Modeling of crack propagation in spacecraft reinforced pressure wall damaged by orbital debris

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Outline

• Introduction
• Critical Components
• Objective
• Impact Damage Pattern
• Modeling of Fracture
• Stiffening Elements
• Model Validation
• Discussion/Conclusions
Introduction

What is Orbital Debris?

Man-made objects which orbit about the Earth, no longer serving a useful purpose

Sources Include:

- Solid Propellant Slag
- Defunct Satellites
- Collision Fragments
Introduction

Low-Earth Orbit

Geostationary Orbit

Average Velocity = 11 km/s

Source: NASA Orbital Debris Program Office
Introduction

Low-Earth Orbit

Growth of Catalogued LEO Debris

Average Velocity = 11 km/s
Introduction

Low-Earth Orbit

Growth of Catalogued LEO Debris

Only one or two collisions can drastically change the orbital debris population leading to the uncertainties in the protection requirements.

Source: NASA Orbital Debris Program Office
Critical Components of Spacecraft

Interagency Space Debris Coordination Committee (IADC) identified pressurized structure as the most critical components on-board spacecraft (IADC Protection Manual, Ver. 5.0, 2012)
Critical Components of Spacecraft

- Spacecraft pressurized modules (low pressure)
- Onboard system pressure vessels (high pressure)

Source: NASA
Critical Components of Spacecraft

- Spacecraft pressurized modules (low pressure)
- Onboard system pressure vessels (high pressure)

Source: European Space Agency
Concept of Shielding

• The hypervelocity impact with the bumper will generate a debris cloud.

• This cloud expands resulting in the impactor momentum being distributed over a wide area of the rear wall.

Source: NASA
Effect of Shield

Momentum is distributed over a wide area => no perforation

Source: NASA
Effect of Shield

Momentum is distributed over a wide area => bigger impact damage

Source: NASA

Source: IJIE, 33(1-12), p.219
Effect of Shield

Momentum is distributed over a wide area => bigger impact damage

Case of both shield and pressurized wall perforation presents a potential for the pressure wall failure in an abrupt fashion - “unzipping”

Source: IJIE, 33(1-12),p.219
Effect of Shield

Momentum is distributed over a wide area => bigger impact damage => possible “unzipping”

Source: IJIE, 33(1-12), p.219
Source: ESA
The answer to the question whether the spacecraft pressurized structure would undergo “unzipping” due to the impact of undetectable debris is crucial for the

a. mission success

b. compliance with the post-mission disposal requirements
• Each satellite break-up causes not only the loss of space assets but the considerable addition to the orbital debris population

Growth of Catalogued LEO Debris
• Worsening orbital debris situation creates a new reality for the orbital debris environment where all functioning spacecraft are under higher risk than they were designed.
• Addressing this problem will not only improve the survivability of spacecraft itself but also will provide the mitigation effect
Recommendation for future design

A. To provide a required probability of no penetration (PNP)
B. To provide 100% probability of no “unzipping” for the selected (shield+pressure vessel) configuration and specified debris particle diameter
In other words the suggested requirements for (shield+pressure wall) are

**Condition A**: No penetration of pressure wall for debris diameter $< d_1$

**Condition B**: No “unzipping” of pressure wall for debris diameter $< d_2$
In other words the suggested requirements for (shield+pressure wall) are

**Condition A** = Survivability condition for debris diameter < \( d_1 \)

\( d_1 \) to be discussed and selected by Vendor and Client

**Condition B** = Compliance with disposal requirements for debris diameter < \( d_2 \)

\( d_2 \) to be discussed and approved by IADC (e.g. 10 mm)
Survivability-driven Design Logic

1. Orbital Debris data (untrackable)

2. Pressurized module + shield system

Pressure wall damage?

Yes

No

The spacecraft survived and mission continues if the dimension of debris $d < d_1$
Survivability-driven Design Logic

1. Orbital Debris data (untrackable)

2. Pressurized module + shield system

3. Pressure wall damage?

No → Spacecraft survived, mission continues

The spacecraft survived and mission continues if the dimension of debris $d < d_1$
Now it is assumed that impact of undetectable debris between \( d_1 < d < d_2 \) in size has occurred and the pressure wall is damaged.
The answer to the question whether the spacecraft pressurized structure would undergo “unzipping” due to the impact of undetectable debris is crucial for the 1) mission success; 2) compliance with the post-mission disposal requirements.
Survivability-driven Design Logic

The mitigation and protection measures are assessed for effectiveness through the Fracture Analysis Module.
Survivability-driven Design Logic

3. Pressure wall damage?
   - Yes  → Fracture Analysis
   - No   → 4. Spacecraft survived, mission continues

5. Fracture Analysis
   - Yes  → Pressure wall rupture? ("unzipping")
   - No   → Yes

4. Spacecraft survived, mission continues
Survivability-driven Design Logic

Pressure wall rupture? (“unzipping”)

6

Yes

No

9

Destruction of critical internal components?

Yes

No

10

Actions to enhance the survivability?

Yes

No

11

Disfunctional trackable spacecraft, mitigation requirement is satisfied

12

Seal/repair of damaged pressure wall

13

Spacecraft survived, mission continues

End of analysis

7

Varying the design parameters of pressurized module

8

Varying the characteristics of shield

Yes

No
Survivability-driven Design Logic

If it is predicted to “unzip”, the survivability can be achieved by adding more effective shielding or/and by varying the design parameters.
Survivability-driven Design Logic

New protection measures will be evaluated by repeating the steps until the “no rupture” conditions will be verified.
Survivability-driven Design Logic

1. Pressure wall rupture? ("unzipping")
   - Yes
   - No

2. Destruction of critical internal components?
   - Yes
   - No
Survivability-driven Design Logic

6 Pressure wall rupture? (“unzipping”)
   /\  
  /   \    
No  Yes  No

9 Destruction of critical internal components?
   /\  
  /   \    
Yes  No

12 Seal/repair of damaged pressure wall
Survivability-driven Design Logic

6. Pressure wall rupture? (“unzipping”)
   - No
   - 9. Destruction of critical internal components?
     - Yes
     - 12. Seal/repair of damaged pressure wall
     - 13. Spacecraft survived, mission continues
     - No

Yes

Spacecraft survived, mission continues
Survivability-driven Design Logic

- Pressure wall rupture? (“unzipping”)
  - No
  - Destruction of critical internal components?
    - Yes
    - Seal/repair of damaged pressure wall
    - Spacecraft survived, mission continues
    - End of analysis
    - No

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End of analysis
Survivability-driven Design Logic

The analysis of the equipment inside a spacecraft is illustrated, however it is out of scope of the current paper.
Survivability-driven Design Logic

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Survivability-driven Design Logic

The analysis of the equipment inside a spacecraft is illustrated, however it is out of scope of the current paper.
Survivability-driven Design Logic

- The design logic provides the failure control of spacecraft pressurized structures subject to orbital debris impact.

- The “no rupture” condition will be satisfied which guarantees either the spacecraft survivability or at least compliance with disposal requirements.
Survivability-driven Design Logic

The “Fracture Analysis” Module is viewed as a key element in the survivability-driven spacecraft design procedure providing that under no circumstances will the “unzipping” occur for $d < d_2$.
Objective

To determine whether the damage induced by an orbital debris impact will cause a pressurized vessel to erupt catastrophically.
Modeling of Impact Damage

Petal hole

“Cookie-cutter hole”

Hole with adjacent spall cracks
Modeling of Impact Damage

- $D_{\text{hole}}$ is equal to impact hole diameter
- $D_{\text{crack}}$ is equal to size of damage zone
Modeling of Fracture

1. Start of analysis
2. Initial data:
   - structure
   - material
   - damage
3. Applying the boundary conditions
4. Chebyshev’s nodes generation

\[ \sigma_H \approx \sigma_{\text{hole}} \]
\[ \sigma_{\text{crack}} \]
\[ D_{\text{hole}} \]
\[ D_{\text{crack}} \]
Modeling of Fracture

1. Start of analysis
2. Initial data:
   - structure
   - material
   - damage
3. Applying the boundary conditions
4. Chebyshev’s nodes generation

AUTODYN Snapshot of the stress field evolution
Modeling of Fracture

1. Start of analysis
2. Initial data:
   - structure
   - material
   - damage
3. Applying the boundary conditions
4. Chebyshev’s nodes generation

Non-linear fracture mechanics approach was applied

5-link crack
Modeling of Fracture

1. Start of analysis
2. Initial data:
   - structure
   - material
   - damage
3. Applying the boundary conditions
4. Chebyshev’s nodes generation

Chebyshev’s nodes generation:

\[ \xi_k = \cos\left[\frac{\pi(2k - 1)}{2N}\right], \quad k = 1, N \]
\[ \eta_m = \cos\left[\frac{\pi m}{2N}\right], \quad m = 1, (N - 1) \]
Modeling of Fracture

Building the system of singular integral equations

Applying the method of mechanical quadratures

Solution of normalized and linearized system of equations

\[
\begin{align*}
\int_{-1}^{1} M_{00}(\xi, \eta) \varphi_0(\xi) + [M_{01}(\xi, \eta) + M_{03}(\xi, \eta)] \varphi_1(\xi) + \\
[M_{02}(\xi, \eta) + M_{04}(\xi, \eta)] \varphi_2(\xi) &= \pi \sigma_0(\eta); \\
\int_{-1}^{1} M_{10}(\xi, \eta) \varphi_0(\xi) + [M_{11}(\xi, \eta) + M_{13}(\xi, \eta)] \varphi_1(\xi) + \\
[M_{12}(\xi, \eta) + M_{14}(\xi, \eta)] \varphi_2(\xi) &= \pi \sigma_1(\eta); \\
\int_{-1}^{1} M_{20}(\xi, \eta) \varphi_0(\xi) + [M_{21}(\xi, \eta) + M_{23}(\xi, \eta)] \varphi_1(\xi) + \\
[M_{22}(\xi, \eta) + M_{24}(\xi, \eta)] \varphi_2(\xi) &= \pi \sigma_2(\eta); \\
\int_{-1}^{1} \varphi_0(\xi) d\xi &= 0,
\end{align*}
\]
Modeling of Fracture

The search is performed by golden section method to provide SIF=0 at the end of plastic zone.

Plastic zone length search

Calculation of stress intensity factor (SIF)

SIF = 0 at the end of plastic zone
Modeling of Fracture

Calculation of CTOD/CTOA

CTOD or CTOA > critical value

- No crack propagation
- Pressure wall rupture ("unzipping")

End of analysis
Modeling of Fracture

Calculation of CTOD/CTOA

CTOD or CTOA > critical value

NO crack propagation

Pressure wall rupture ("unzipping")

End of analysis

Source: ESA
Effect of Reinforcement

CAD Depiction of Module Modeled

The case of completely broken central stiffener is considered as most severe scenario.
Effect of Reinforcement

• Semi-analitical approach is employed matching very well with Method of Singular Integral Equations

• When a crack extends, the pressure wall and the stringer will exert the equivalent reaction forces on each other

• The continuous force distribution is replaced by a set of the discrete forces Q1, Q2, etc.

• Method is based on the concept of equal displacements in the cracked panel and in the stiffeners
Effect of Reinforcement

The diagram shows the effect of reinforcement on the distribution of forces and stresses. The graph on the left illustrates the variation of Q-force (N) with the y-coordinate (mm) for different numbers of Q-points: 4, 6, 8, and 21. Each point on the graph corresponds to a specific Q-force at a given y-coordinate.

The diagrams on the right depict the reinforcement patterns and their effects on stress distribution. The patterns are labeled as a), b), and c), indicating different configurations and their impacts on stress concentrations and load distribution.
Computational Results

Convergence of CTOD calculation

\[
\frac{(\text{CTOD}_i - \text{CTOD}_{i-1})}{\text{CTOD}_i} \times 100\% \quad \text{vs.} \quad \text{Number of Chebyshev's nodes}
\]
Computational Results

Evolution of the crack tip opening displacement

- Dhole=20mm, Lrad.cr.=6mm
- Dhole=20mm, Lrad.cr.=2mm
- Dhole=20mm, Lrad.cr.=4mm

CTOD/CTODc vs. Time, µs

Crack starts here
No crack propagation
Computational Results

Critical stress for various \( (L_{rad.cr.}/D_{hole}) \)-ratio

- \( R_{\text{hole}} = 10 \text{ mm} \)
- \( R_{\text{hole}} = 15 \text{ mm} \)
- \( R_{\text{hole}} = 20 \text{ mm} \)

Half damage length, mm
Computational Results

Critical stress (specimen: 2024, ts=3.0 mm)

<table>
<thead>
<tr>
<th>Impact velocity, m/s</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test data ($\sigma_c$), Mpa [1]</td>
<td>303.0</td>
<td>301.1</td>
<td>290.3</td>
<td>294.9</td>
</tr>
<tr>
<td>Numerical data ($\sigma_c$), MPa</td>
<td>317.1</td>
<td>305.4</td>
<td>295.9</td>
<td>286.4</td>
</tr>
<tr>
<td>Deviation, %</td>
<td>4.4</td>
<td>1.4</td>
<td>1.9</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Computational Results

Critical crack length (specimen: 2219-T87, \( ts = 3.17 \) mm)

<table>
<thead>
<tr>
<th>Method</th>
<th>Crack initiation</th>
<th>Crack unstable growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present approach</td>
<td>590</td>
<td>1082</td>
</tr>
<tr>
<td>Deviation, %</td>
<td>N/A</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Computational Results

- Computer code for the reinforced structures is under development, and currently is being integrated into the existing code for the bare pressure wall.

- The numerical experiments on the reinforced habitable modules of the ISS showed that “unzipping” of the pressure wall is unlikely.
Conclusions

Comparisons of the calculated results with the test data and numerical results obtained by finite element method showed good agreement.

The suggested approach is concluded to be effective way of assessing the fracture behaviour of thin-walled pressurized structure subjected to orbital debris impact.
Acknowledgements

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