Modeling the Fragmentation of Hypervelocity Impacts on a Dual-Wall Shield

Joshua E. Miller
NASA JSC/KX[JETS]
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Survivability assessments of space hardware require the use of ballistic performance models to predict the performance of a structure over a broad range of impact conditions and configurations.

Hypervelocity impact experiments, hydrodynamic simulations, and analytical model development have been performed to improve the dual-wall shield models over a variety of impact conditions:

- Data from over 500 hypervelocity impact experiments on dual-wall shield configurations have been collected and analyzed.
- Hydrodynamic simulations have extended some of these configurations to above the 7-10 km/s threshold of low temperature launches.
- Empirical ballistic performance models have been developed that approximate the data, but extrapolation of the models can lead to incorrect conclusions.

A solution-based ballistic performance modeling approach has been developed here that improves the reliability of the extrapolations.
Survivability Assessment Process

Spacecraft Configuration (I-DEAS)

I-DEAS Finite Element Model
- Describes spatial relationships of spacecraft components
- Defines spacecraft orientation (velocity and zenith directions)
- Defines MM/OD shield regions

Meteoroid & Debris Environments (GEOMETRY)
- Threat directions
- Velocity distribution
- Shadowing

Critical Particle Diameter Calculation (RESPONSE)
- Protection capability

- Whipple Shield Ballistic Limit (failure above lines)

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<th>System</th>
<th>Loss of Crew</th>
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<td>IMEX</td>
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Hypervelocity Impacts Database

- Spherical projectile launches performed by:
  - UDRI with maximum velocities of ~10 km/s
  - WSTF with maximum velocities of ~8.5 km/s
  - Many others at JSC, MSC, ARC and by contract companies to ~7.5 km/s
- ~500 double wall impacts have been performed
  - Impactors include Cadmium, Copper, Nylon, Glass, Aluminum, Alumina and Steel
  - Impact obliquities from normal to 75° to normal
  - Impact velocities from 3 to 10 km/s
Empirical Ballistic Performance Models Can Lead to Discrepancies

Aluminum dual-wall shows non-linear scale effects
Hydrodynamic Simulations Extend Impact Conditions Beyond Limits

Steel

Impact Velocity km/s

Critical Diameter cm

NASA TM-2009-214785
Dashed $V_{hi}=7$ km/s
Dot-Dashed $V_{hi}=9.1$ km/s
First Wall Interaction

\[ u_o = \frac{m_W}{m_i + m_W} \left( 1 + \frac{\rho_i (s_i (u_i - u_\infty) + c_i)}{\rho_W (s_W u_\infty + c_W)} \right) u_\infty \]

\[ + \frac{m_i}{m_i + m_W} \left( 1 - \frac{m_W \rho_i (s_i (u_i - u_\infty) + c_i)}{m_i \rho_W (s_W u_\infty + c_W)} \right) u_i \]
Expansion Gap

\[ \omega = \frac{x-x_0}{Z} = \frac{c_s}{c_s + u} \frac{\varepsilon_T}{\varepsilon_i} = \frac{c_s}{c_s + u_0} \left( 1 - \frac{u_o^2}{u_i^2} - \frac{E_d}{\rho_i u_i^2} \left( \frac{\sigma}{\kappa} \right)^2 \right) \]

\[ c_s \approx \sqrt{\frac{4G}{3 \rho} + \sqrt{(2s-1)u((s-1)u + c)}} \]

\[ m_o = m_i \left( \frac{r_i}{r_i + \omega_i S} \right)^{2/3} + m_W \left( \frac{r_i}{r_i + \omega_W S} \right)^{2/3} \]
Second Wall Interaction

\[ u_e = \left( u_\infty' + \frac{c_W'}{s_{W'}} + 1 \right) \left( \frac{m_0}{m_0 + m_W} \left( 1 + \frac{\rho_W u_\infty'}{\rho_i (s_i u_o - u_\infty') + c_i} \right) \right)^{\frac{s_{W'} + 1}{2}} - \left( u_F' + \frac{c_W'}{s_{W'}} + 1 \right) \]

\[ u_F'^2 = \frac{2}{\rho_W'} \int_0^{\varepsilon_F} \sigma(\varepsilon, \varepsilon) d\varepsilon \approx \frac{2}{\rho_W'} \left( a' + \frac{b' \varepsilon_F^n}{n + 1} \right) \left( 1 + c' \log \left[ \frac{\rho_i u_o}{2m_W} \right] \right) \]

\[ d_i = \frac{3}{2} \left( \frac{m_W'}{\rho_i} \left( \sqrt{\rho^* / \rho_i + \omega_i S / r_i} \right)^{\frac{2}{3}} \frac{\hat{u}'}{1 + \hat{R}_W'} - \hat{u}' \right) \]

\[ \hat{u}' = \left( \frac{u_F' + c_W'}{u_\infty' + c_W'} \right)^{\frac{2}{s_{W'} + 1}} \]

\[ \hat{R}_W' = \frac{\rho_W' (s_{W'} u_\infty' + c_W')}{\rho_i (s_i (u_o - u_\infty') + c_i)} \]

Obliquity addressed by correcting lengths to flight path
Solution-Based Ballistic Performance Model Corrects Scale Discrepancies

Simplified solution of hydrodynamic equations resolves scaling effects

Solid-This Paper
Dashed-NASA TM-2009-214785
Removal of empirical quantities allows extrapolation to other conditions.
Summary/Conclusions

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