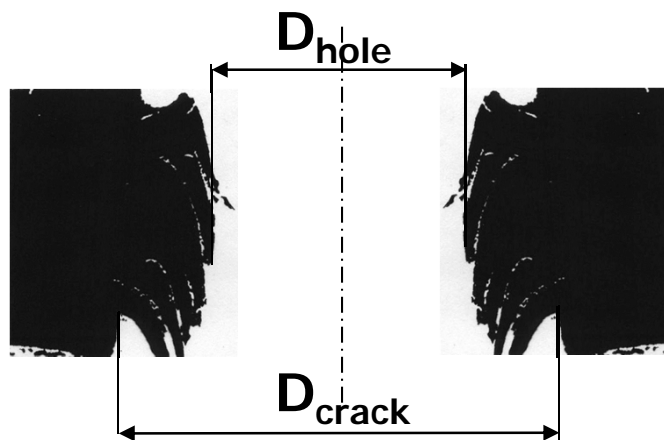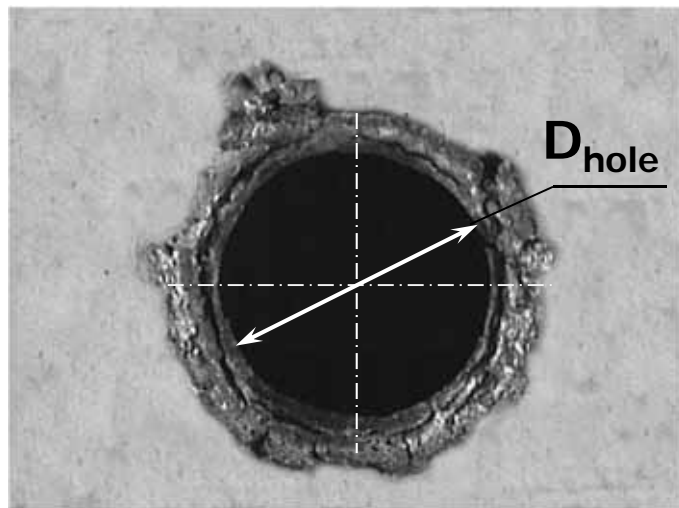- Onboard system pressure vessels (high pressure)

Smaller size (ID<1.0 m) and significantly higher internal pressure (up to 40 MPa)

Purpose of the study

The main purpose of the study is to define the border between simple perforation and catastrophic fracture of pressure vessels subjected to high-velocity impact
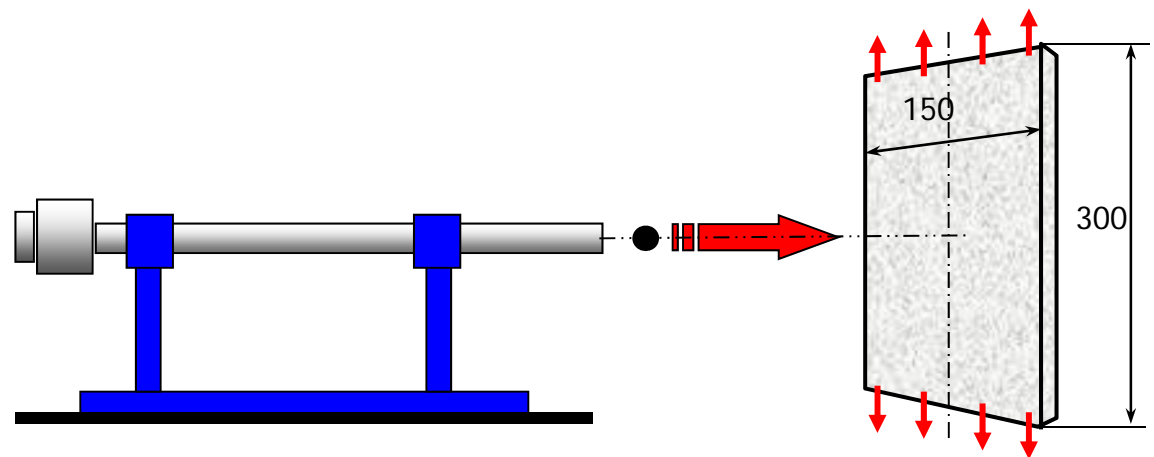
Impact and Tensile tests
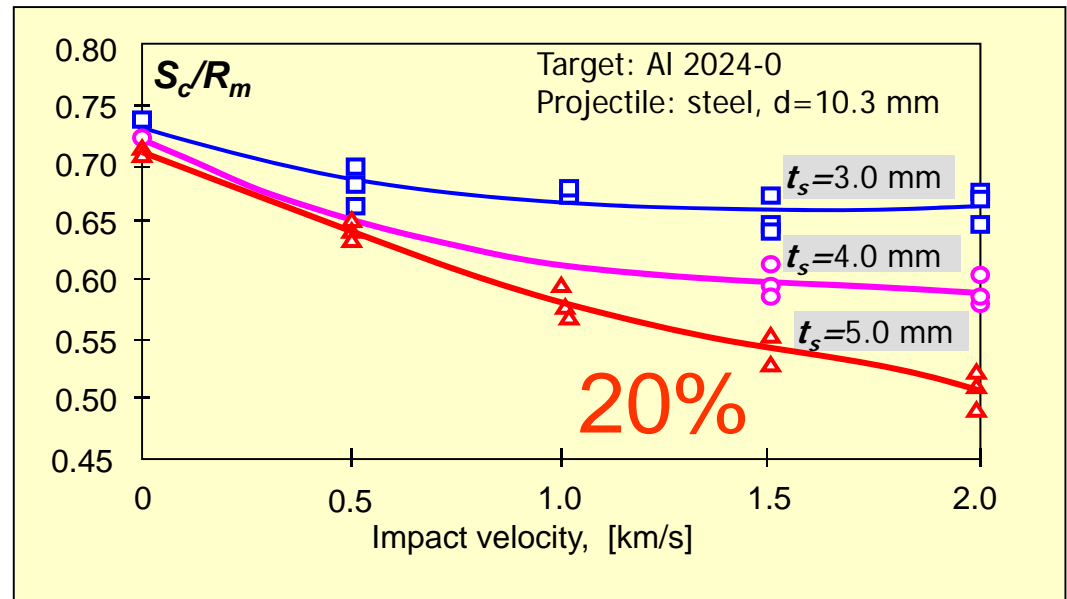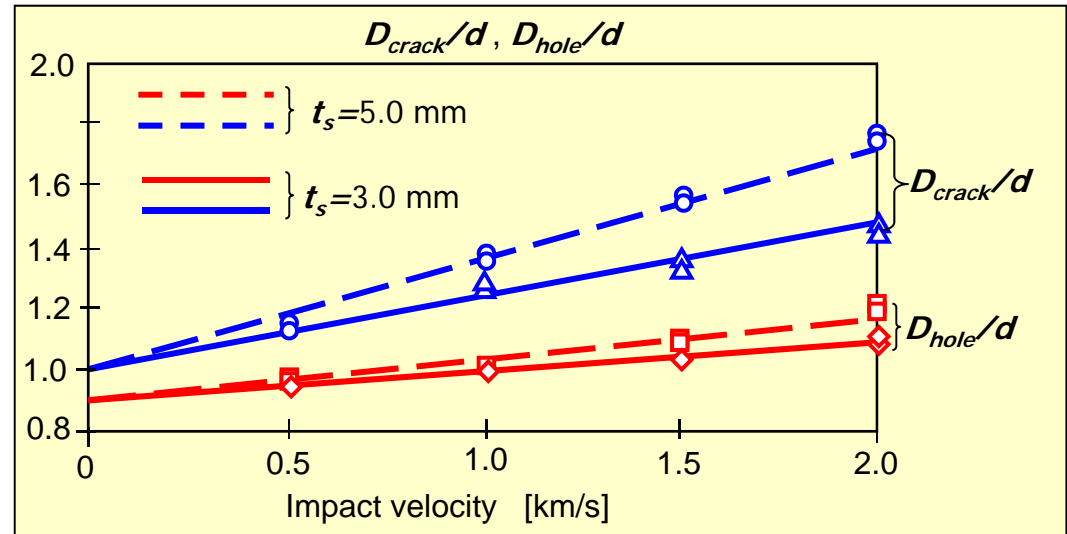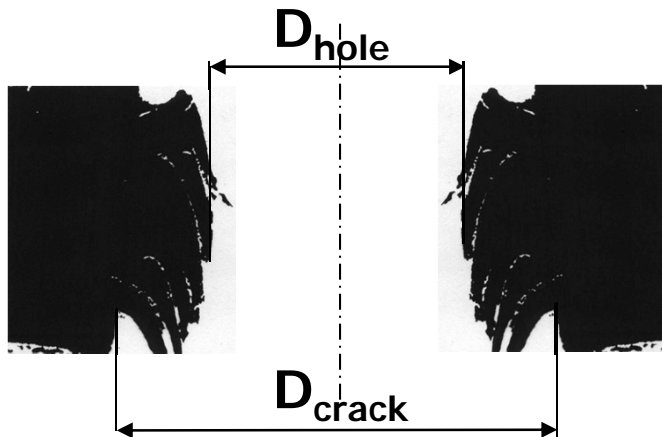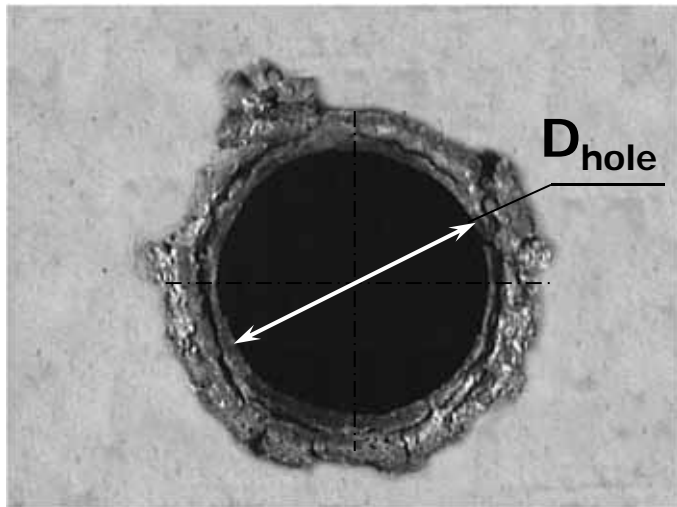
Parameters of damaged zone

Impact test setup

- Impact velocity: V=0.5…2.0 km/s
- Projectiles: Al, steel spheres; d=4.5…17.5 mm
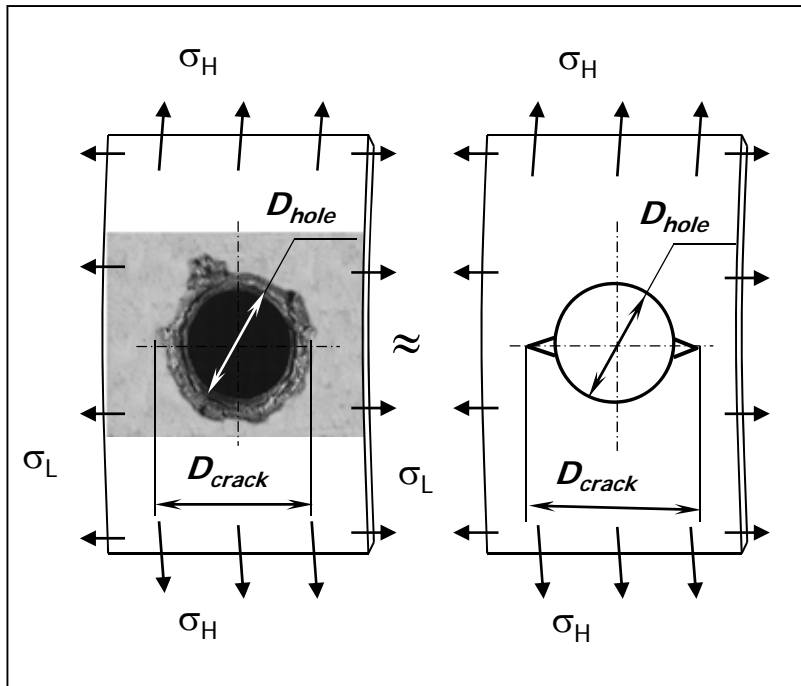- Target: Al 2024-0, AlMg6, steel; t_s=0.5…5.0 mm
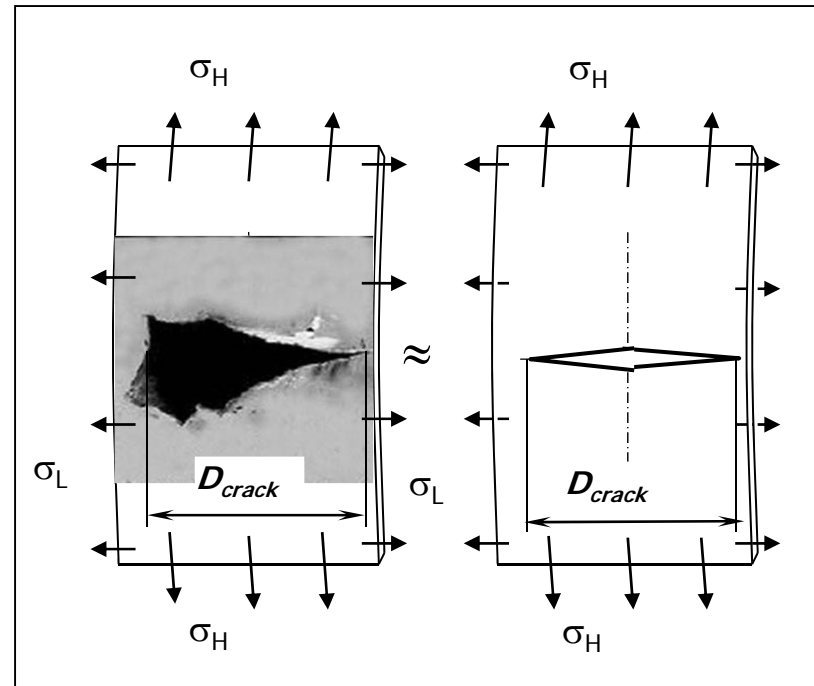
Residual Strength of Impacted Samples

Parameters of damaged zone

D_{hole}

D_{hole}

D_{crack}

D_{crack}/d, D_{hole}/d

t_s=5.0 mm

t_s=3.0 mm

D_{crack}/d

D_{hole}/d

Impact velocity [km/s]

S_c/R_m

Target: Al 2024-0
Projectile: steel, d=10.3 mm

t_s=3.0 mm

t_s=4.0 mm

t_s=5.0 mm

20%

Impact velocity, [km/s]
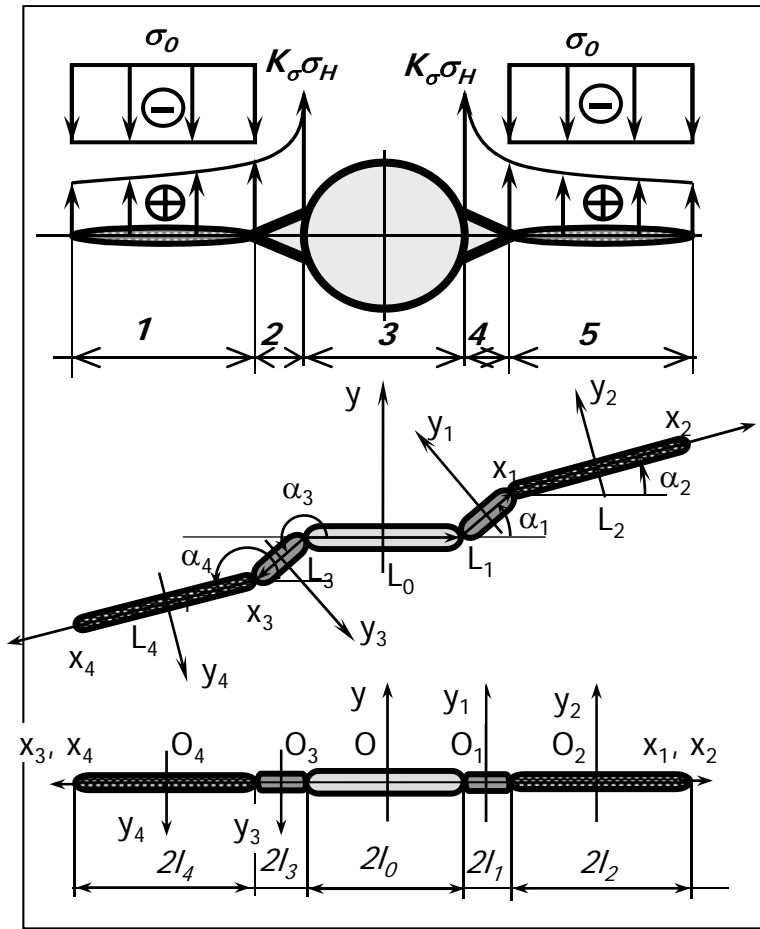
Models of Impact Hole

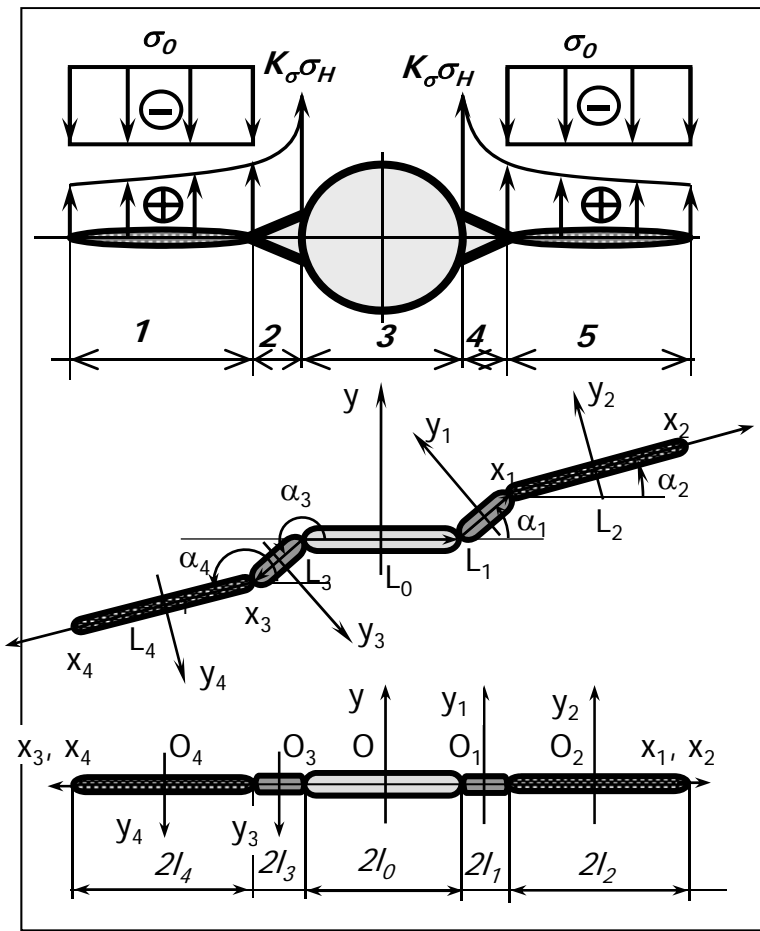Model of front impact hole   Model of rear impact (petal) hole
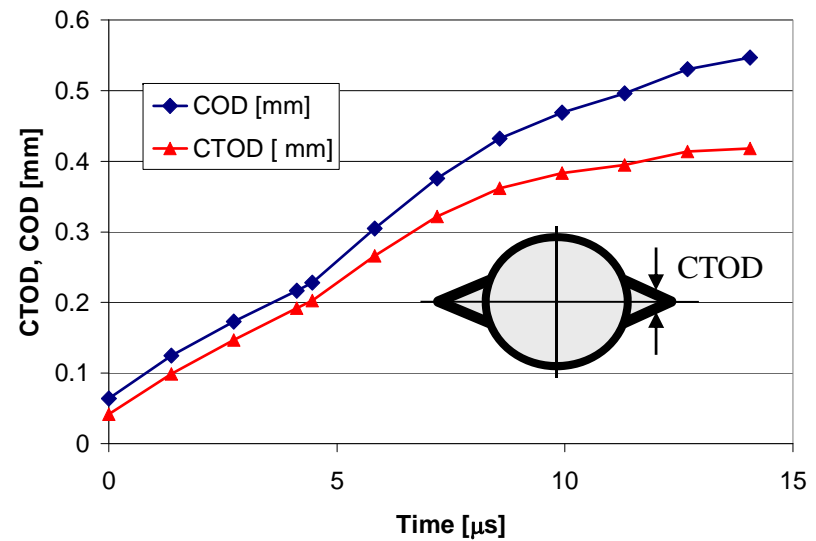
Model of Crack Initiation and Propagation

The crack will grow if the crack tip opening displacement (CTOD) exceeds its critical value (CTOD-criterion)
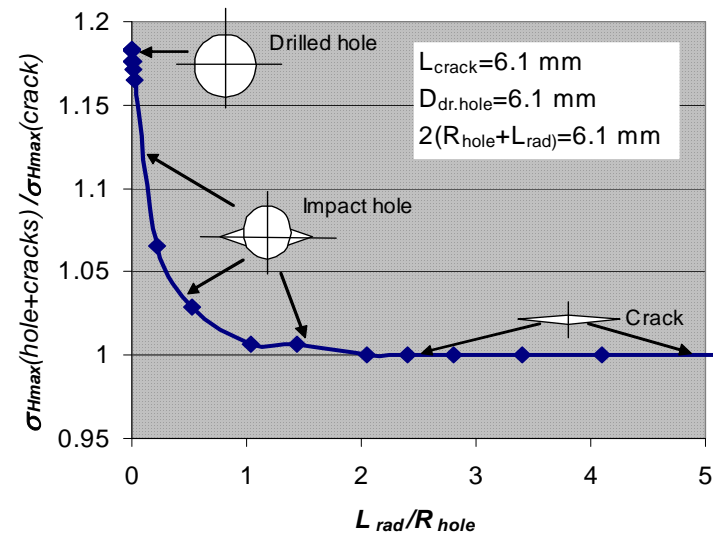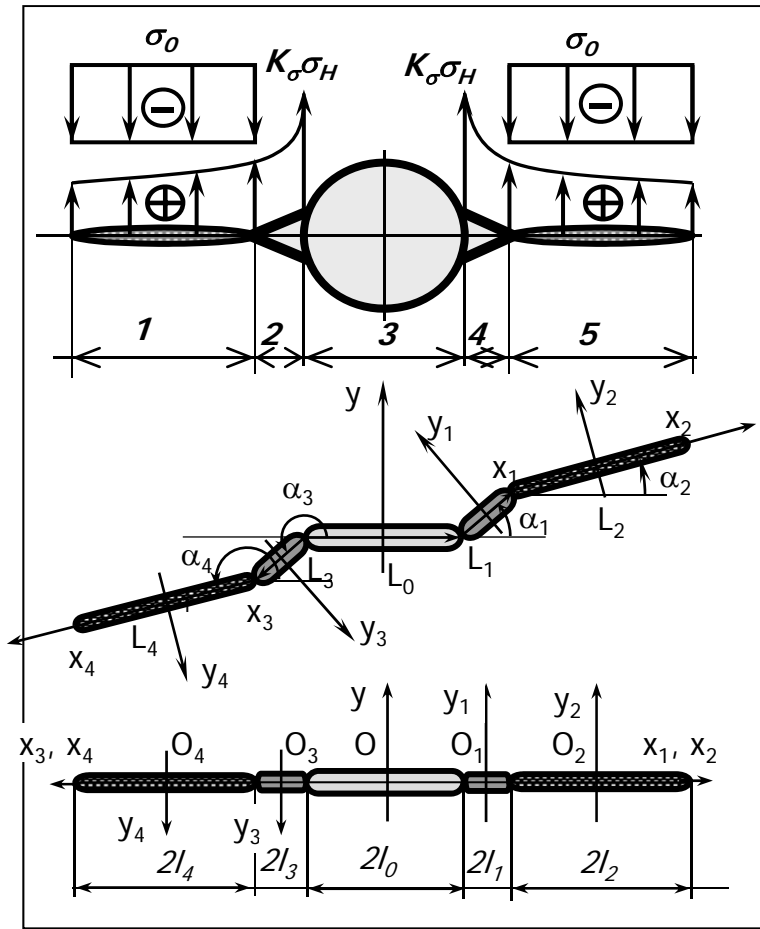
Model of Crack Initiation and Propagation

Evolution of CTOD (crack tip opening displacement)

Model of Crack Initiation and Propagation

Code for impact-damaged Pressure Vessels

- Survivability analysis (burst/no burst)
- Residual strength analysis (critical pressure)
- Simulation of crack propagation

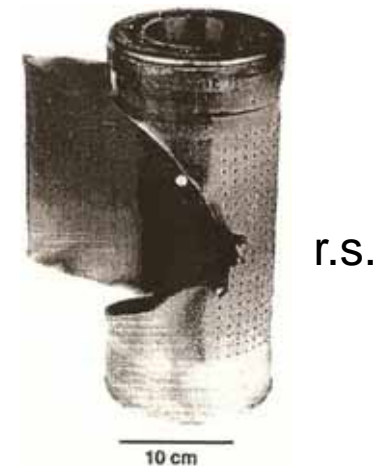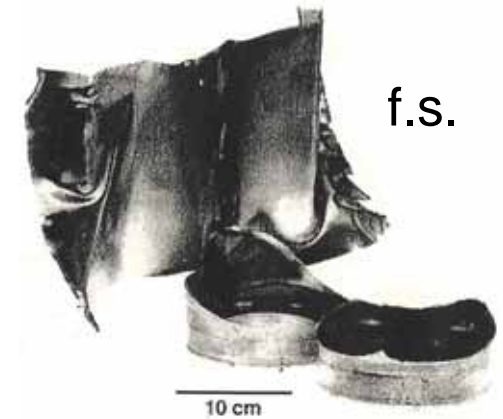EMI

Institut
Kurzzeitdynamik
Ernst-Mach-Institut

esa   Columbus Mission

European Space Agency
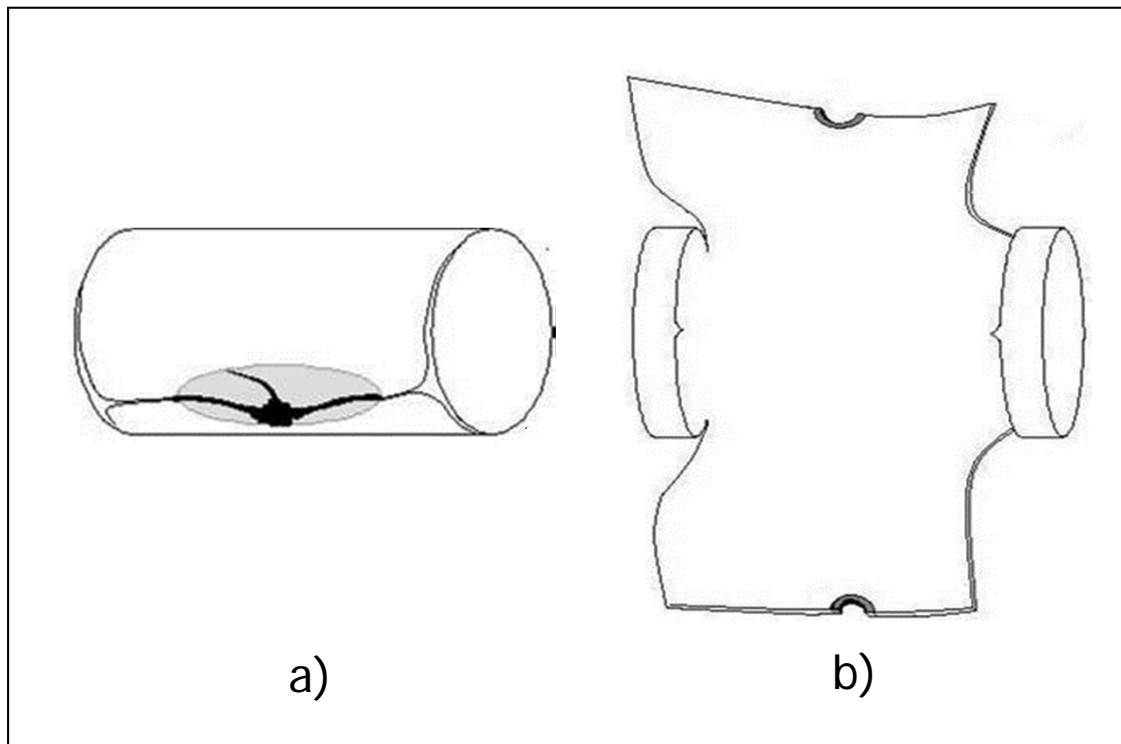
Failure analysis of pressure vessels onboard International Space Station-module Columbus

f.s.

10 cm

r.s.

10 cm

Pressure vessels failure
© ESA

Pressure Vessels Failures
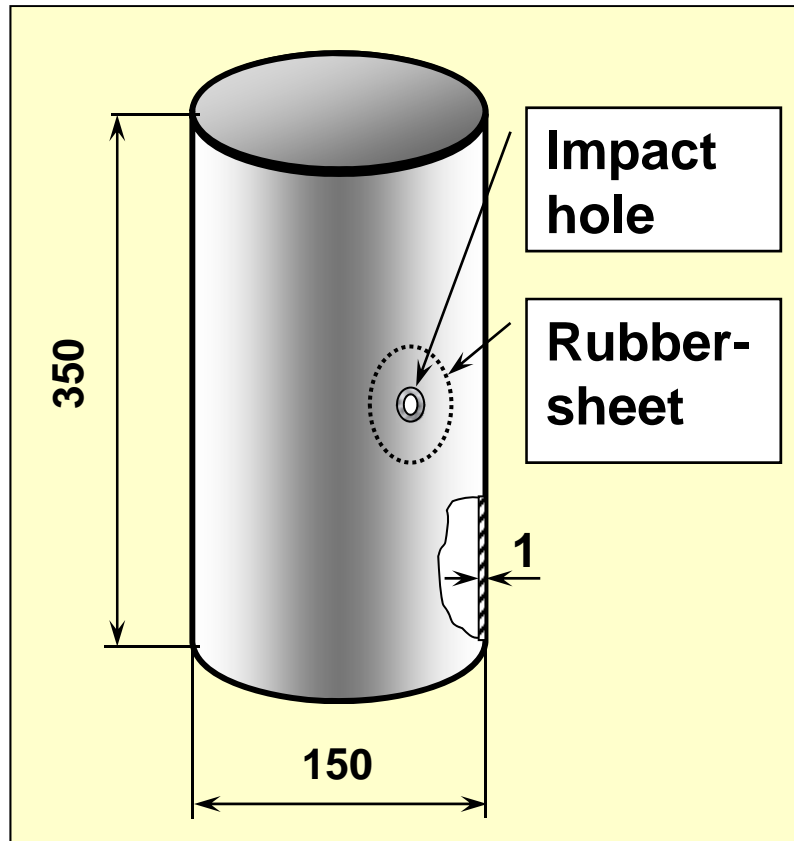

a)   Rear side rupture

b)   Front side fracture

a)   b)

Fracture of the damaged pressure vessels under quasi-static inflation

Test sample (AlMg3)

Impact hole

Rubber-sheet

350

1

150
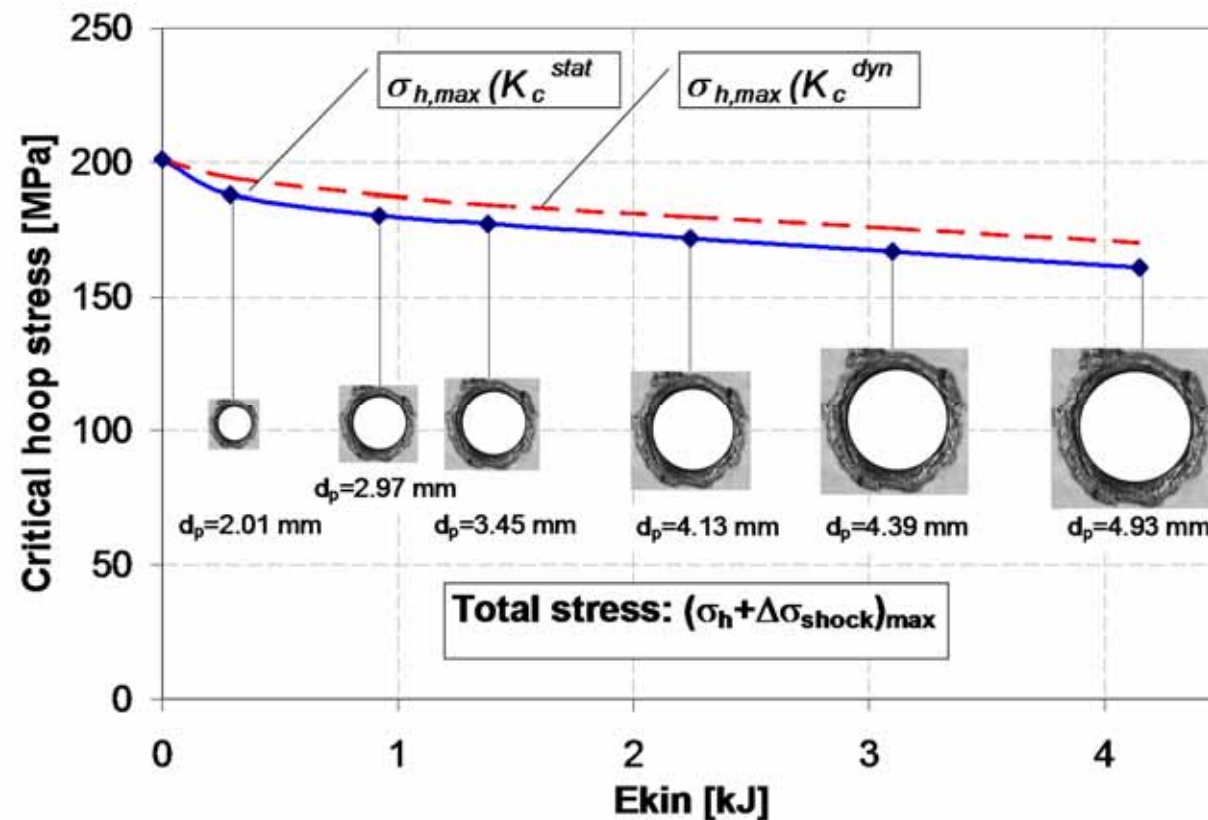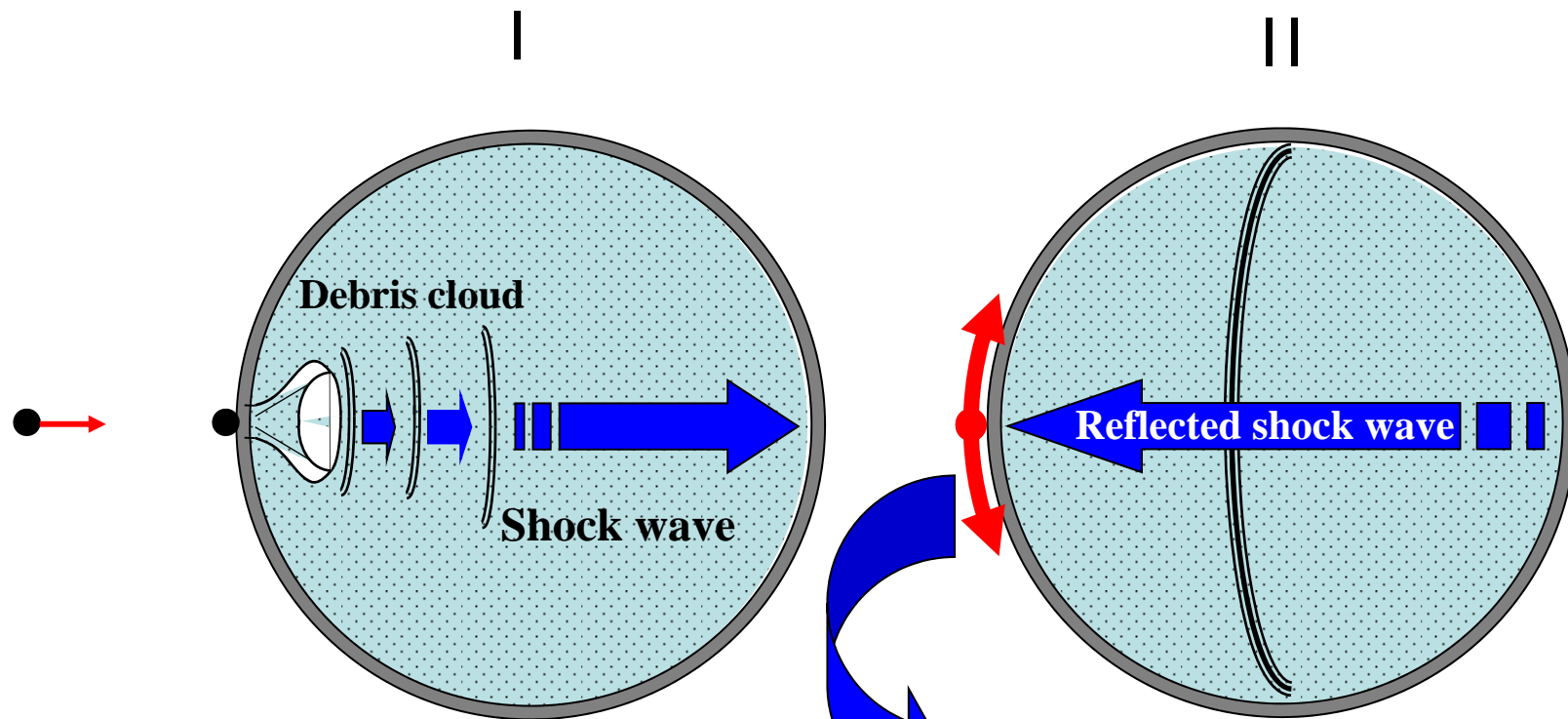
- **Test:** inflation until burst occurred
- **Goal:** burst pressure

Calculation/test variation < 5%

Computed values of critical hoop stress (fracture from the front side)

Basic stages of pressure vessel fracture

I

II

Debris cloud

Shock wave

Reflected shock wave

I. Ye. Telitchev, D. Eskin, "Engineering model for simulation of debris cloud propagation inside gas-filled pressure vessels", *International Journal of Impact Engineering*, Elsevier Science, Vol. **29**, pp. 703-712, 2003.

Total stress: $\sigma_h + \Delta\sigma_{shock}$

Critical stress: $\sigma_c(p_0, E_{kin})$

Debris Cloud

Impact of al. sphere on a titanium shield at 5.7 km/s (Fhg-EMI)
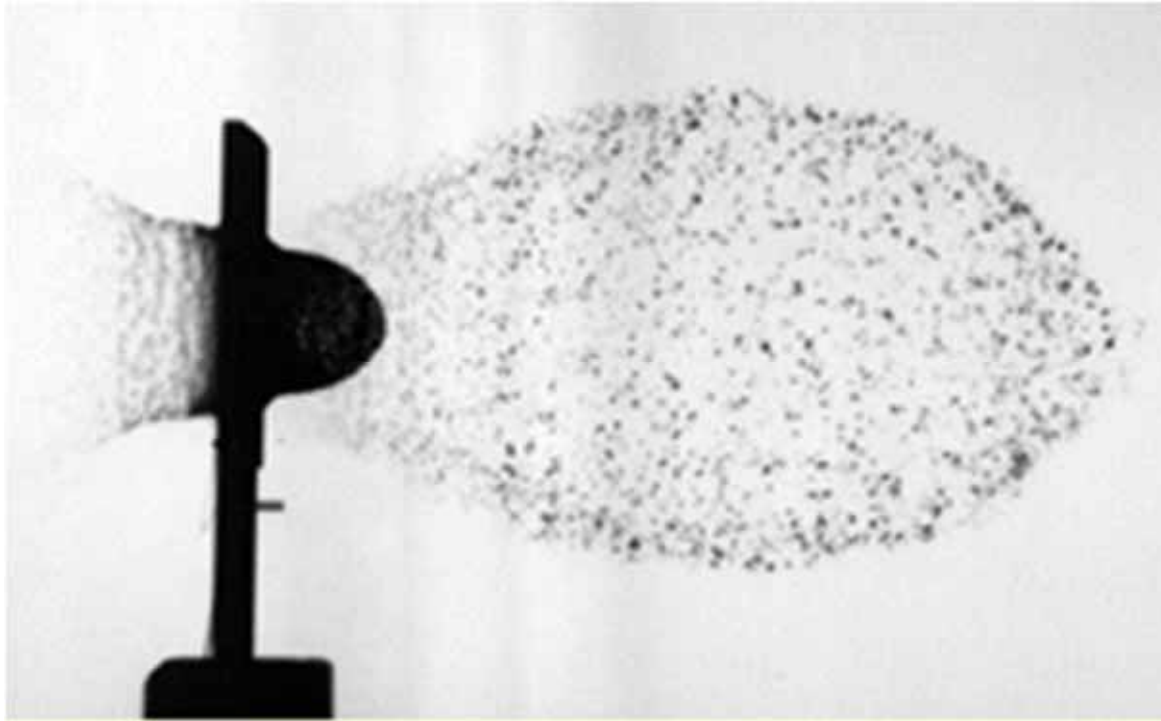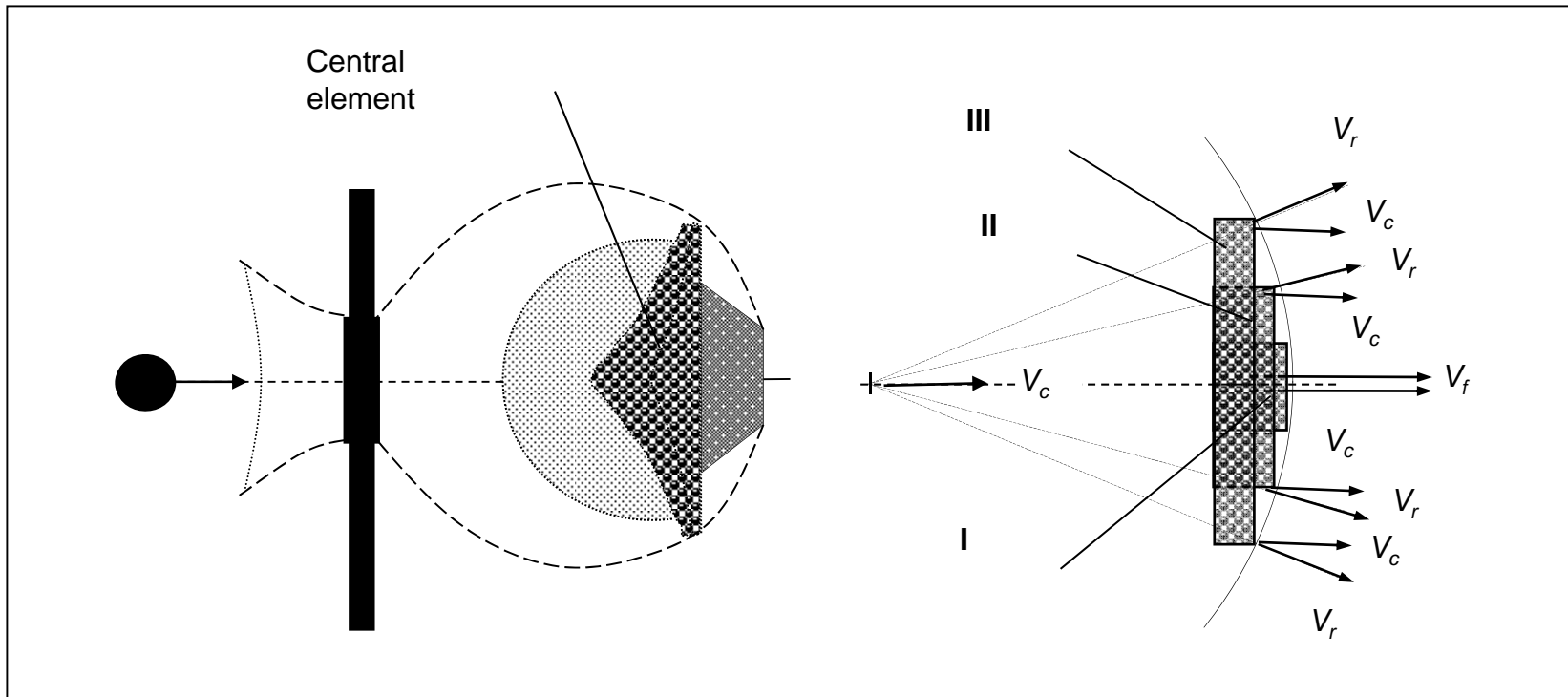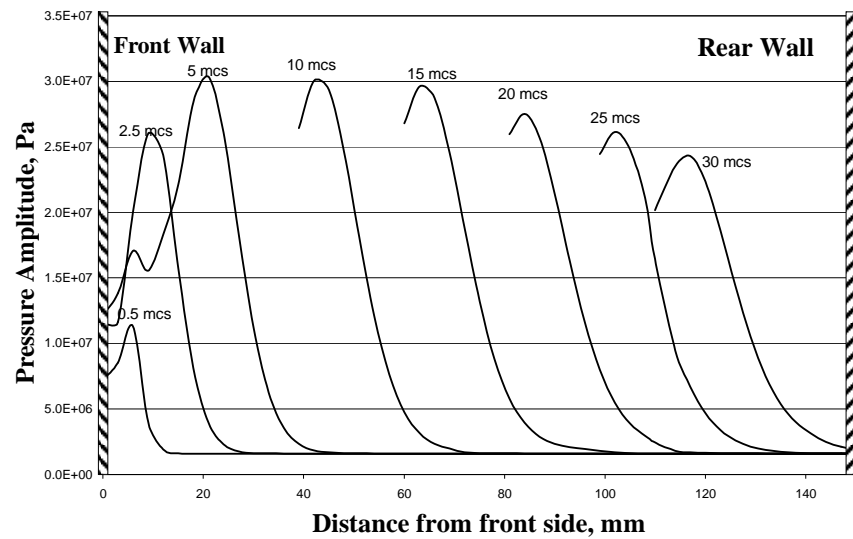
Model of Debris Cloud

I. Ye. Telitchev, D. Eskin, "Engineering model for simulation of debris cloud propagation inside gas-filled pressure vessels", _International Journal of Impact Engineering,_ Elsevier Science, Vol. **29**, pp. 703-712, 2003.
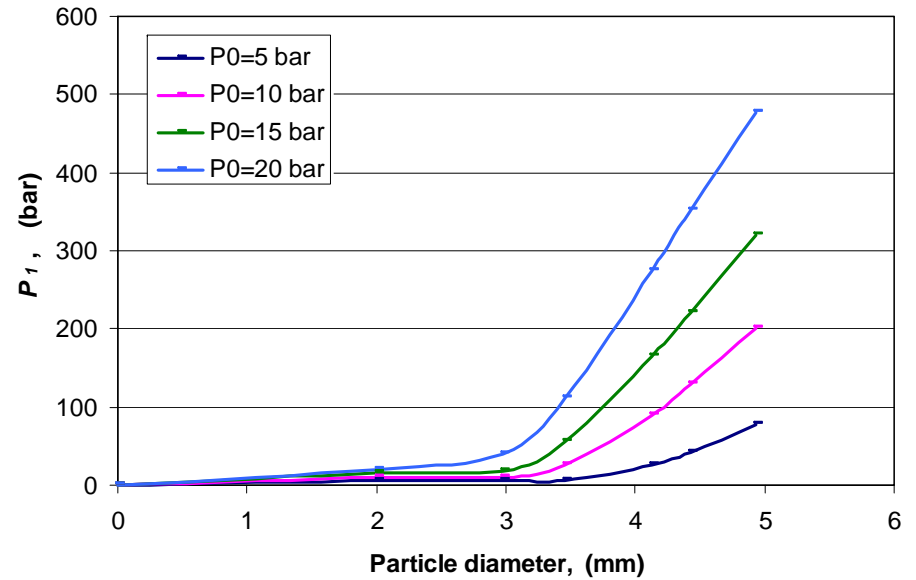
Debris Cloud/Gas Interaction

- Two-phase flow model

- Dual role of the density of gas inside the vessel:

   a) protection of pressure vessel back wall due to fragments deceleration;

   b) generation of the strong shock wave which can cause failure of structure.
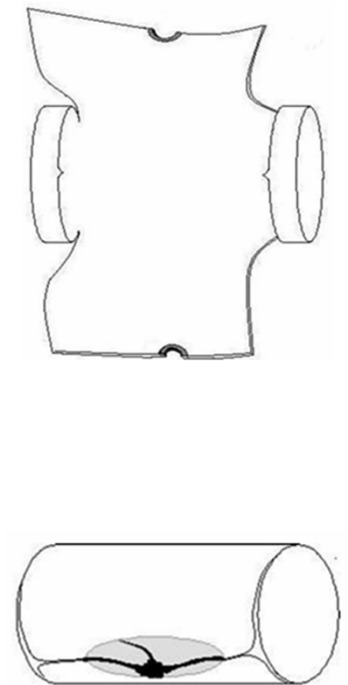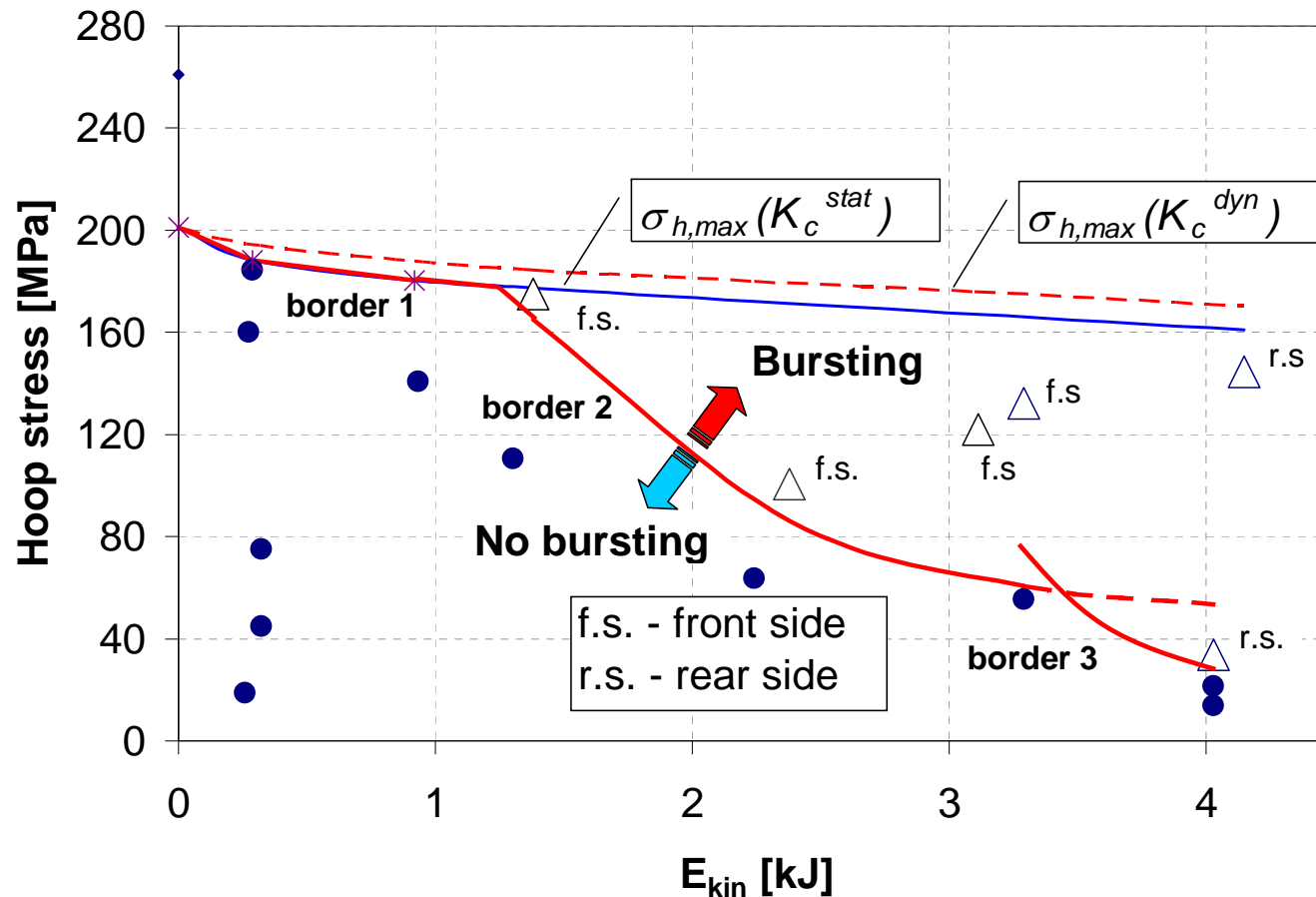
Model of Debris Cloud –Gas Interaction

a)

b)

Borders between smple perforation and catastrophic facture

$\sigma_{h,max}(K_c^{stat})$

$\sigma_{h,max}(K_c^{dyn})$

border 1

f.s.

Bursting

border 2

f.s

f.s

f.s.

f.s

r.s

No bursting

f.s. - front side
r.s. - rear side

border 3

r.s.

Hoop stress [MPa]

E_{kin} [kJ]

I. Ye. Telitchev, F. Schaefer, E. Schneider, and M. Lambert, "Analysis of the fracture of gas-filled pressure vessels under hypervelocity impact", *International Journal of Impact Engineering*, Elsevier Science, Vol. **23**, pp. 905-919, 1999.

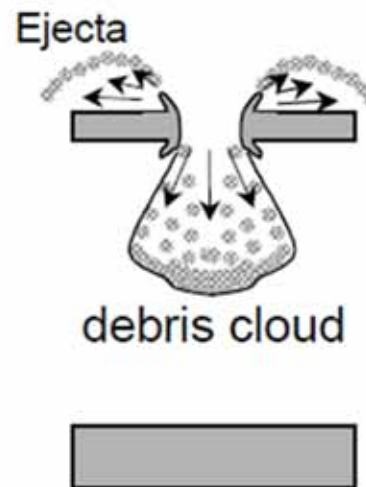# Effect of Shield on Damage Pattern
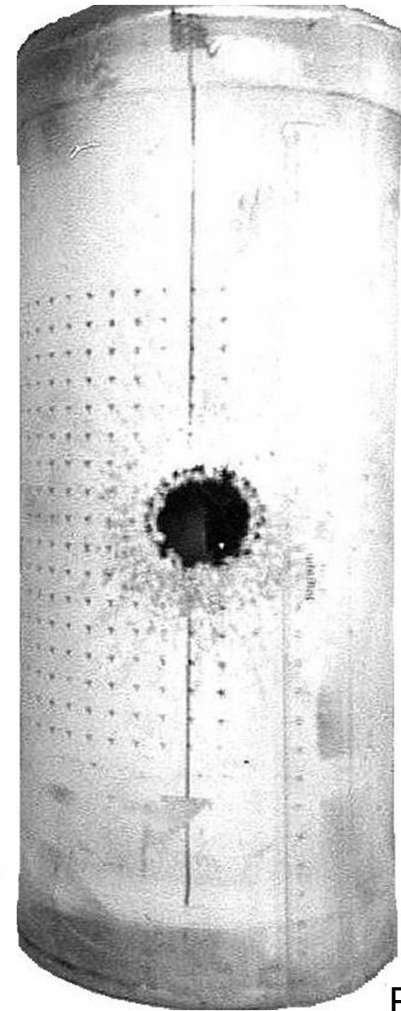
Pressure vessels failure
© ESA

Whipple Shield Concept

Ejecta

bumper

standoff

rear wall

debris cloud

Craters & holes

Detached Spall
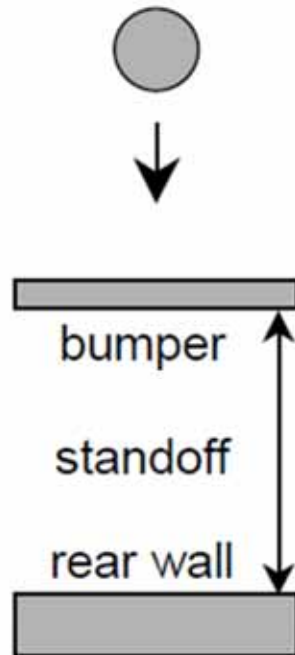
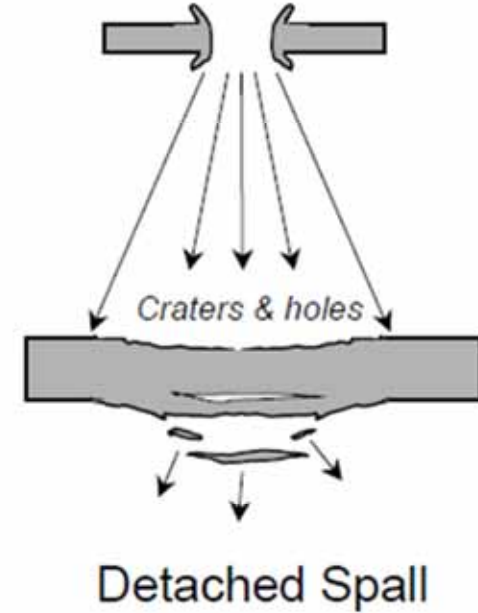a) Whipple shields consist of a bumper, standoff (gap or spacing), and rear wall.

b) Hypervelocity impacts will generate a cloud of bumper and projectile debris that can contain solid fragments, liquid, and vapor particles.

c) The rear wall must survive the fragments and debris cloud impulsive loading. It could fail by perforation from solid fragments, spall, or tear and petal from the impulsive loading.

Debris Cloud
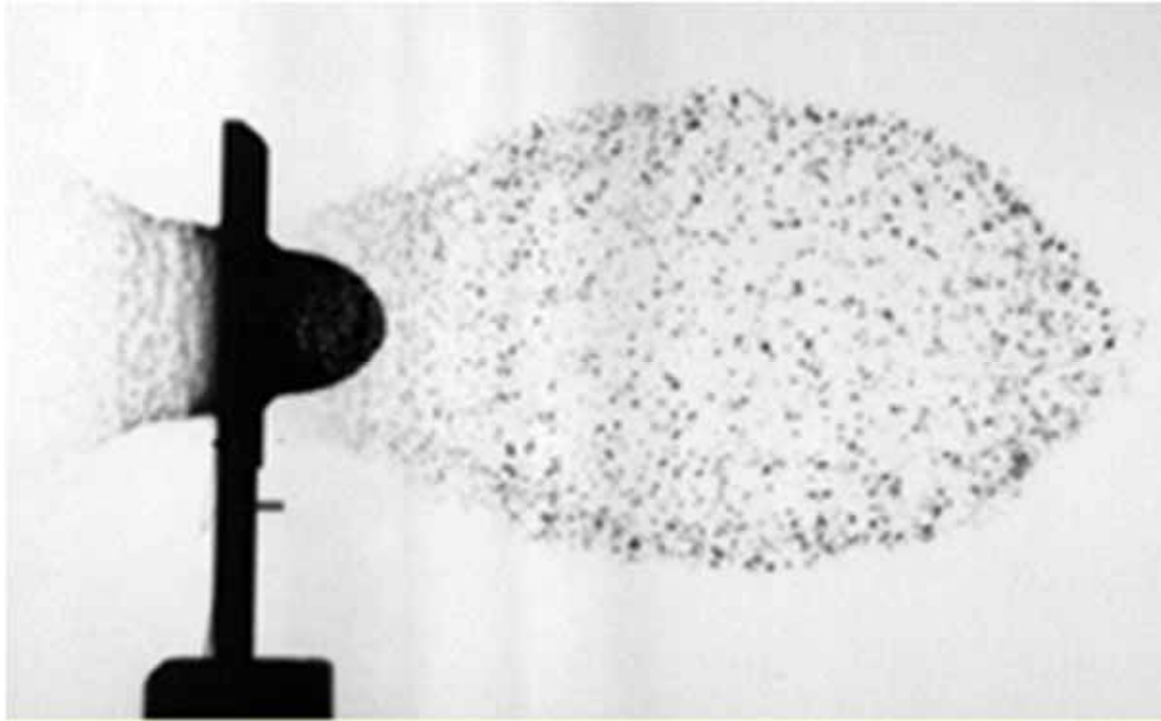
Impact of al. sphere on a titanium shield at 5.7 km/s (Fhg-EMI)

Ballistic Limit Curves
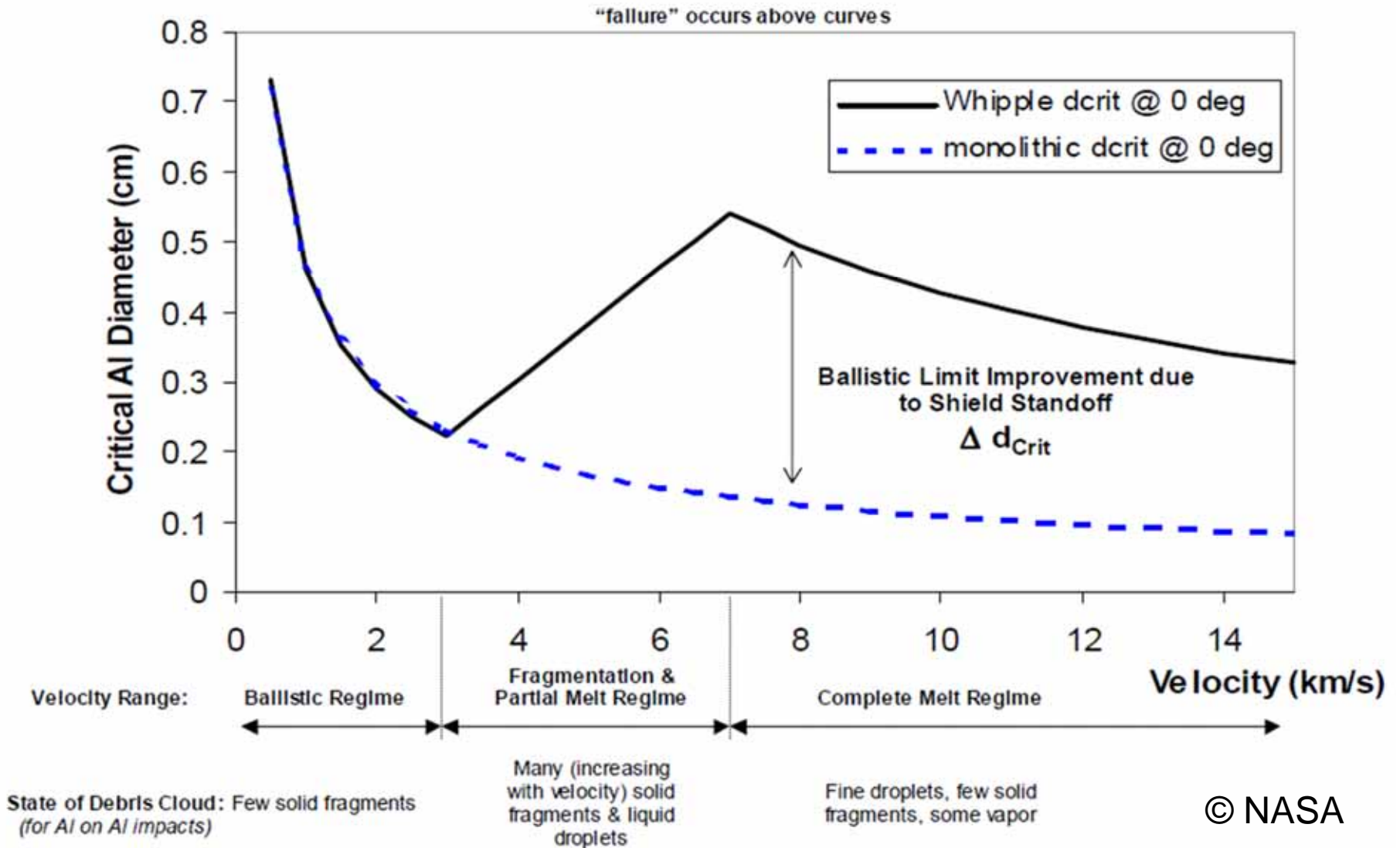
Effect of Shield on Damage Pattern

Effect of Shield on Damage Pattern

Impact angle

traces of projectile fragments

traces of shield fragments

a) Oblique impact

b) Normal impact

Classification of post-impact scenarios

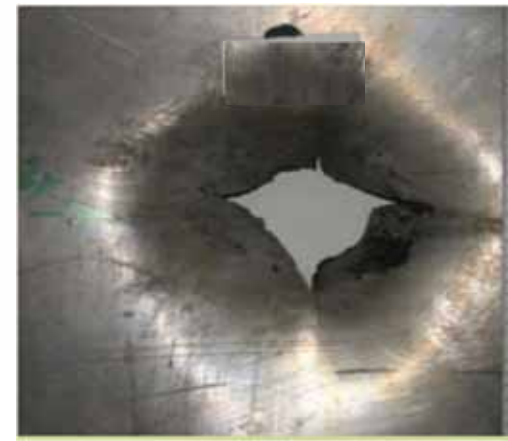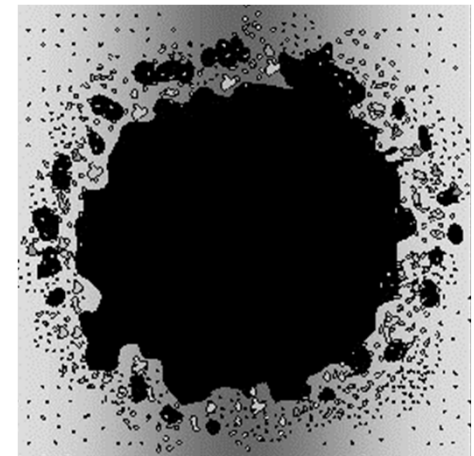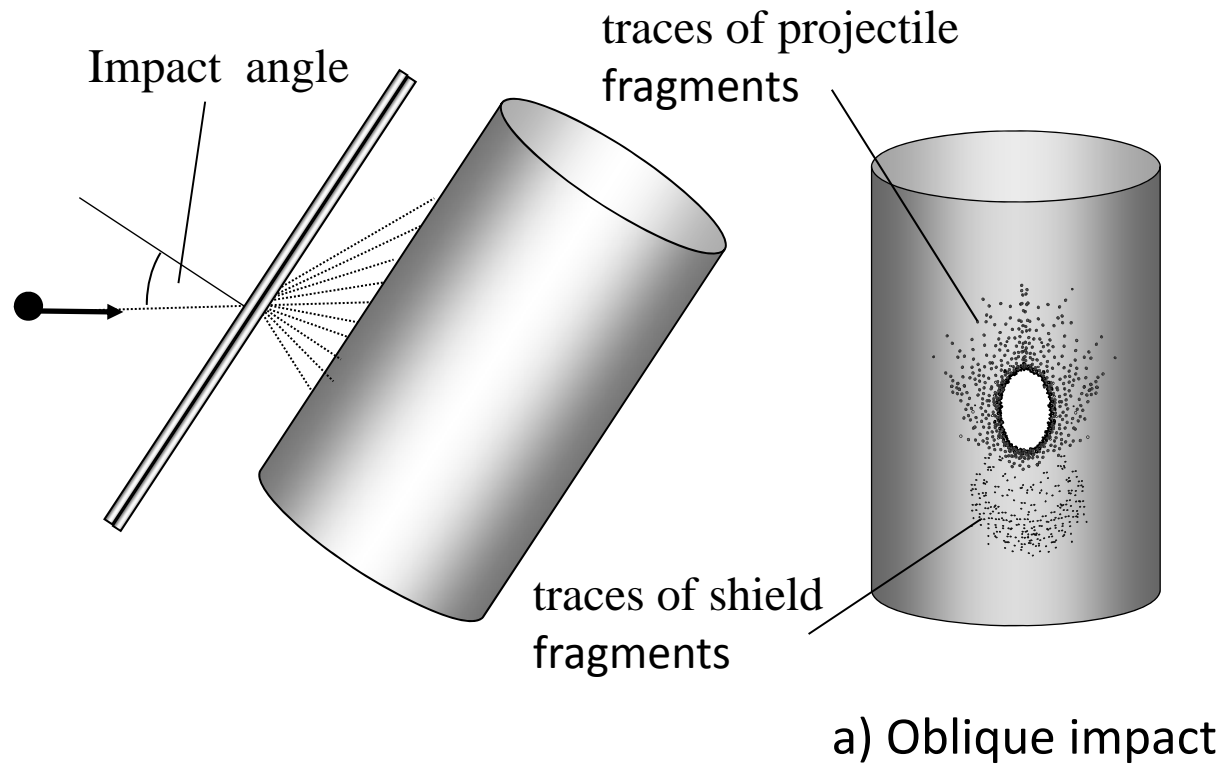Case 1: Shallow craters on the surface of structure. No perforation of primary wall. No unstable crack propagation. The spacecraft is capable to continue its mission.

Case 2: Surface of primary wall is densely cratered and has few small perforations. No unstable crack propagation. Possible pressure decay. Under normal conditions the spacecraft is capable to continue its mission.

Case 3: Perforation, bulging and petalling at the pressurized wall. Possible unstable crack propagation. **Possible termination of the mission.**

Case 4: Large impact hole with rough rim surrounded by a densely cratered ring with small perforations in the pressurized wall. Possible unstable crack propagation. **Possible termination of the mission .**

Model of shielded+damaged structure
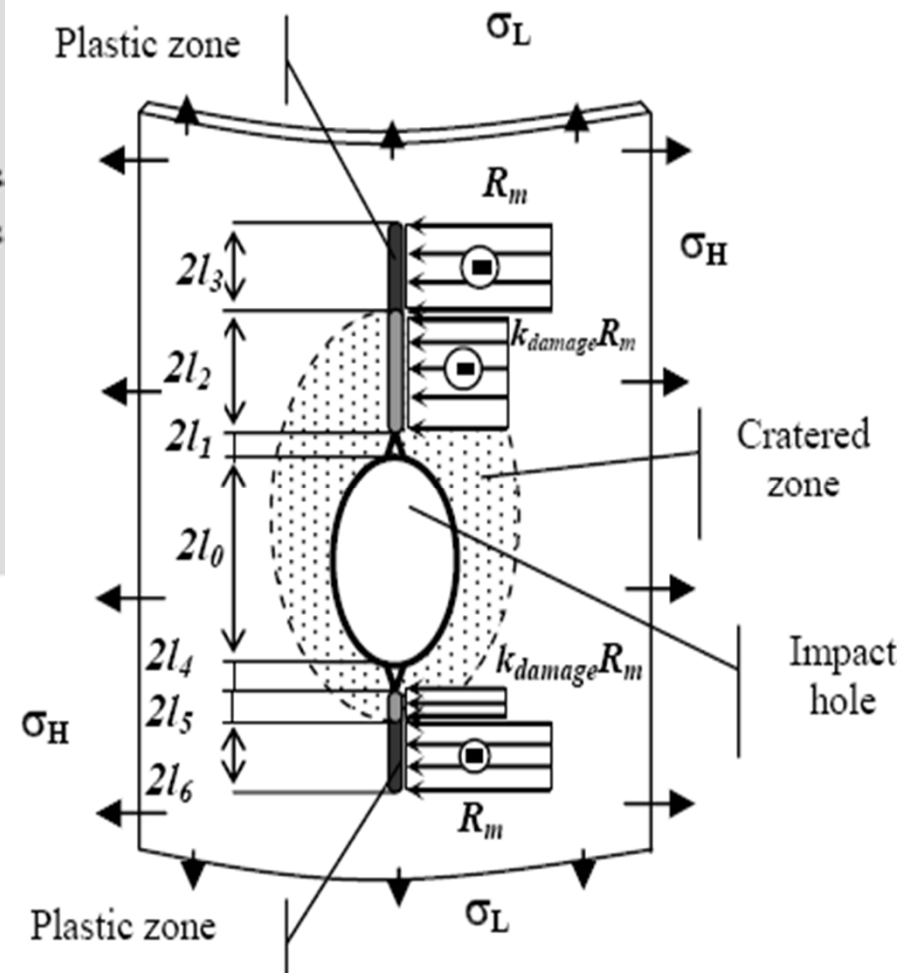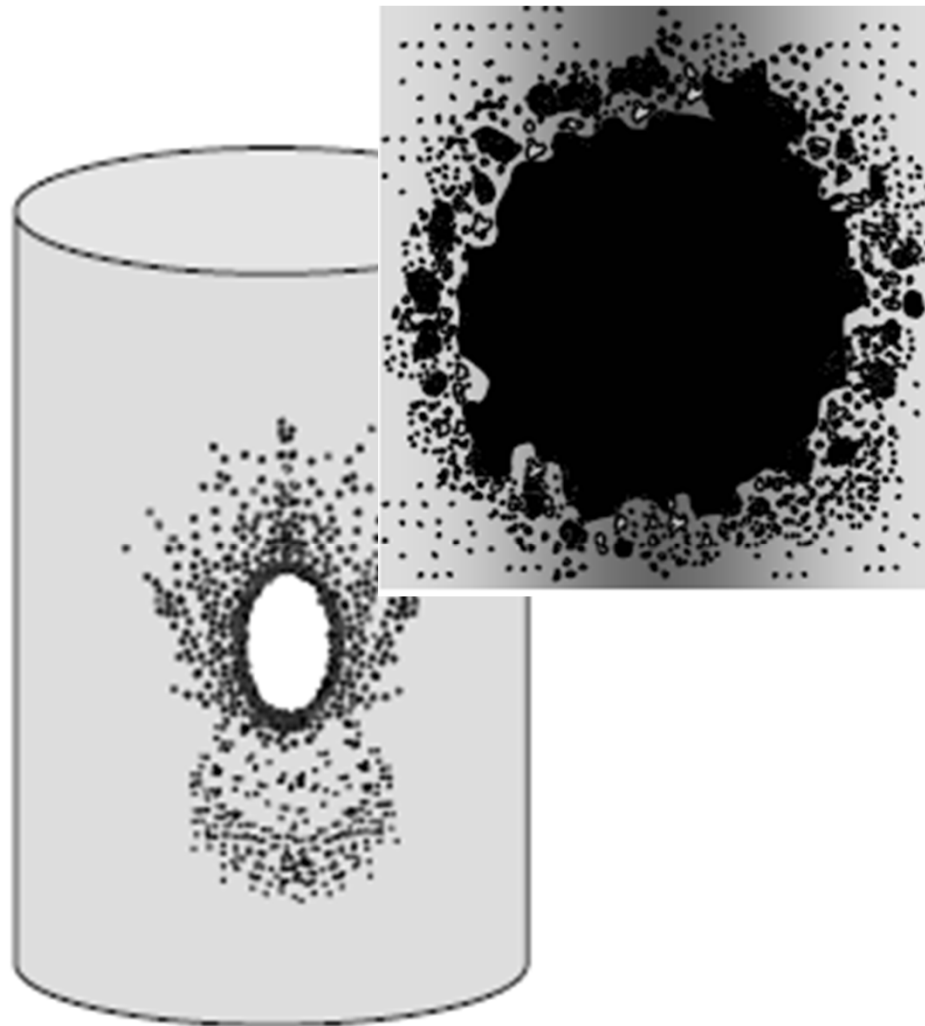
Model of shielded+damaged structure
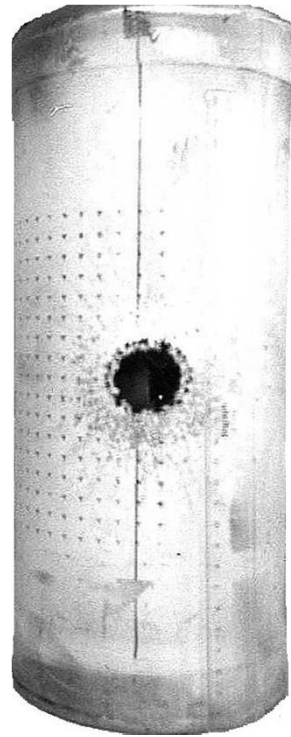
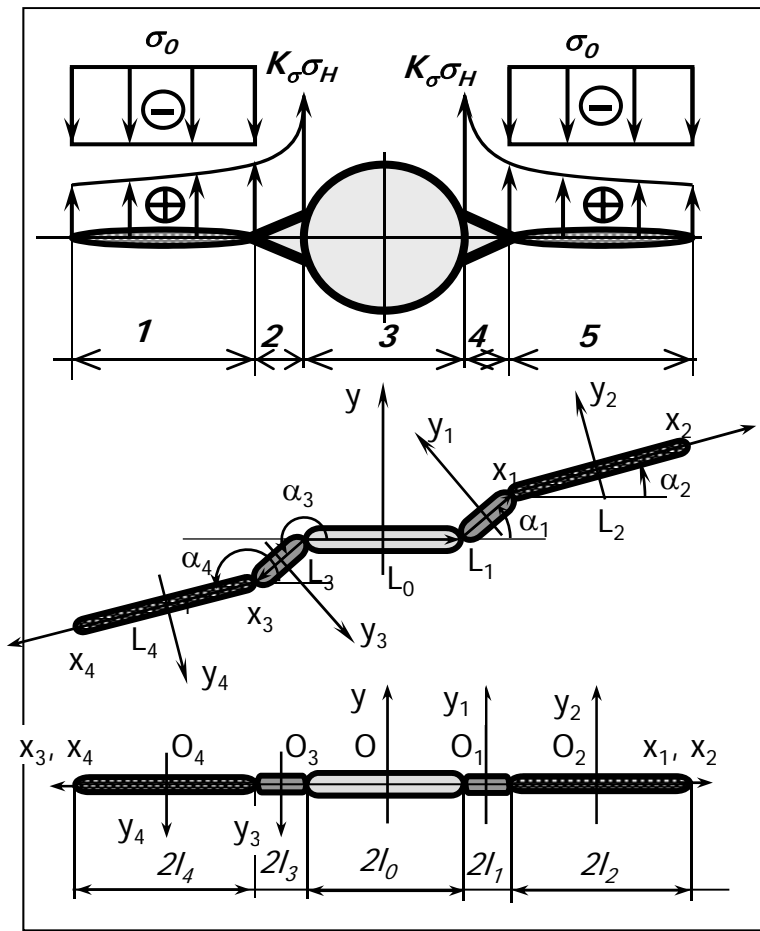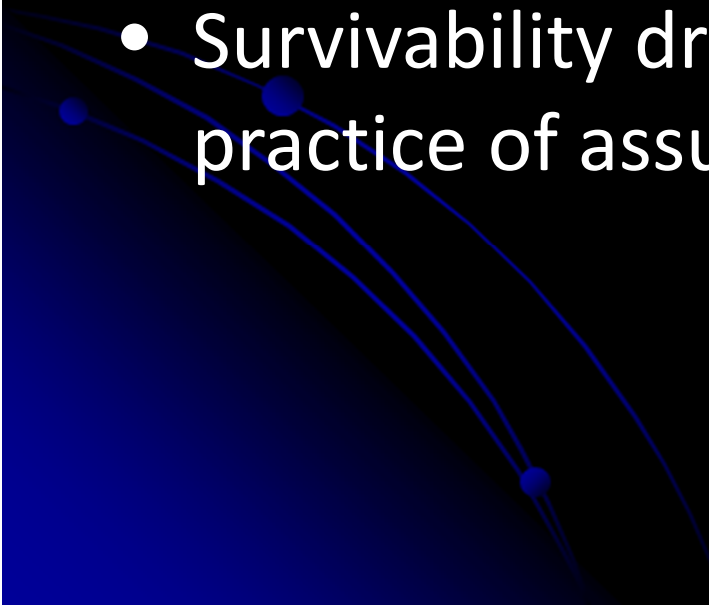|	Exp. #20	Exp. #21
Hoop stress, MPa	80.3	83.3
Secondary impact hole, mm	36	33
Impact test result	No crack propagation	No crack propagation
Numerical test result	No crack propagation	No crack propagation

Model of Crack Initiation and Propagation

- deviation of crack from the original path due to the structural irregularities
- Effect of stiffeners on crack propagation/arrest

Survivability Driven Design Approach

- Traditional safety requirements only look at the "probability of no penetration"

- Survivability driven design is based on the practice of assuming the hazard has occurred

Space Debris Study at the University of Manitoba

- The <u>long-term objective</u> is to develop a strong scientific basis for design of spacecraft working in orbital debris environment

- The <u>short-term objective</u> is to advance the understanding and modeling techniques of spacecraft pressurized structures response to hypervelocity impact

Acknowledgement

- Dr. M. Lambert, ESA/ESTEC
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- Dr. Robert Sierakowski, AFRL/MN
- Dr. John Rogacki, Univ. of Florida-REEF