TETHERS AS DEBRIS: HYDROCODE SIMULATION OF IMPACTS OF POLYMER TETHER FRAGMENTS ON ALUMINUM PLATES

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ABSTRACT

Tethers promise to find use in a variety of space applications. Despite being narrow objects, their great lengths result in them having large total areas. Consequently, tethers are very susceptible to being severed by orbital debris. Extensive work has been done designing tethers that resist severs by small debris objects, in order to lengthen their working lives. It is from this perspective that most recent work has considered the tether – debris question. The potential of intact tethers, or severed tether fragments, *as debris*, to pose a significant collision risk to other spacecraft has been less well studied. Understanding the consequences of such collisions is important in assessing the risks tethers pose to other spacecraft. This paper discusses the damage that polymer tethers may produce on aluminum plates, as revealed by hypervelocity impact simulations using the SPHC hydrodynamic code.

INTRODUCTION

Studies of orbital debris and of tethers have been active fields for the past several years [1,2,3,4]. The majority of previous work was done from the perspective of tether vulnerability to severance by debris impacts, so considerable effort has been expended designing tethers that can suffer impacts and continue to function [5,6,7]. This paper considers the impact hazard that polymer tethers may pose *as debris* to other spacecraft.

Concerns about tethers as debris objects are beginning to be addressed. NASA issued Orbital Debris Mitigation Guidelines [8] which included a section on tether debris hazard calculations. In addition, the Inter-Agency Space Debris Coordinating Committee, functioning under the auspices of the United Nations Committee for the Peaceful Uses of Outer Space, is preparing a Protection Manual [9] with respect to orbital debris issues; this manual includes a section on protecting tethers from destruction by debris and on the hazards tethers may pose as debris.

In this paper the damage potential of impacts by polymer tethers will be examined by simulation, using a hydrodynamic code whose previous results have been validated by test.

LIFETIMES AND SEVER ANALYSES

Concerns about the limitation of single-strand tether lifetimes by meteoroid and debris impacts have led to predictions of tether lifetimes against sever [7, 10, 11], estimation of collision rates [4, 12], and development, analysis, and testing of several mitigating designs [5, 6, 13]. One aspect of the analyses of tether lifetimes against impact sever is the characterization of the impactor size required to sever a strand [7, 11]. This is typically expected to be between 0.1 and 0.4 of the strand diameter.

The collision hazard that free tether fragments pose to other spacecraft will be a function of orbital lifetime [3, 4, 12]. Tethers are more affected by atmospheric drag than other classes of space objects, due to their large ballistic coefficients, β, given by:

$$\beta = C_D A / M \qquad (1)$$

where C_D is the drag coefficient, A is the cross sectional area, and M is the mass. The cross sectional area of a tether is very large, since, even though it may have small diameter, d, it tends to have great length, L. Consequently, tether β's are large.

Warnock and Cochran [3] performed analyses of orbital lifetimes for initially radially-oriented tethers and tethered satellites. They ran simulations of tethers orbiting about an oblate Earth with an oblate, rotating atmosphere, and considered atmospheric drag, gravitational forces, and tension forces in the tethers. Their tethers were assumed to be cylindrical in cross section, and made of Kevlar™ 29. They found that for cylindrical tethers of a given length and material density starting at a given altitude, larger-diameter tethers had longer lifetimes than small ones due to the decrease in ballistic coefficient. For tethers of the same diameter and material, they found that shorter tethers had longer lifetimes. For this reason, short tether fragments generated by hypervelocity collisions are of more concern as debris objects than long, intact tethers.

The initial altitudes studied by Warnock and Cochran were in the range of 400 to 500 km. The corresponding lifetime values for 20-km tethers were rather short, ranging from a few hours to not quite ten days. For tethers to constitute long-term collision hazards, their initial altitudes will have to be higher than this, or the tethers must be considerably shorter or more dense than Warnock and Cochran's examples.

SPHC

In addition to other kinds of analysis, simulations have been used to examine the effect of hypervelocity impacts on tethers [14]. One particular computational method, known as Smooth Particle Hydrodynamics (SPH), was developed by Lucy [15], Monaghan [16], and Stellingwerf [17]. SPH is a gridless Lagrangian computational technique which solves the continuity, momentum, and energy equations of fluid dynamics by reformulating the analytical expressions in terms of an interpolation theory. As derived, the interpolation is made for "particles" that represent mathematical interpolation points at which the fluid properties are known. A version of SPH written for the C programming language (SPHC) has been in development by Stellingwerf [18] since the early 1990's, and results from this code have been verified by comparison with laboratory tests [9, 20]. SPHC was the code used in the simulations reported in this paper.

SPHC is structured so that linear momentum, angular momentum, and energy are conserved, within the adjustable accuracy of a fourth-order Runge-Kutta integration scheme. A Mie-Grueneisen multiphase equation of state was used for the aluminum plate target in the current simulations. For this target a strength model accounting for high strain rate behavior was used. A modified Mie-Grueneisen equation of state was applied to the tether material, which treated this material as a 'fabric' having a specified porosity which must be 'crushed' to the full material density before bulk strength properties are realized. The fabric strength applies only in tension.

SETUPS

In these simulations tether fragments were modeled as arrays of eight Kevlar 49 ™ strands, with approximate lateral dimensions 0.75 x 0.30 mm, and different lengths. These models approximate a type of tether used in the SEDS Project [7,21,22]. A tether model impacted its target at various flight orientations and velocity obliquities. The target material was a 2-mm thick plate of aluminum 6061-T6, reminiscent of the outer bumper layer of Whipple shields on the International Space Station [2]. Tether spatial velocities ranged from 4.6 to 10 km/s. In each case, 100,000 SPH particles were used in the simulation.

SIMULATION RESULTS

The first case considers a tether impacting near an edge of the aluminum plate, with velocity normal to the plate's front surface. The tether is oriented such that its long axis is at an angle of about 10 degrees to the plane of the plate's front surface, and strikes with its 0.3-mm edge first. Figure 1 shows the pre-collision configuration. Figure 2 shows a snapshot at 0.5 μs into the collision: the portion of the tether beyond the end of the plate continues to the left at its original speed, while a splash of ejecta moves to the right, and a shock propagates into the aluminum. Figure 3 shows the situation after 10 μs have elapsed: large spall fragments move to the left, low-density ejecta fragments move to the right, and the plate has been severely fractured and thoroughly penetrated. Fragments leaving the back surface of the plate are moving in the velocity range of 1 - 3 km/s. If this plate were the bumper layer of a Whipple shield, the backwall would suffer hypervelocity impacts of bumper debris. Another run with the same setup except with the 0.75-mm side of the tether striking the plate first shows similar damage.

Subsequent cases examine the effect of velocity obliquity on the damage inflicted by the tether on the aluminum panel. 'Obliquity' refers to the

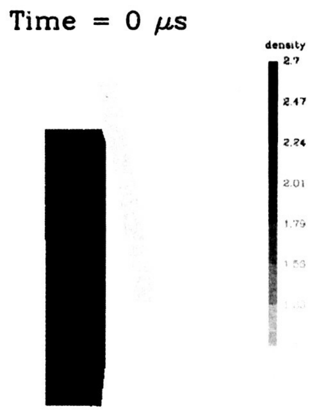

Figure 1. Tether and aluminum plate just before contact.

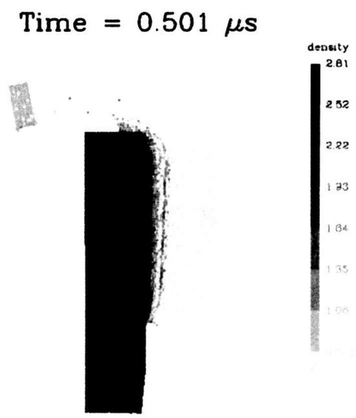

Figure 2. Half a microsecond into the run, the undamaged tether fragment continues to the left, while an ejecta backsplash moves right.

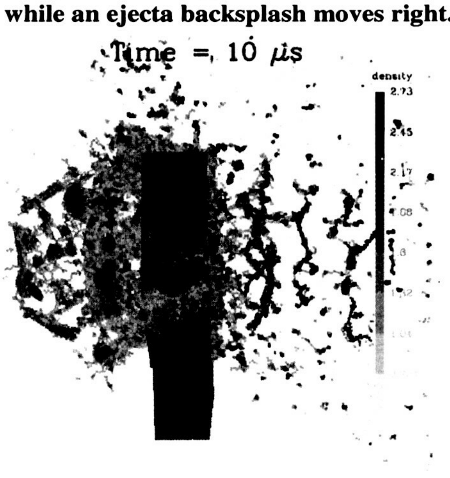

Figure 3. Debris, shattered plate, and ejecta.

angle between the velocity direction and the normal to the plate. Impact obliquities of 70, 60, 45, and 0 degrees were simulated, in addition to the zero obliquity cases above. For the obliquity test cases the long axis of the tether is parallel to the plate surface, and the 0.75-mm width of the tether is inclined at 45 degrees to the plate face. Results for an obliquity of 70 degrees are shown in Figure 4. At this obliquity, little damage is seen on the target plate, which is slightly bent

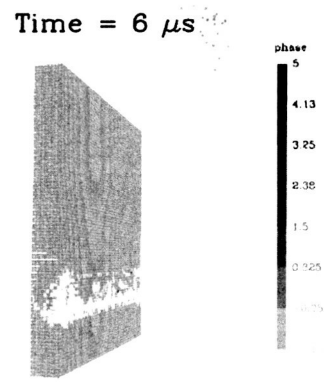

Figure 4. Results of tether impact at 70 deg obliquity: slight plastic deformation and bending of the plate; ricochet of shattered tether particles.

and has a small region of plastic deformation at the immediate impact site; the impacting tether ricochets off the front surface, and there is no aluminum ejected in this direction. The tether velocity component normal to the plate surface is 3.42 km/s. Similar results, with bending, minor plastic deformation, and ricochet are observed for an impact at 60 degrees obliquity, for which the closing speed is 5.00 km/s.

In the 45 degree obliquity case significant damage is seen on the plate. Here the closing speed is 7.07 km/s, high enough that the impact shock fractures and melts the metal, and propels a large spall strip off the back side, as seen in Figure 5. Also, fractured and melted aluminum ejecta leaves the front surface, following the ricochet of the disrupted tether particles, as seen in Figure 6.

In the zero obliquity case, as expected, the plate suffers catastrophic fracture, spall, and melting, and is completely severed, as shown in Figure 7.

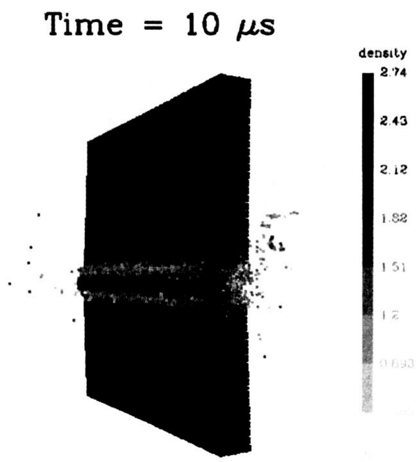

Figure 5. Impact damage at 45 degrees obliquity: spall strip detaching from rear surface.

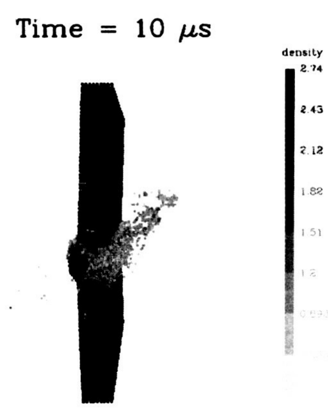

Figure 6. Impact damage at 45 degrees obliquity: fractured and melted aluminum ejecta leaving front surface of plate.

An examination of the energetics of the collision and the resulting damage is given in Table 1. The mass of the 2-cm length of the tether striking the plates in the obliquity test cases was 2.1 mg. Table 1 gives the obliquities and corresponding projected areas, velocities normal to the aluminum plate, and normal kinetic energy fluxes during the collisions. These data suggest that if between 80 and 250 J/cm^2 is normally deposited on the surface of a 2-mm thick aluminum plate, the plate will be penetrated. This suggestion was investigated in another

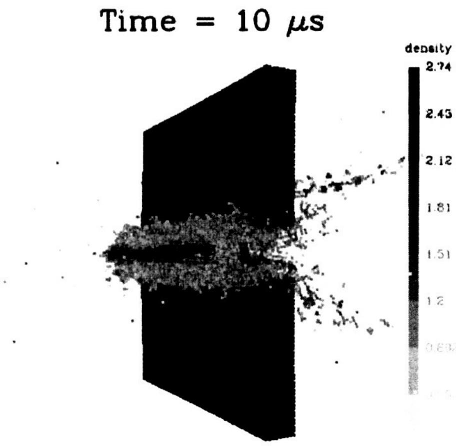

Figure 7. Catastrophic impact at zero degrees obliquity, 10 km/s.

Table 1. Obliquity cases' normal energy fluxes for 2.1-mg tether fragment on 2-mm thick Al 6061-T6.

Obliquity (degrees)	Proj. Area (cm^2)	Normal Vel. (km/s)	KE/Area (J/cm^2)	Pen?
0	0.149	10.0000	713.3	Yes
45	0.212	7.0711	250.7	Yes
60	0.322	5.0000	82.5	No
70	0.472	3.4202	26.3	No

series of simulations, wherein the tether fragment impacted the plate at zero obliquity, but varying speed, with the damage results given in Table 2.

Table 2. Normal incidence impact results for 2.1-mg tether fragment on 2-mm thick Al 6061-T6. Tether projected area: 0.149 cm^2.

Normal Velocity (km/s)	KE/Area (J/cm^2)	Damage
4.61	150	Crater-trench
4.76	160	Crater-trench
5.33	200	Crater-trench
5.59	220	Attached spall
5.84	240	Detached spall

The 'ballistic limit' areal energy deposition is apparently near 220 J/cm^2 for this plate.

CONCLUSION

During high velocity impacts, polymer tethers can be expected to produce severe damage on thin aluminum plates (or other materials). For the test case of a 2-mm thick aluminum plate, normal impacts depositing 220 J/cm^2 or more of kinetic energy will cause failure of the plate. For the SEDS-like tether studied here, the requisite closing speeds for significant damage begin at ~5.6 km/s.

Low altitude tethers, such as the various incarnations of SEDS, pose minimal risk to other spacecraft due to their short lifetimes on orbit. However, because of their destructive potential, their large projected areas, and the fact that they are undetectable by radar (and so cannot be tracked and avoided) polymer tether fragments a few centimeters or more in length that are high enough to have extended orbital lifetimes constitute an unusually dangerous class of orbital debris.

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