Orbital Debris: Effect on Spacecraft Pressurized Structures

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Presentation outline

Introduction

Part I: HVI on unshielded PV

Part II: HVI on shielded PV

Current/Future research plans
- 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**: \( V = 0.5 \ldots 2.0 \text{ km/s} \)
- **Projectiles**: Al, steel spheres; \( d = 4.5 \ldots 17.5 \text{ mm} \)
- **Target**: Al 2024-0, AlMg6, steel; \( t_s = 0.5 \ldots 5.0 \text{ mm} \)
Residual Strength of Impacted Samples

Parameters of damaged zone

Impact velocity, [km/s]

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

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

Impact velocity [km/s]

$S_c/R_m$

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

20%
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
Failure analysis of pressure vessels onboard International Space Station-module Columbus

Pressure vessels failure © ESA
Pressure Vessels Failures

a) Rear side rupture

b) Front side fracture
Fracture of the damaged pressure vessels under quasi-static inflation

Test sample (AlMg3)

- **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


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

**Critical stress:** $\sigma_c(p_0, E_{\text{kin}})$
Debris Cloud

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

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
Borders between simple perforation and catastrophic fracture

Effect of Shield on Damage Pattern
Whipple Shield Concept

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

- Critical Al Diameter (cm)
- Velocity Range (km/s)

- Ballistic Regime
- Fragmentation & Partial Melt Regime
- Complete Melt Regime

State of Debris Cloud:
- Few solid fragments (for Al on Al impacts)
- Many (increasing with velocity) solid fragments & liquid droplets
- Fine droplets, few solid fragments, some vapor

Ballistic Limit Improvement due to Shield Standoff $\Delta d_{\text{Crit}}$
Effect of Shield on Damage Pattern
Effect of Shield on Damage Pattern

a) Oblique impact  
b) Normal impact

traces of shield fragments
traces of projectile fragments

Impact angle
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

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<th>Exp. #20</th>
<th>Exp. #21</th>
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<td>Hoop stress, MPa</td>
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<td>83.3</td>
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<td>Secondary impact hole, mm</td>
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<td>33</td>
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<td>Impact test result</td>
<td>No crack propagation</td>
<td>No crack propagation</td>
</tr>
<tr>
<td>Numerical test result</td>
<td>No crack propagation</td>
<td>No crack propagation</td>
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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 long-term objective is to develop a strong scientific basis for design of spacecraft working in orbital debris environment.

• The short-term objective is to advance the understanding and modeling techniques of spacecraft pressurized structures response to hypervelocity impact.
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