SYSTEMA-DEBRIS: RISK ASSESSMENT TOOL

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ABSTRACT

Systema-Debris is a plug-in application of Systema develop by Airbus and used to assess the probability of space debris and micro-meteoroid (MMOD) causing damage on a spacecraft or its components. It includes a variety of capabilities, such as 3D modeling, the ability to read the standardized file STENVI and to apply customized equations to allow the use of a large variety of Ballistics Limit Equations (BLEs) available in the literature.

One of the Systema-Debris capabilities is to provide probabilities of impacts by undersized bumpers like Multiple Layout Insulator (MLI). Hypervelocity impact tests were performed on MLI blankets by THIOT Ingénierie with the HERMES two-stage light gas gun, in the frame of a CNES Research & Technology contract [3]. The results are compared with the Systema-Debris methodology to assess the critical diameter of a thin bumper like MLI.

1 INTRODUCTION

Due to their high velocity, micrometeoroids and small orbital debris represent a threat to spacecraft or its components. Moreover, the amount of debris in space is continuously increasing. It is thus necessary to assess the probability of spacecraft damage or failure due to a MMOD impact during its mission lifetime. The aim of a risk assessment is to identify the spacecraft components sensitive to MMOD, provide inputs to assess the spacecraft reliability and, if necessary, support the implementation of shielding to improve spacecraft survivability. Systema-Debris is a software that perform this kind of risk assessment analysis.

In order to perform a risk assessment analysis for a spacecraft under a specific environment, it is necessary to evaluate whether or not the impacting particle will penetrate the sensitive target. A variety of ballistic limit equations have been implemented for many types of structural wall configurations to identify the minimum critical particle diameter that can penetrate the target. These equations depend on several parameters like the size and the density of the particle, the material type and thickness of the impacted target, and the speed of the impacting particle, which makes the analysis difficult to perform without the support of a dedicated software like Systema-Debris.

The Whipple shield equation [4] allows computing the critical particle diameter, and it is assumed that the bumper shield is well designed which means its thickness is sufficient to fragment the impacting particle.

Some elements like MLI, already present on the spacecraft design, can act as a bumper to the sensitive components. As they are designed for thermal needs, they are most of the time undersized. Reimerdes [2] modified the Whipple shield equation to take into account the bumper thickness. This methodology has been implemented into Systema-Debris to help the user to find mass effective protection concepts with undersized bumpers.

Hypervelocity impact tests were performed on MLI blankets by THIOT Ingénierie with the HERMES two-stage light gas gun, in the frame of a CNES Research & Technology contract [3]. The results are compared with the Systema-Debris methodology to assess the critical diameter of a thin bumper like MLI.

2 RISK ASSESSMENT PROCESS WITH SYSTEMA-DEBRIS

Larger on-orbit objects are tracked and orbit changes manoeuvres of the spacecraft can be performed to avoid a collision. For non-trackable objects, shields or other means are used to control risks.

The prevention of critical damages on sensitive surfaces that might compromise mission and lifetime interest more and more the satellite design engineers. In order to improve the design of the spacecraft, impact risk assessment tools Systema-Debris was developed.

Debris is a plug-in application of Systema. It evaluates the number of penetrations by micrometeoroid and orbital debris and thus the Probability of No-Penetration (PNP) of selected targets.

This risk information can then be used to identify sensitive targets and develop risk mitigation strategies such as adding shielding or modifying the spacecraft

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attitude. Similarly, the same risk results can help identify if some elements can be hollowed out, that may be opportunities for mass reduction and cost savings.

Debris uses generic Ballistic Limit Equations (single-wall, multiple walls) or SRL equation. The generic BLE can be customized which allows the use of a large variety of equations available in the literature. Debris uses the standardized STENVI files as input to describe orbital debris and meteoroid environment models. Debris also has several additional features to support data visualization.

Systema-Debris has been used to assess MMOD risk on many spacecraft and their components. The software is used to analyze telecom satellites (E3000, Euro-starNeo), LEO/earth observation satellites and it is also used to analyze interplanetary spacecraft such as JUICE, SOLO or Mars Sample Return missions.

The Systema-Debris MMOD risk analysis process is shown in Figure 2-1.

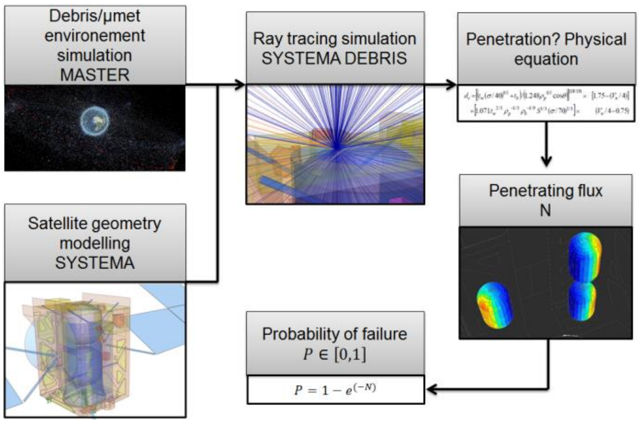

Figure 2-1: Systema-Debris MMOD risk analysis process

- **Generation of a realistic debris/micrometeoroid environment:**

Various type of environment can be used, ranging from detailed to simplified isotropic environment on 4π steradian. The STENVI format, recommended standard by the IADC, is used to feed the computation module. Environment models used are for exemple MASTER which is the ESA standard, ORDEM and MEME which are the NASA standards. Models generate fluxes of particles around the concerned orbit. Those fluxes give information about the particles velocity, density and size.

The STENVI is a standardized interface between MMOD environment models and damage prediction tools. This file contains the flux contribution for each bin as a function of:

- impact azimuth,
- impact elevation,
- impact velocity,
- particle diameter,
- argument of true latitude,
- particle density.

```
#--------------------------------------------------------------------------------
#                         STANDARD ENVIRONMENT INTERFACE
#--------------------------------------------------------------------------------
# Interface Version
STENVI      1.0
#
# Environment Model
MODNAME   IMEM
#
# Run Comment (2 lines)
COMMENT   Standard Environment Interface
COMMENT   Version 1.0
#
#----------------------------< Mission Parameters >------------------------------
# Begin and end of analysis time interval
MISSBEGIN  2029   01   01   01     00   00          Begin [yyyy mm dd hh  mm ss]
MISSEND    2030   01   01   01     00   00          End [yyyy mm dd hh  mm ss]
# Target orbit
SEMIAXIS         0.0                        Semimajor axis [km]
ECCENTRI         0.0                        Eccentricity of the orbit [-]
INCLIN           0.0                        Orbit inclination [deg]
RAAN             0.0                        Right ascension of ascending node [deg]
ARGPERI          0.0                        Argument of perigee [deg]
#
#--------------------< Definition of the output spectrum >----------------------
#             Bin       Min        Max
AZIMUTH        72    -180.0      180.0         Azimuth   [deg]
ELEVATION      36     -90.0       90.0         Elevation [deg]
VELOCITY        1     10.0        10.0         Velocity  [km/s]
DIAMETER       48  1.00E-07   1.00E-02         Diameter  [m]
LATITUDE        1       0.0      360.0         Argument of True Latitude [deg]
DENSITY         1       1.0        1.0         Density   [g/cm^3]
#
#--------------------------------------------
# Impact Azimuth [deg]: Intervals
#       No   Lower Border   Upper Border
DISTAZI 1   -1.80E+02   -1.75E+02
DISTAZI 2   -1.75E+02   -1.70E+02
```

Figure 2-2: Standard environment interface

For further information on the STENVI format see [5].

- **Generation of a realistic satellite model:**

This is done in Systema-Debris 3D graphical user interface allowing an adapted modelling from CAD files. During this step, BLE are chosen and adapted to the considered geometrical shielding configurations, material and mechanical properties are assigned to the geometries. The model is then used to generate a meshing.

Figure 2-3 shows an example of a spacecraft configuration modeled with Systema-Debris.

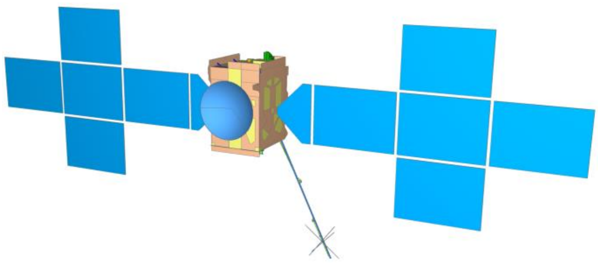

Figure 2-3: Geometrical example model

- **Backward ray tracing as a support to physical equation:**

The fluxes from the environment model are projected onto the satellite geometry allowing to trace the trajectory of each particle through the satellite structure. It tracks which layer of which material have been impacted by the particle before hitting the equipment. On each ray, application of standards IADC and ECSS recommended ballistic equations allows the software to check whether or not the particle being traced penetrates the sensitive element. Shadowing effects are captured by Systema-Debris.

Figure 2-4 shows an example of the backward raytracing of Systema-Debris.

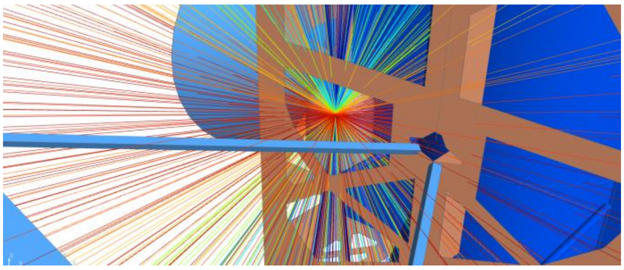

Figure 2-4: Backward ray tracing example

- **Balistic limit equations:**

4 parametric equations are implemented in Systema-Debris:

- One wall standard equation,
- Two walls standard equation,
- Schäfer Ryan Lambert (SRL) equation,
- Crater sized standard equation.

One wall standard equation:

For the single-wall configuration, user can customize the coefficient in order to obtain the desire BLE as shown equation (1) provided in [4].

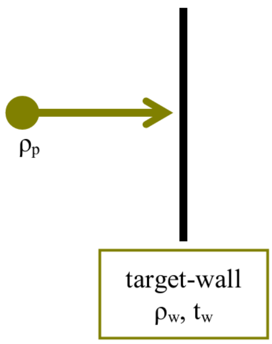

Figure 2-5: Single wall configuration

$$d_c = \left[\frac{t_w}{K_f \cdot K_1 \cdot v^{\gamma} \cdot (\cos\theta)^{\xi} \cdot \rho_p^{\beta} \cdot \rho_t^{\kappa}}\right]^{1/\lambda} \quad (1)$$

Where

- **BHN** = Brinell hardness of the target
- **Ct** = speed of sound in the target (km/s)
- **dc** = critical projectile diameter on threshold of given damage mode (cm)
- $\mathbf{K_f}$ = damage parameter, either 1.8, 2.2, or 3.0 for perforation, detached spall or incipient attached spall
- $\boldsymbol{\rho_p}$ = projectile density (g/cm3)
- $\boldsymbol{\rho_t}$ = target density (g/cm3)
- $\mathbf{t_w}$ = rear wall thickness (cm)
- $\boldsymbol{\theta}$ = impact angle from target normal (deg); $\theta = 0°$ impacts normal to target
- $\boldsymbol{v}$ = projectile velocity (km/s)

It is possible to use the predefined Christiansen equation (Table 2-1) or to modify the parameters of the equation directly into the Systema-Debris interface.

Equation	K_f	K_1	β	γ	κ	λ	ξ
Christiansen 1993 [3] $\rho_p/\rho_w < 1.5$	1.8	$5.24 \cdot BHN^{-1/4} \cdot C_s^{-2/3}$	1/2	2/3	-1/2	19/18	2/3

Table 2-1: Christiensen direct impact equation

Two walls standard equation:

For the double-wall configuration, user can also customize the coefficient in order to obtain the desire BLE as shown equation (2) provided in [4].

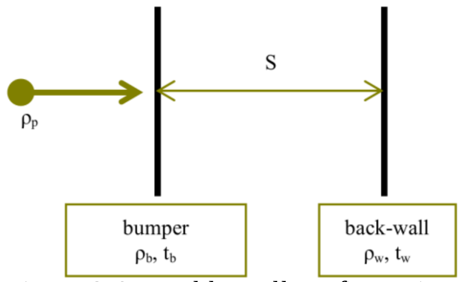

Figure 2-6: Double-wall configuration

$$d_c = \left[\frac{t_w + k_2 \,.\, t_b^{\mu} \,.\, \rho_b^{\nu_2}}{k_1 \,.\, \rho_p^{\beta} \,.\, v^{\gamma} \,.\, (\cos\theta)^{\xi} \,.\, \rho_t^{\kappa} \,.\, S^{\delta} \,.\, \rho_b^{\nu_1}}\right]^{1/\lambda} \quad (2)$$

Where

- **dc** = critical projectile diameter at shield failure threshold (cm)
- $\boldsymbol{\rho_p}$ = projectile density (g/cm3)
- $\boldsymbol{\rho_t}$ = target density (g/cm3)
- $\mathbf{t_w}$ = rear wall thickness (cm)
- $\mathbf{t_b}$ = bumper wall thickness (cm)
- $\boldsymbol{\theta}$ = impact angle from target normal (deg); note impact at $\boldsymbol{\theta}$ =0 deg is normal to the target.
- $\boldsymbol{v}$ = projectile velocity (km/s)
- **S** = spacing (cm)

It is possible to use the predefined Wipple Shield equation (Table 2-2) or to modify the parameters of the equation directly into the Systema-Debris interface.

Equation		K_1	K_2	β	δ	γ	κ	λ	μ	ν_1	ν_2	ξ
Christiansen 1993 [3]	V<3 km/s	$0.6 \cdot (\sigma_{y,ksi}/40)^{-1/2}$	$(\sigma_{y,ksi}/40)^{-1/2}$	1/2	0	2/3	0	19/18	1	0	0	5/3
	V>7 km/s	$\left[3.918(\sigma_{y,ksi}/70)^{1/3}\right]^{-3/2}$	0	1/2	-1/2	1	0	3/2	0	1/6	0	1

Table 2-2: Wipple Shield indirect impact equation

The Wipple Shield equations assume that the bumper thickness is adequate to fragment the projectile at high velocities. For undersized bumpers, the computing process is presented in §3.

SRL equation:

The SRL equation is a ballistic limit equation developed for the case of a double wall configuration or a sandwich panel with honeycomb core placed in front of a back wall (cf Figure 2-7).
The objective of this BLE is to consider explicitly the three plate thicknesses, materials and spacing and also the presence of MLI. Thus it can be used at a component level in order to predict the probability of no failure of equipment such as fuel and heat pipes, pressure vessels, electronic boxes, harness, and batteries placed behind the satellite structure wall. This equation is describe in [6].

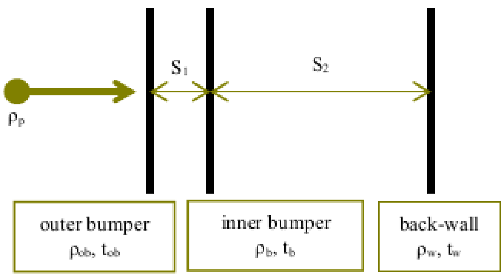

Figure 2-7: SRL configuration

Crater sized equation:

The parametric form of the Crater Size Equation for the penetration depth P is implemented into Systema-Debris:

$$P = k_1 . d_p^{\lambda} . \rho_p^{\beta} v^{\gamma} . (\cos\theta)^{\xi} . \rho_t^{\kappa} \tag{3}$$

Where

- **dp** = projectile diameter (cm)
- $\boldsymbol{\rho_p}$ = projectile density (g/cm3)
- $\boldsymbol{\rho_t}$ = target density (g/cm3)
- $\boldsymbol{\theta}$ = impact angle from target normal (deg); note impact at q=0 deg is normal to the target.
- $\boldsymbol{v}$ = projectile velocity (km/s)

The diameter D of the crater is given by:

$$D = 2 . k_c . P \tag{4}$$

with Kc varying from 1 to 10 depending on the nature of the target.

It is possible to use the predefined Christiansen equation (Table 2-3) or to modify the parameters of the equation directly into the Systema-Debris interface.

Equation	K_c	K_1	β	γ	κ	λ	ξ
Christiansen 1993 [3] $\rho_p/\rho_w < 1.5$	1	$5.24 \cdot BHN^{-1/4} \cdot C_s^{-2/3}$	1/2	2/3	-1/2	19/18	2/3

Table 2-3: Crater equation parameter

- **Penetration flux:**

Penetrating flux is computed. It is the cumulative penetration flux that the sensitive element withstands during the mission, averaged over the surface.

$$N = \sum_{i=1}^{n} N_i = \sum_{i=1}^{n} (FAt)_i \tag{5}$$

With:

- $\boldsymbol{N}$ = the average number of penetration of the equipment,
- **F** = the penetration flux on the mesh i (penetration/year/m2),
- **A** = the surface of the mesh i (m2) and
- **t** = the mission time.

- **Probability of Failure:**

From the penetration flux, the probability of failure (if the failure is the penetration) can be computed using a Poison law.

$$P = 1 - e^{-N} \tag{6}$$

with $\boldsymbol{P} \in [\mathbf{0}, \mathbf{1}]$ the probability of failure of the equipment due to a micrometeroid impact.

Systema-Debris has two output types to support analysis: a text file and the possibility to visualize a color risk contour on the 3D geometry.

The text file contains the following informations:

- **Area [m²]:** Area of the selected mesh.
- **Number of Craters [1/m²/yr]:** Number of Craters with a penetrating depth larger than the user specified depth.
- **Number of Direct Impacts [1/m²/yr]:** Number of particles impacting directly the mesh.
- **Number of Penetrations [1/m²/yr]:** Number of particles with a diameter larger than the associated critical diameter.
- **Number of Shadowed Impacts [1/m²/yr]:** Number of particles encountering one or more elements during backwards ray tracing.
- **Relative crater area:** Area of Craters with a penetrating depth larger than the user specified depth relative to the area of the selected mesh.

Figure 2-8 shows an example of the output file of Systema-Debris.

```
#*********************************************#
#                                             #
#          Results computed by Debris         #
#                                             #
#*********************************************#

  File          :  Example.out
  Version       :  Debris  V.4.8.0P1 released on December 2016
  Input files   :
     - Sysset   :  Example.sysset
     - Sysmdl   :  Z:/projects/Example.sysmdl
     - Sysmsh   :  Z:/projects/Example.sysmsh
     - sei file :  Example.sei
  Parameters     :
     - Seed                     :  876743
     - Number of rays per bin :  1
     - NORM for flux method     :  Average
     - Mission Duration         :  1.000000
     - radial.x                 :  -0.000000
     - radial.y                 :  -0.000000
     - radial.z                 :  1.000000
     - transversal.x            :  1.000000
     - transversal.y            :  0.000000
     - transversal.z            :  0.000000
     - outOfPlane.x             :  -0.000000
     - outOfPlane.y             :  1.000000
     - outOfPlane.z             :  0.000000
---------------------------------------------
Number of Meshes              = 49155
Number of Directions          = 2592
Number of Debris              = 124416
Number of Loops               = 1820701184
---------------------------------------------|
Number of Diameters          = 64
Minimum Diameter             = 9.000000e-08
Maximum Diameter             = 9.000000e-03
---------------------------------------------
---------------------------------------------
                Groups results
---------------------------------------------
---------------------------------------------
Number of Direct Impacts for DROP_TANK_MMH             = 0.000000e+00
Probability of No Direct Impact for DROP_TANK_MMH      = 0.000000e+00

Number of Shadowed Debris for DROP_TANK_MMH            = 0.000000e+00
Probability of No Shadowed Debris for DROP_TANK_MMH    = 0.000000e+00

Number of Penetration/Failure for DROP_TANK_MMH(mZpY)        = 0.000000e+00
Probability of No Penetration/Failure for DROP_TANK_MMH(mZpY) = 0.000000e+00

Number of Crater for DROP_TANK_MMH(mZpY)                     = 0.000000e+00
Probability of No Larger Crater for DROP_TANK_MMH(mZpY)      = 0.000000e+00
```

Figure 2-8: Results output examplecomputed by Debris

Systema-Debris generates an output containing the same outputs as the text file for each mesh.This information can then be displayed on the meshing to produce images like these shown in Figure *2-9*. Note that the colors in this example are set to show high risk as red and low risk as blue with other colors for intermediate risk values. The color-risk scale can be modified.

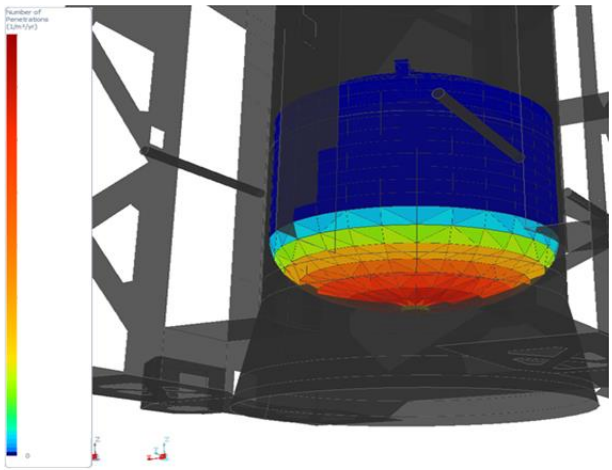

Figure 2-9: Debris color risk images

Systema-Debris can also display information on each ray like the ray type (Figure 2-10), the velocity or the number of impacts (Figure 2-11).

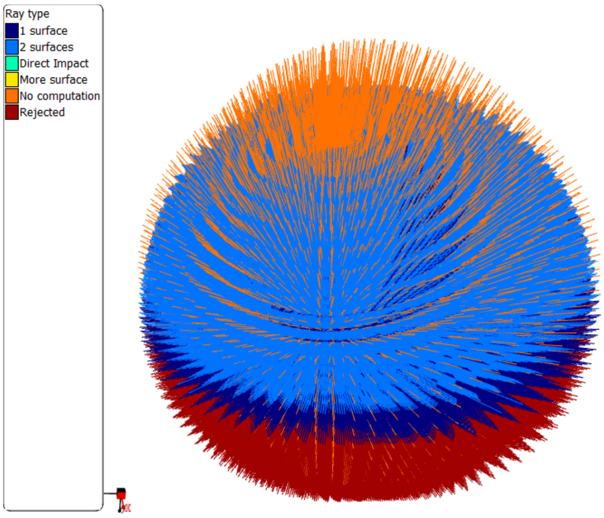

Figure 2-10: Systema-Debris ray type display

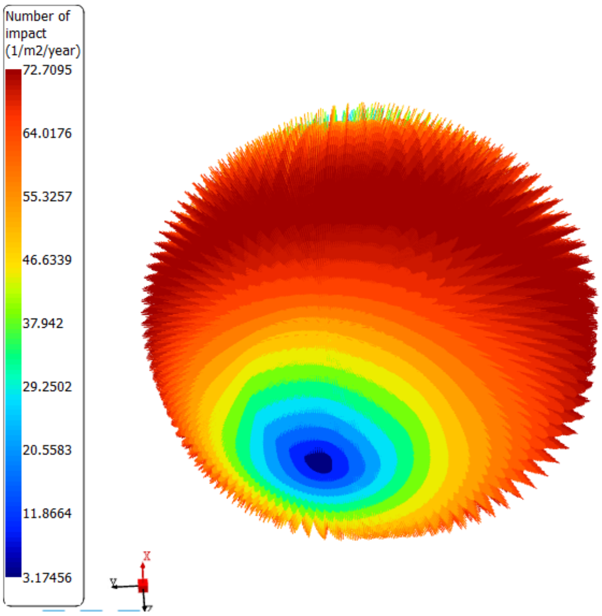

Figure 2-11: Systema-Debris ray number of impact display

3 UNDERSIZED BUMPER MODELING WITH SYSTEMA-DEBRIS

As one of the solutions to better protect a sensitive component is the use of MLI (MLI blankets are expected to disrupt millimetric debris), this approach is routinely used on most of Airbus programs such as JUICE or ERO spacecraft.

Christiansen equations assume that the bumper thickness is adequate to fragment the projectile at high velocities, i.e., the bumper thickness must verify:

$$t_b^{\text{sized}} = \frac{c_b\, d_c\, \rho_p}{\rho_b} \qquad (7)$$

Where

- $\mathbf{t_b}^{\mathbf{sized}}$ = bumper thickness sized (cm)
- $\mathbf{c_b}$ = coefficient 0.25 when S/d < 30, and c_b = 0.2 when S/d ≥ 30
- $\mathbf{d_c}$ = projectile diameter (cm)
- $\boldsymbol{\rho_p}$ = projectile density (g/cm3)
- $\boldsymbol{\rho_t}$ = target density (g/cm3)

for Vn = 7 km/s. If:

- $t \geq t_b^{\text{sized}}$: the Christiansen equations can be applied. However the bumper is oversized and extra bumper mass will not improve shielding performance.
- $t = t_b^{\text{sized}}$: the bumper is optimized. The protection is optimal.
- $t \leq t_b^{\text{sized}}$: the bumper is undersized, which means that the equations overestimate the performance of the shield. Indeed, the bumper is too thin to allow a complete breakup of the projectile. Depending on how undersized is the bumper; the particle upon impact will be partially fragmented to unfragmented. The Christiansen equations have been modified to model undersized bumper.

A factor F2* was introduced in the Christiansen equation to take into account thinner shields effects:

- If the shield thickness approaches zero, the back-up wall acts as a single wall.
- If the shield thickness is sized, the equation converges into the double-wall equation

This leads to a general formulation of F2*:

$$F_2^* = \begin{cases} 1 \ if \ \dfrac{t_b}{d_p} \geq \left(\dfrac{t_b}{d_p}\right)_{crit} \\ r_{s/D} - 10\,\dfrac{t_b}{d_p}\,(r_{s/D} - 1) + 25\left(\dfrac{t_b}{d_p}\right)^2 (r_{s/D} - 1) \ if \ \dfrac{t_b}{d_p} < \left(\dfrac{t_b}{d_p}\right)_{crit} \end{cases} \qquad (8)$$

With $r_{s/D}$ the ratio between the requirement wall thickness to stop the particle if no bumper is present and the requirement thickness when the bumper is properly sized $\frac{t_b}{d_p} = \left(\frac{t_b}{d_p}\right)_{crit}$ at a velocity of 7 km/s.

$$r_{s/D} = \frac{t_w,\ \text{required at}\ (t_b = 0)}{t_w,\ \text{required at}\ \left(\frac{t_b}{d_p} = \left(\frac{t_b}{d_p}\right)_{crit}\right)} \qquad (9)$$

Finally solution is corrected (for V > 7 km/s):

$$d_{c\ Modify\ eq} = d_{c\ 2\ wall} * {F_2}^{*\ -2/3} \quad (10)$$

Using the "validy check option" in the Christiansen equation allows the user to model undersized bumper on Debris.

This approach can be compared to the hypervelocity tests in [3] on undersized MLI bumpers (Figure 3-1). More details about the tests set-up and the results can be found in [3].

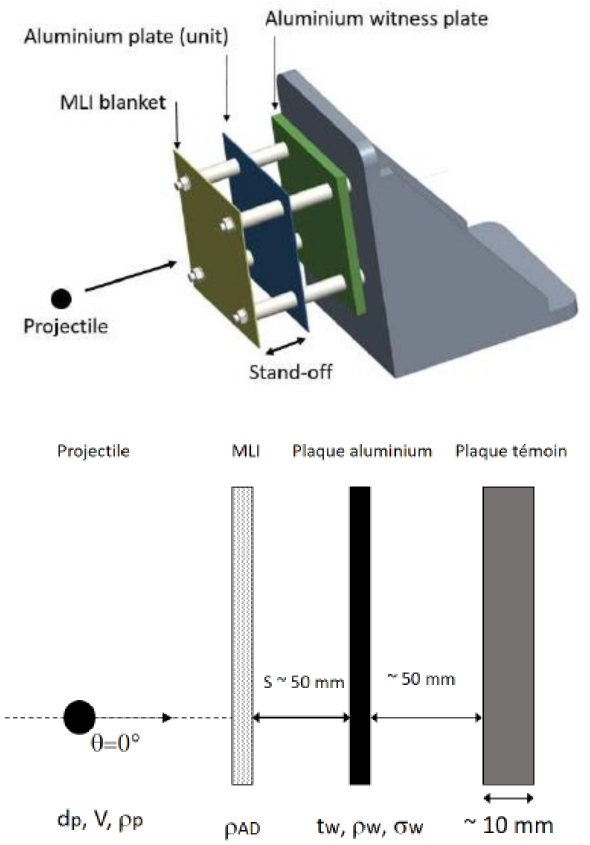

Figure 3-1: Test set-up [3]

Figure 3-2 shows the Systema-Debris approach compared to the hypervelocity tests in [3].

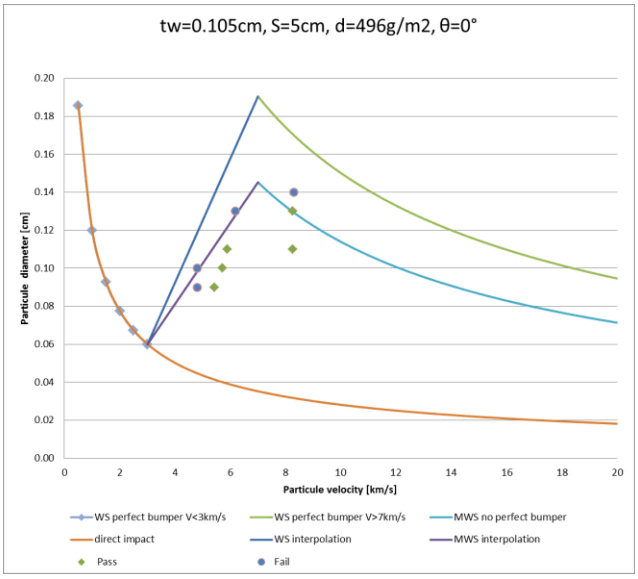

Figure 3-2: Systema-Debris approach compared to the hypervelocity tests in [3]

- The orange curve is the solution without bumper (equation (1) with Christiansen parameters).
- The blue curve with the diamond shapes is for a perfectly sized bumper for velocity particles below 3km/s (equation (2) with Christiansen parameters).
- The green curve is for a perfectly sized bumper for velocity particles under 7km/s (equation (2) with Christiansen parameters).
- The blue curve is for the undersized bumper for velocity particles under 7km/s (equation (10)).
- The two other curves are the interpolation between the two velocity regime.
- The blue dots represent the no-perforation of the aluminium plate, the green diamond shapes represent the perforation of the aluminium plate.

CONCLUSION

This paper described the Systema-Debris MMOD risk analysis process. Debris has been used to reduce MMOD risk of many spacecraft including JUCE, ERO or SOLO.

Systema-Debris can provide spacecraft MMOD risk for a wide variety of Ballistics Limit Equation and space environments due to their standardization. Debris has many analysis capabilities including the type of threat like meteoroids or orbital debris, type of analysis results like impact or penetration, type of spacecraft orientation, exposure time period, and several features to support data visualization. Systema-Debris had also capabilities to model undersized bumpers like MLI.

3.1 References

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