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Predicting orbital debris-induced failure risk of wire harnesses using SPH hydrocode modeling

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Abstract

This paper describes a method derived to assess the probability of two types of complex cable failures (partial and full wire breaks), considering their location with respect to the debris spray from penetration of multi-layer insulation (MLI) suspended over them, and the likelihood of impacting particle sizes and velocities as predicted by NASA's model for predicting orbital debris impact size and velocity distributions for satellites in low earth orbit, ORDEM. The smooth particle hydrodynamics (SPH) code was used to determine the onset of these two failure types following hypervelocity impact for different orbital debris velocities, sizes and orientations relative to four different wire locations for a prototypical satellite in a 98-degree polar orbit at an altitude of approximately 750 km (i.e., a typical weather satellite). Interpolations between hydrocode results, combined with ORDEM predictions of orbital debris likelihoods, were used to predict overall risk of each failure type. Adding a few layers of beta cloth over the wires cut the risk of each failure type in half.

Keywords: Orbital debris, spacecraft wiring failure, risk prediction, spacecraft failure prediction, hypervelocity impact.

Nomenclature

cm	centimeters
km	kilometers
km/s	kilometers per second
EMI	Electromagnetic Interference

1. Background and Approach

The National Aeronautics and Space Administration (NASA) recently released a new orbital debris environment (ORDEM 3.0) that included an increase in the orbital debris population for many satellites in low earth orbit [1]. In the light of this increased environment, the NASA Engineering and Safety Center (NESC) has sponsored several recent assessments of the risk of orbital debris impact-induced failures of satellites in low Earth orbit [2]. Part of this assessment was an effort to predict failure risk of wire harnesses, usually located in cable trays under thin layers of multi-layer insulation (MLI). This paper describes a method derived to assess the probability of two types of complex cable failures, considering their location with respect to the debris spray from penetration of MLI suspended over them, and the likelihood of impacting particle sizes and velocities as predicted by ORDEM. The Smooth Particle Hydrodynamics (SPH) code was used to determine the onset of these two failure types following hypervelocity impact for different orbital debris velocities, sizes and orientations, relative to four different wire locations for a prototypical satellite in a 98-degree polar orbit at an altitude of approximately 750 km (i.e., a typical weather satellite).

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Interpolations between hydrocode results, combined with ORDEM predictions of orbital debris likelihoods, were used to predict overall risk of two failure types (partial and full wire breaks).

1.1. *Objectives*

The two objectives of this task were to estimate the number of failures for the cables for primarily aluminum projectiles, and identify potential risk reductions by modifying the design.

1.2. Approach

As shown in Figure 1, the wires were assumed to be located in a tray inclined "back" at a 45-degree angle to the spacecraft velocity vector (or "ram direction"). An MLI blanket is positioned parallel to the cable mounting surface at a distance of 2.54 cm from the surface (this MLI layer is referred to as the "bumper"). Any impacting particle will break up on contact with the MLI bumper and produce a spray of particles onto the cables. Because of this effect, cables that are not directly in the path of the particle can still be affected. The analyses considered four cable positions relative to the impact point: on the shot line (P1), 2.54 cm below the shot line (P2, normal to the impact point), 1 cm below the shot line (P3), and 1 cm above the shot line (P4). Each cable is oriented so that the long side faces the impact point on the MLI, which is consistent with most cable runs (i.e., wires run along, not perpendicular to a cable tray).

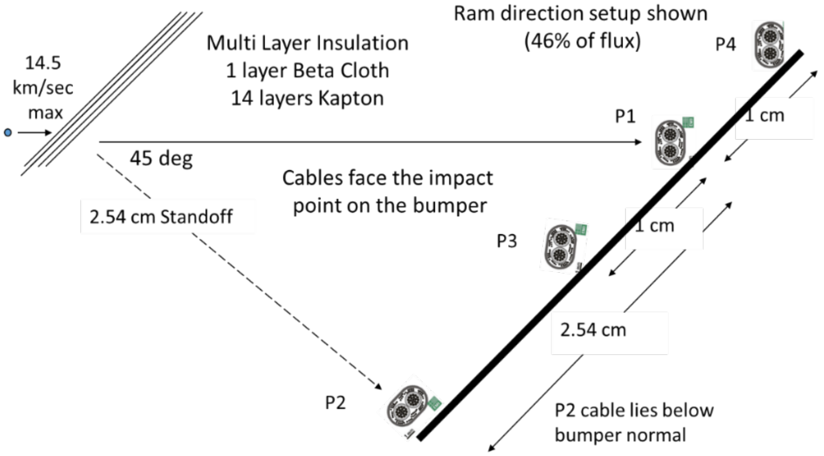

Fig. 1. Wire positions relative to impact point considered in analyses

Per ORDEM3.0, the maximum orbital debris impact velocity in a 90-degree polar orbit will be 14.52 km/s and be from the ram direction (i.e., 0° impact angle). The impact velocity decreases as the impact angle (from the ram direction along the orbital plane) increases, as shown in Table 1.

Table 1. Orbital debris impactor velocity as a function of impact angle derived from ORDEM.

Velocity (km/s)	Angle (degrees) from Ram	Cumulative Percentile Flux by Impact Direction
14.52	**0 (5)**	**.46**
14.52	15	.62
13.58	25	.71
12.30	35	.78
10.76	45	.84
8.76	55	.89
6.40	65	.94
3.96	75	.98
2.16	85	1.0

As shown in Figure 2, the cable was assumed to comprise two 19-strand copper wires. Each of the two wires was encased in a Teflon® insulator, and the pair was wrapped in copper, Kapton®, and electromagnetic interference (EMI) tape (metal and nylon).

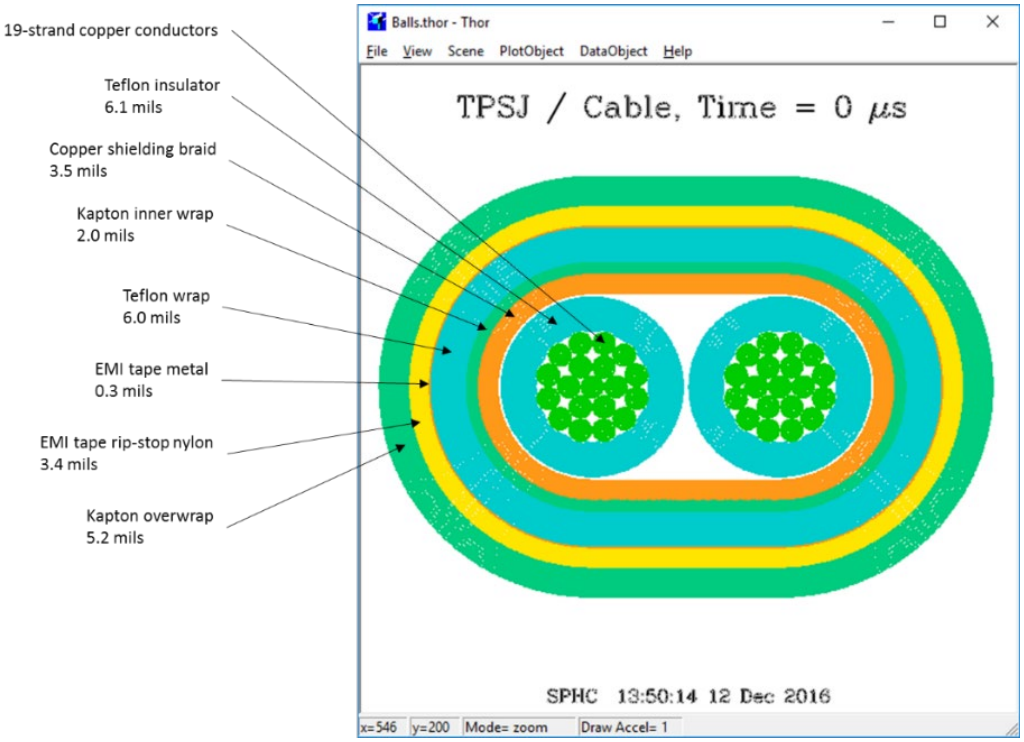

Fig. 2. Modelled characteristics of wire cable

In this example, the dimensions of the region with the cables was taken as 0.10 m by 2.31 m. The percentage of the cabled area at risk to MMOD damage for each of the positions was estimated by taking a scaled drawing of one-third of the region and overlaying a grid. The number of grid elements covered by possible impact points relative to each of the four cable positions defined (P1 through P4) was counted to estimate the total area at risk for each of the cable positions. Using this method, for any given impact, there was a 38 percent probability that there was an affected cable in the P1 position (that is, closer to P1 than any of the other three postulated wire positions). The probabilities for the four cable positions, plus the regions where no wires are affected, are shown in Table 2.

Table 2. Cable impact position coverage following examination of overall cable runs

Cable Position	Coverage Percentage
P1 (on shot line)	38%
P2 (normal to impact/2.54 cm below shot line)	4%
P3 (1 cm below shot line)	20%
P4 (1 cm above shot line)	24%
No wires affected	14%

All hydrocode runs in this study were made considering two velocities: 14.52 km/s (i.e., from the ram direction), resulting in a 45-degree obliquity to the MLI, and at 12.30 km/s (35 degrees off the ram direction), resulting in a 67-degree obliquity to the MLI, representing a range of ~78 percent of the expected flux velocities. Type 1 failures (potentially leading to shorts) were those hydrocode runs that exposed the wire conductors, while type 2 failure (potential wire breaks) were taken in hydrocode runs to show more than 50% conductor penetration. According to Miller, et al, [3] type 1 failures typically manifest as a short, and type 2 failures manifest as an open circuit failure in the power or data cable.

Figures 3 and 4 show examples of simulations of Type 1 and Type 2 failures, respectively. The simulation critical diameter results were interpolated for approach angles between 0 degrees and 35 degrees. Above 35 degrees (below 12.30 km/sec), the results were assumed to be the same as the 35-degree results (considered a conservative assumption, since these impact velocities are lower, and generally less energetic/damaging). Once critical diameters were obtained, ORDEM3.0 determined the flux for particles of that size. That flux was then multiplied by the effective area for each approach angle from 5 degrees to 85 degrees in five-degree increments, and by the coverage percentage for the cable position (from Table 2) to obtain the total predicted number of failures for a 3.5-year mission. The use of 5 degrees for the direct shot line was to avoid singularities that were associated with using 0 degrees. The predicted number of values were then summed to calculate a total number of predicted failures of that failure type and wire position.

Figures 3 and 4 show typical results of SPH hydrocode runs resulting in Type 1 and Type 2 failures. By rotating the 3D hydrocode outputs, one can more easily interpret the onset of each failure type.

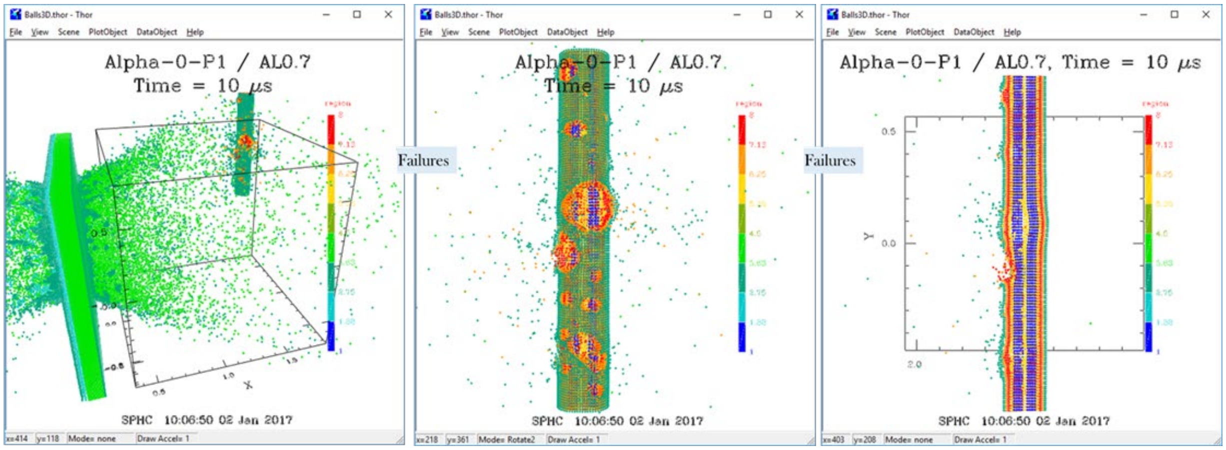

Fig. 3. Example of SPH simulation of a Type 1 failure (exposed conductor)

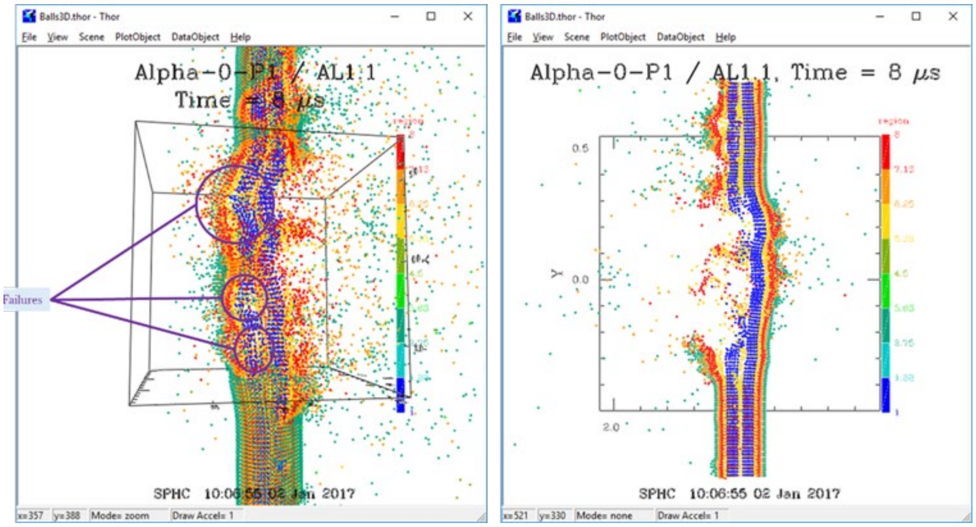

Figure 4. Example of SPH simulation of a Type 2 failure (>50% conductor penetration)

2. Baseline Results

SPH runs were performed for aluminum particle sizes from 0.5 mm up to 1.7 mm, in increments of 0.2 mm for each of the four cable positions. Damage to the cable after each run was evaluated and judged to be either a Type 1 or Type 2 failure, or no failure at all. The smallest particle size to cause damage defined the critical diameter for that damage type. The results of the simulations are summarized in Table 3 (0-degree approach angle) and Table 4 (35-degree approach angle). For these tables and all others like them, T1 = Type 1 failure, T2 = Type 2 failure, NF = no failure, red text = inferred value (i.e., no simulation was run at these conditions).

Table 3. SPH Results for Aluminum Particles Approaching at 0°/14.5 km/s

	Particle Size (mm)					
Position	**0.5**	**0.7**	**0.9**	**1.1**	**1.3**	**1.5**
P4	NF	T1	T1	T1	T2	T2
P1	NF	T1	T1	T2	T2	T2
P3	NF	T1	T1	T1	T1	T2
P2	NF	T1	T1	T1	T1	T1

Table 4. SPH Results for Aluminum Particles Approaching at 35°/12.3 km/s

	Particle Size (mm)						
Position	**0.5**	**0.7**	**0.9**	**1.1**	**1.3**	**1.5**	**1.7**
P4	NF	NF	T1	T1	T1	T1	T1
P1	NF	T1	T1	T1	T2	T2	T2
P3	NF	T1	T1	T1	T1	T2	T2
P2	NF	NF	T1	T1	T1	T1	T1

Using the values in Tables 3 and 4 for critical diameter, the exposed area of the cable tray (0.10 m by 2.31 m), and the probabilities of impacting each of the wire positions P1-P4 from Table 2 as inputs, the ORDEM3.0 analysis was applied to derive the number of failures (for 2 failure types) as shown in Table 5 over 3.25 years starting in 2018 considering only medium density (aluminum) particles (at the request of the sponsor).

Table 5. Predicted Number of Failures

	Calculated Number of Failures				
Failure Type	**P1**	**P2**	**P3**	**P4**	**Total**
Type 1	1.001	0.082	0.527	0.497	**2.107**
Type 2	0.128	0.002	0.0206	0.038	**0.194**

Recall that the critical diameter for any impact angle greater than 35 degrees was assumed to be equal to that for the 35-degree conditions. This is a conservative assumption, so a sensitivity study was performed to assume perfect shields for impact angles above 35 degrees, meaning damage would not be possible for any particle size (this would be an extreme non-conservative assumption). This assumption had a small effect on the results, where the Type 1 damage dropped from 2.1 to 1.9 impacts, and the Type 2 dropped from 0.19 to 0.18 impacts. Therefore, the assumption stated at the beginning of this paragraph was appropriate for this exercise.

3. Improved Design Results

Next, two layers of beta cloth were simulated adjacent to the cable (see Figure 5). The critical diameter results for these SPH runs are shown in Table 5.

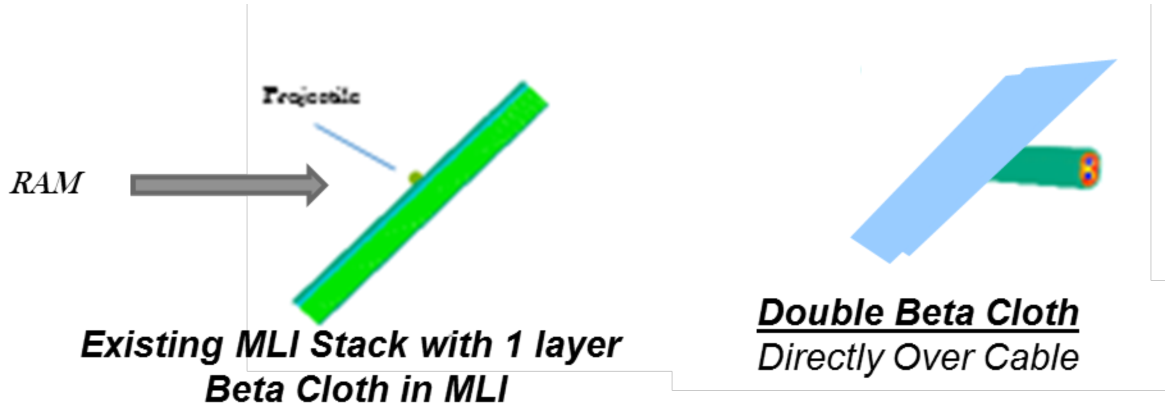

Figure 5. Improved design, with double Beta cloth placed directly over cables

Table 5. SPH Results for aluminum particles at 0°/14.5 km/s for baseline configuration plus two layers of Beta cloth adjacent to cables

	Particle Size (mm)					
Position	**0.5**	**0.7**	**0.9**	**1.1**	**1.3**	**1.5**
P4	NF	NF	T1	T1	T1	T1
P1	NF	NF	T1	T1	T1/T2	T2
P3	NF	NF	T1	T1	T1	T1
P2	NF	NF	T1	T1	T1	T1

Both Type 1 and Type 2 failures were improved with the additional beta cloth layer. The adjusted predicted numbers of impacts for the new critical diameters are shown in Table 6.

Table 6. Predicted number of impacts for the dual layer beta cloth (BC) adjacent to the cables configuration (changes from baseline are shown in red)

	Calculated Number of Failures					
	Failure Type	**P1**	**P2**	**P3**	**P4**	**Total**
Baseline	Type 1	1.001	0.082	0.527	0.497	**2.107**
	Type 2	0.128	0.002	0.0206	0.038	**0.194**
Dual BC Adjacent	Type 1	0.386	0.032	0.203	0.191	**0.812**
	Type 2	0.056	0.002	0.014	0.018	**0.090**

In this case, adding the two layers of beta cloth resulted in a significant (over 50 percent) reduction in risk for both Type 1 and Type 2 failures. Type 1 failures decreased from 2.107 to 0.812 and Type 2 failures from 0.194 to 0.090. All of the SPH runs for the risk reduction were at 14.5 km/s impact velocity, and the results were extrapolated to the other velocities. The intent of this activity was to produce a first-order approximation of the impact risk to the cables and show how it can be reduced. More detailed models and runs using the Bumper software, higher fidelity cable models, and inclusion of steel particles would be necessary to produce results that are more accurate.

Acknowledgements

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References

[1] Matney, et al., 2014. Orbital Debris Environment Model, ORDEM 3.0, NASA Johnson Space Center Presentation to NESC, March 2014.

[2] Squire, M., et al., 2014. Joint Polar Satellite System Micrometeoroid and Orbital Debris (MMOD) Assessment, NASA Engineering and Safety Council (NESC) Study TI-14-00948, April 2015.

[3] Miller, J.E., et al., 2019. Cumulative distribution of ballistic impact failures of common twisted-pair data cables at orbital speeds," Int. J. Imp. Engng. 124 (2019) 61-66.