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A new Ballistic Limit Equation for thin tape tethers

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ABSTRACT

Electrodynamic tethers represent one of the possible means to de-orbit defunct satellites from Low-Earth-Orbit at end of life. However, tethers survivability to orbital debris impacts is still debated because of the large area they expose to the space environment. Recently, increasing consideration has been given to thin-tape tether geometries, whose response to space debris threat is believed to be better than that of round wires. This paper describes a new Ballistic Limit Equation (BLE) applicable for thin tapes, to go beyond previous investigations referring at most to the impact resistance of round-wires (furthermore neglecting the damage dependence from the impact velocity and angle). In this paper, a new approach for BLE derivation is presented, which combines experimental results (in total 24 impact tests) and numerical simulations (in total 112 runs). The resulting BLE is non-monotonic with respect to the impact angle and presents a minimum at certain values of the impact obliquity, depending from the debris size and speed. In other words, the minimum particle diameter which is just able to cut a tape at a given velocity decreases with increasing impact obliquity up to a certain angle above which the damage is reduced due to early debris fragmentation triggered by shock waves propagating into the material. Notably, it has been observed that there is a minimum value of debris velocity v* below which no critical damage is possible and, furthermore, there is a minimum velocity-dependent value d* of debris diameter below which no critical damage is possible. This feature of BLE is extremely important, since it sets a minimum particle diameter for risk assessment and thus excludes a large part of the flux from risk computations. In conclusion, the newly-developed BLE confirms that thin tapes are significantly more resistant than round wires of equivalent cross-section; this is due to the intrinsic ballistic response of tapes, not only to their reduced cross-section at high impact obliquity.

1. Introduction

This paper describes a new Ballistic Limit Equation (BLE) applicable for thin tape tethers. Such equation has been developed using an original empirical approach which makes it possible to predict the impact damage evolution till the failure threshold. Having a suitable equation which makes it possible to predict the survivability of tapes to Hyper Velocity Impact (HVI) is a fundamental step to enhance the accuracy of risk computations for flat tethers, since previous investigations were mostly focused to the evaluation of the impact resistance of round-wires. These studies showed that a particle with size from 1/5 to 1/2 of the tether diameter is enough to cut the rope [1–4], and they indeed provide a first estimation of the ballistic limit of a tether. However, they are based on the assumption that any impact on the wire excavates a crater whose volume depends on the Meteoroids/Orbital Debris (M/OD) kinetic energy, and their application is not rigorously valid for tethers whose cross section is thin, e.g. tapes. Furthermore, the damage dependence from the impact velocity and impact angle is not considered and this latter parameter could be particularly important for tethers with non-axis-symmetric cross section. Concerning the impact resistance to thin tapes, only few works have been completed to date, in part based on the extension of existing results for round wires [5,6], and in part using original impact test results on tapes [7,8]. In this paper, the results presented in the latter reference are further generalized thanks to the use of new test results and a significant numerical simulation campaign aiming at exploring impact conditions not achievable in laboratory (i.e. impact speed up to 20 km/s and impact angle up to 90°).

The remainder of this paper is organized as follows: the approach used for BLE development is described in Section 2; a summary of experimental results and numerical simulations is then given in Sections 3 and 4, data analysis and BLE derivation are discussed Section 5, and conclusions are finally given in Section 6.

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Nomenclature

A	Damage's major axis (mm)
A_{90}	Damage's major axis for α_{loc}=90°
A_{crit}	Damage's major axis critical value (mm)
c_1, c_2	Damage equation parameters
d^*	Minimum debris diameter below which no critical damage is possible (mm)
d_{crit}	Minimum particle diameter which produce a tether critical damage (mm)
d_p	Particle diameter (mm)
k_1, k_2, k_3, k_4	Damage equation parameters
k_5	Damage equation parameter (km/s)
$k_{w,\,Al1100}$, $k_{w,\,PEEK}$	Minimum amount of material that has to be removed from the tethers to cause cut-off divided by the original tapes width
R^2	Fit correlation index
v^*	Minimum debris velocity below which no critical damage is possible (km/s)
v_n	Impact velocity normal to the tape (km/s)
$v_{n,\,thr}$	Impact velocity normal to the tape threshold value(km/s)
v_p	Particle velocity (km/s)
v_{shock}	Speed of propagation of shock waves in the debris material (km/s)
w	Tape width (mm)
α_{loc}	Impact angle (°)
σ	Empirical coefficient designed to implement a transition from 1 to 0 across $v_{n,\,thr}$
σ_{fit}	Fit standard deviation

2. Ballistic Limit Equation development approach

BLE provides the minimum particle diameter d_{crit}[1] which produce a tether critical damage (cut-off) at given speed v_p and impact angle α_{loc}, measured in the tape reference frame, see Fig. 1 (left). Fig. 1 (right) presents the definition of "edge impact": this type of impact occurs when the projectile's projection is not entirely contained in the tape surface, which is not unlikely since the size of critical debris can be close to the tether's width.

In the following, BLE is given in the following form:

$$d_{crit}=f\,(v_p,\ \alpha_{loc}) \tag{1}$$

Considering the tether flat shape, special attention is paid to the BLE accuracy for highly oblique impact angles (close to 90°). For BLE derivation, a new empirical approach is employed [9,10], which makes it possible to estimate the uncertainty in the failure prediction. The new method consists of four steps (for each type of tether, Al1100-H19 and PEEK):

a. Automatic analysis of the impact damage on high-resolution images of samples after impact. The damage's shape is assumed to be elliptical, and its size is therefore specified by the values of the ellipse's major and minor axes A and B, respectively along the y and x directions (see Fig. 1).
b. Derivation of empirical co-relations (damage equations) between the damage's major axis A and the impact parameters (particle size, speed and impact angle):

$$A=f_D\,(v_p,\ d_p,\ \alpha_{loc}) \tag{2}$$

c. Empirical determination (and/or assumption based upon available data or theoretical modeling) of the damage's major axis critical value (A_{crit}). By definition, if $A \geq A_{crit}$, the tether is cut-off, i.e. the tether is severed when the damage extension in the y direction reaches a certain critical percentage of the tape width.
d. BLE derivation by introducing the critical value A_{crit} in the damage equation and inverting the formula:

$$d_{p,crit}=f_D{}^{-1}-1\,(A_{crit},\ v_p,\ \alpha_{loc}) \tag{3}$$

The key advantage of this method is that BLE is given with uncertainty bands, thanks to the fact that both the damage equation f_D and the critical damage value A_{crit} are obtained from experiments and hence they can be related to suitable confidence intervals. On the contrary, as pointed out by Schonberg et al. [11], following traditional approaches BLEs are simple "demarcation lines" between fail and no-fail conditions, with no statistical significance.

Differently, the method here described is based upon the definition of a damage parameter (A) that is physically related to the tether cut-off phenomenon. Such parameter varies monotonically across the failure threshold, assuming a particular critical value A_{crit} (that can be predicted from the experiments) at the ballistic limit. All the available data, even well away from the ballistic limit, can be therefore used to statistically follow the critical parameter evolution. In this way, it is possible to provide an estimation of the test conditions at the ballistic limit, even inside the bounds defined by the two closest non-critical and critical experiments.

In this paper, the damage parameter A is obtained from experimental as well as numerical results:

- Experiments (Section 3) are used for BLE preliminary derivation, simulations tuning and validation;
- Simulations (Section 4) are employed for BLE extrapolation outside the test range (impact velocity up to 20 km/s, impact angle up to 90°).

3. Impact experiments

Impact tests have been conducted at CISAS Hypervelocity Impact Facility, using a two-stage light-gas gun (LGG) capable of accelerating particles in the range 0.6–3 mm at speed up to 6 km/s [12–14].

3.1. Test setup

The standard test set up consisted in Al-1100 spheres impacting on a 25.4 mm-wide tape with thickness equal to 0.05 mm (for projectiles, the spherical shape and the aluminum-alloy material are widely accepted as first representation of untrackable space debris).

Two different materials were used for the tapes, i.e. Al-1100-H19 and PEEK (see materials properties in Table 1). This choice corresponded to the preliminary design solution for the electro-dynamic tether system developed in the framework of the EU FP7 program "BETs" (www.thebetsproject.com): a 6 km long tape was foreseen as baseline, made of a 3 km conducting aluminum part acting as the anode, in series with a 3 km non-conducting PEEK part to increment the overall system length and provide the requested gravity gradient stabilization, while keeping low mass and ensuring good mechanical properties. The size of the tape cross section was selected to meet the requested anode conductance, without exposing excessive area to the space debris threat.

A total number of 24 HVI experiments was performed. Both the two tape tethers (Al-1100-H19 and PEEK) were subjected to impact at different angle and speed. A special tether support structure (Fig. 2)

[1] See Nomenclature at the end of paper.