Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01)

METEOROID AND DEBRIS IMPACTS ON ORBITING STRUCTURES: A METHODOLOGY

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ABSTRACT

Alenia is currently involved in a number of long-term space projects (Columbus APM, MPLM, ACRV) as part of the European / Italian participation in the Space Station Freedom. A methodology for the analysis of potential damage caused by M/D impacts for these projects is currently under development. This methodology, together with some examples of the tasks to be performed, is discussed in the present paper. A particularly significant task, hazard analysis and the related identification of thresholds for damage occurrence are investigated, including a detailed evaluation of fast module decompression. The development of empirical equations to predict damage created by M/D impacts is supported by a database containing hypervelocity test data. Damage formulae and software to predict the hole diameter in a thin plate, the ballistic limit and the hole diameter in a 2,3-plate structure are examined. Finally, results obtained for the APM and MPLM projects are summarized.

ACRONYMS AND SYMBOLS

ACRV	Assured Crew Return Vehicle
APM	Attached Pressurized Module
BW	Back-up Wall
DBS	Double Bumper Shield
M/D	Micrometeoroids and Debris
MDPS	Meteoroids and Debris Protection System
MPLM	Mini Pressurized Logistic Module
SBS	Single Bumper Shield

c = velocity of sound in the target material, [km/s]
d = projectile diameter, [cm]
hd = hole diameter in the target, [cm]
m = projectile mass, [g]
sp = spacing between bumper and back-up wall, [cm]
ts = bumper shield thickness, [cm]
tbt = target thickness to avoid perforation, [cm]
v = projectile velocity, [km/s]
ρ_p = projectile density, [g/cm^3]
ρ_t = target density, [g/cm^3]
σ_1 = target 0.2% yield strength, [N/mm^2]
σ_2 = reference 0.2% yield strength (Al 7075-T6), [N/mm^2]
γ_s = spray angle, [rad]

1. M/D ANALYSIS LOGICAL FLOW

Ambitious space programs initiated in recent years, employing large and permanently manned orbiting structures, have to face the problems related to the tremendous increase in the orbital debris population over the last decade.

In the past, the analysis of the potential meteoroid and debris (M/D) induced damage was frequently based on simplified assumptions. Unfortunately, due to the greatly increased risk of impact, the past approach is no longer valid. System engineers now have to deal with various topics in an increasingly more detailed and complex way. Such topics include: the mathematical models for the M/D environment, the analysis of M/D related safety requirements and the relevant risk assessment, spacecraft structure and configuration, mission profiles, hypervelocity impact physics, etc.. The flowchart in Fig. 1 (following page) shows the logical flow of the tasks to be performed in the frame of the M/D damage analysis. These tasks not only have to be analysed thoroughly, they also have to be evaluated together to take into account their mutual interaction. Sections 2 through 6 of this paper address specific aspects of the M/D analysis.

2. HAZARD ANALYSIS

A M/D hazard analysis is based on several correlated steps which involve the requirements and the study of M/D induced phenomena. The preliminary configuration of a spacecraft has to be carefully investigated to obtain a screening of the items that, if impacted, can be the origin of severe damage propagation.

For each selected item, the M/D induced failure modes have to be defined; for instance, the loss of the integrity of the pressure wall or the loss of the functional capabilities of many items. A matrix such as the one reported in Table 1 (following pages), is used to relate each critical item to the relevant failure modes, to the protection methods proposed (i.e., the techniques to mitigate the occurrence of damage or the damage propagation), and to the applicable M/D requirements (i.e., the numerical probability for the occurrence of the unwanted event). Note that every item can be associated to several protection methods and several failure modes.

An example of a failure mode is external coating degradation, that is particularly interesting because the degradation is caused by the synergistic effect of M/D and other components of the natural space environment. As far as the potential damage to the pressurised hull is concerned, several failure levels are identified: i.e. surface craterisation, leakage, burst, etc.. The various corresponding hazards are related to different required probabilities (for instance, 0.995 over 1 year for no-leakage, 0.995 over 10 years for no-burst).

Once the critical items have been mapped with respect to the applicable protection methods, failure modes and probability values, a further step must be taken to realise a precise and quantitative description of the failure mode, i.e., the threshold for the occurrence of the unwanted failure is defined.

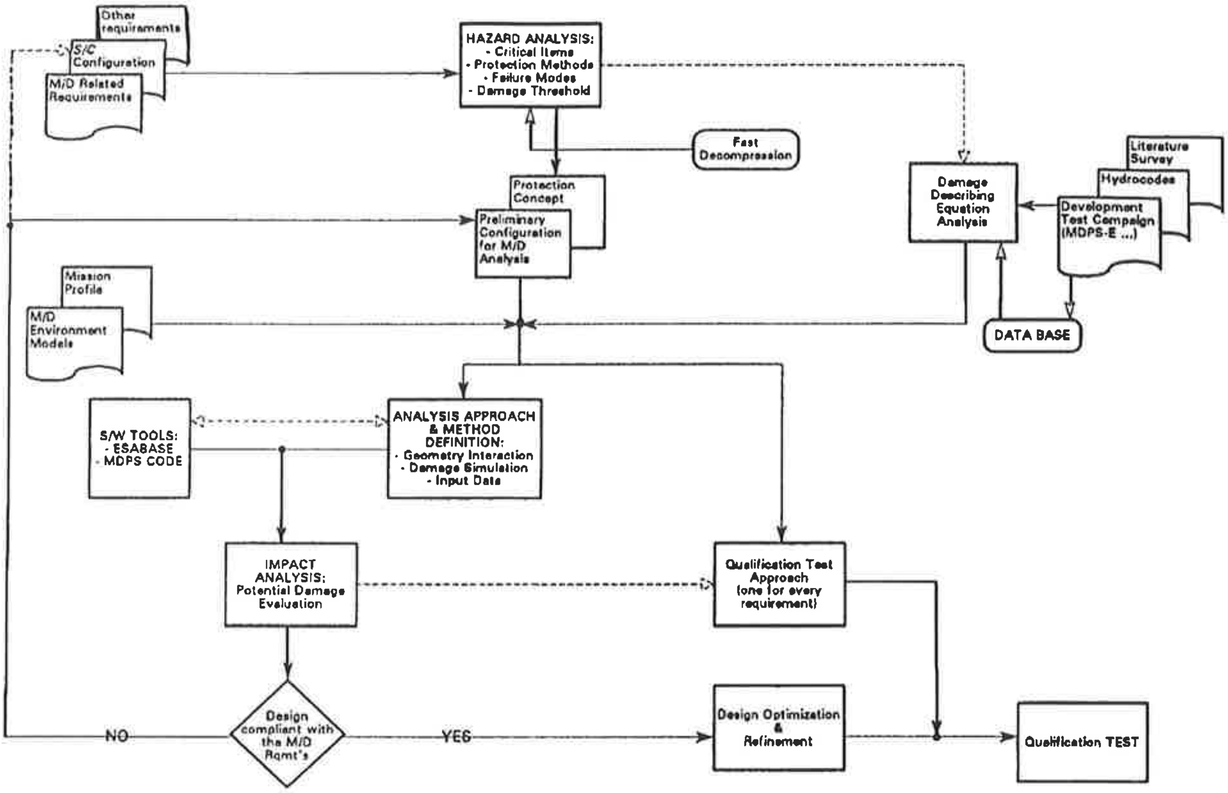


Fig. 1 - M/D analysis logical flow

Table 2 (following pages) gives an example of this exercise. The identification of a damage threshold can be rather complex and may require a prolonged and detailed analysis. An example is the determination of the hole dimensions that cause a pressure decrease, thus endangering crew survivability.

Note that the damage threshold list is still preliminary. Thermal and structural analyses are necessary to understand better the threshold causing thermal coating degradation or propulsive venting. Other damage thresholds must be completely reviewed, for example a module burst or a CO_2 tank explosion as soon as significant experimental results become available.

3. EXAMPLE OF A DAMAGE THRESHOLD: A FAST MODULE DECOMPRESSION

A M/D impact may produce a large hole in a module (like the APM) causing a rapid depressurisation that endangers crew survivability. Hence, the maximum hole size that the crew can tolerate, either in terms of minimum pressure or maximum depressurisation rate sustainable by human beings, must be determined (Ref. 3).

Medical criteria

From a literature survey (Refs. 4 and 5), the following mechanisms of injury to man due to a fast decompression are identified:

- Reduction of total pressure
  The minimum level that can be sustained by human beings (if not reached very slowly and with intermediate pauses) is: 515 hPa.
  The maximum pressure decrease in one step (and in a short time) that affects the crew capability to escape from the module (i.e. causes severe pain, eardrum rupture, dizziness, etc.) is: 300 hPa.
- Depressurisation rate
  The maximum depressurisation rate that exceeds the capability of the lungs to absorb the internal expansion of the air volume is: 11.6 hPa/s.
- O_2 partial pressure
  The minimum value of the O_2 partial pressure that can be sustained by the crew without hypoxia is: 142 hPa. This value corresponds to a total pressure of approximately 700 hPa.

Depressurisation scenario

To determine the depressurisation scenario, the following assumptions on the APM and crew conditions at the instant of perforation are selected:

- Crew-in time
  The APM is assumed to be permanently manned. The presence of the crew inside the module while a perforation occurs (i.e., the conditional probability for the crew presence) can be inserted later in the hazard analysis.
- Emergency procedure
  Following a penetration, the crew is assumed to escape from the module immediately. The maximum time necessary to escape (given as a requirement for the APM project, Ref. 6) has been assumed to be 120 seconds.
- Total volume of air available
  The total volume of air available has been treated as a parameter in the analysis. However, the reference scenario considered is characterised by an open hatch, connecting the APM to the adjacent resource node, and a closed hatch, connecting the resource node to the other elements of the space station. This assumption leads to a total internal air volume of 192 cubic meters. The space station is considered to be at nominal pressure (i.e., 1027 hPa).

	ITEMS	PROTECTION METHODS	FAILURE MODES	M/D RELATED REQUIREMENTS
UNPRESSURIZED STRUCTURAL ITEMS	MDPS	/	A1: Superficial degradation of Bumper Shield	#7 : NO LOSS OR MAJOR DEGRADATION OF OP. CAP. (0.995 / 1 YEAR)
			A2: Mechanical degradation of the MDPS panels	#7 : NO LOSS OR MAJOR DEGRADATION OF OP. CAP. (0.995 / 1 YEAR)
	MLI	- MDPS/Upgrading	A3: MLI thermal properties degradation	#7 : NO LOSS OR MAJOR DEGRADATION OF OP. CAP. (0.995 / 1 YEAR)
PRESSURIZED STRUCTURAL ITEMS	SHELL	- MDPS/Upgrading	B1: Back-Up Wall superficial damage	/
			B2: Fragments Hazard	#2 : NO FAILURE ENDANGERING CREW OR APM SURVIVABILITY (0.995 / 10 YEARS)
			B3: Leakage	#3 : NO PENETRATION (0.995 / 1 YEAR)
			B4: Fracture formation	#2 : NO FAILURE ENDANGERING CREW OR APM SURVIVABILITY (0.995 / 10 YEARS)
			B5: Fast Decompression	#2 : NO FAILURE ENDANGERING CREW OR APM SURVIVABILITY (0.995 / 10 YEARS)
			B6: Propulsive Venting	#2 : NO FAILURE ENDANGERING CREW OR APM SURVIVABILITY (0.995 / 10 YEARS)
			B7: Module Burst	#4: NO BURST
EXTERNAL EQUIPMENT	FITTINGS	- MDPS/Upgrading - Dedicated Protection	C1: Fittings Degradation	#7 : NO LOSS OR MAJOR DEGRADATION OF OP. CAP. (0.995 / 1 YEAR)
	MGF & PDGF	- Dedicated Protection	C2: MGF/PDGF Deformation	#7 : NO LOSS OR MAJOR DEGRADATION OF OP. CAP. (0.995 / 1 YEAR)
	HATCH / VIEWPORT	/	C3: Hatch plate/glass rupture	#3 : NO PENETRATION (0.995 / 1 YEAR)
	HX & Water loop	- MDPS/Upgrading -Redundant	C4: Heat Exch. & Water Loop	#7 : NO LOSS OR MAJOR DEGRADATION OF OP. CAP. (0.995 / 1 YEAR)
INTERNAL EQUIPMENT	CO2 TANKS	- MDPS/Upgrading - Available Structural Items -Redundant	D1: CO2 Tanks Explosion	#2 : NO FAILURE ENDANGERING CREW OR APM SURVIVABILITY (0.995 / 10 YEARS)
	CHX	- MDPS/Upgrading - Available Structural Items -Redundant	D2 : Condensate Heat Exchanger failure	#2 NO FAILURE ENDANGERING CREW OR APM SURVIVABILITY (0 995 / 10 YEARS)
	ACTIVE WATER LOOP	- MDPS/Upgrading - Available Structural Items -Redundant	D3: Water Loop leakage	#2 NO FAILURE ENDANGERING CREW OR APM SURVIVABILITY (0.995 / 10 YEARS)
	P/D HARNESS	- MDPS/Upgrading - Available Structural Items -Redundant	D4: Power & Data Harness damage	#2 : NO FAILURE ENDANGERING CREW OR APM SURVIVABILITY (0 995 / 10 YEARS)

Table 1 - Potential failure modes matrix (Columbus APM)

FAILURE MODE	DAMAGE THRESHOLD (Preliminary)	PROBABILITY REQUIREMENT	RATIONALE
A1: Surface degradation of MDPS	- Overall Craterized Area larger than 20% of the total surface (O.E.)	0.995 / 1 year	# See Ref. 1 #300 F=150 C Aluminium begin to loose its temper
A2: Mechanical degradation of MDPS panels	- Craterized Area affecting Penetration Probability during APM life-time (O.E.)	0.995 / 1 year	# See Ref. 2
A3: MLI Thermal properties degradation	- MLI Area disrupted (shell perforated) larger than TBD m^2 (O.E.)	0.995 / 1 year	# Temperature inside below Dew Point
B1: Shell Surface Damage	- Crater beyond the leakage threshold, i.e. maximum depth 80% of the total thickness (L.E.)		# Ten pressurization/depressurization cycles do not lead to leakage
B2: Fragments Hazard	- Perforation or Spallation of APM shell in non-shielded aisle zones (O.E.)	0.995 / 10 years	# Each fragment impact on crew leads to its loss
B3: Leakage	- Crater Depth larger than 85% of Shell thickness (L.E.)	0.995 / 1 year	# The remaining 15% of material does not maintain the initial characteristics
B4: Fracture Formation	- Cone crater depth/diameter = 0.8/380 mm - Cylinder crater depth/diameter = 0.83/394 mm (L.E.)	0.995 / 1 year	# Ten pressurization/depressurization cycles lead to burst
B5: Fast Decompression	- Hole diameter > 69 mm (L.E.)	0.995 / 10 years	# Crew inside lethal risk # See Ref. 3
B6: Propulsive Venting	- Hole diameter > 69 mm (L.E.)	0.995 / 10 years	# force exerted by air flow about 380 N
B7: Burst under M/D impact	- Cylinder Hole diameter > 52 mm - Cone Hole diameter > 45 mm (L.E.)	0.995 / 10 years	# Through crack computed as 1/3-1/2 of quasistatic crack size
C1: Fittings degradation	- Overall craterized area (O.E.)	0.995 / 1 year	# Superficial degradation affects fittings I/F with NSTS
C2: MGF/PDGF deformation	- Number of impacts causing craters more than 2 mm deep (O.E.)	0.995 / 1 year	# 2 mm deep craters perforate the GF plate
C3: Hatch plate rupture	- Hatch wall perforation during transfer operations (docking-berthing) (L.E.)	0.995 / 1 year (limited period)	# APM depressurized before docking/berthing
C4: IHX & Water Loop damage	- Perforation of the MDPS in the IHX Water Tubes allocation zones (L.E.)	0.995 / 1 year	# Dangerous leack of water # Uncontrollable hazard propagation # Critical repair
D1: CO2 Tanks explosion	- Perforation of the APM Shell in the Tanks allocation zones (L.E.)	0.995 / 10 years	# Any impact on pressurized tanks must be avoided due to the high differential pressure
D2: CHX Failure	- Perforation of the APM Shell + Rack back panel in the CHX allocation zone (L.E.)	0.995 / 10 years	# Dangerous leack of water # Uncontrollable hazard propagation # Critical repair
D3: Water Loop leakage	- Perforation of the APM Shell in the Water tubes allocation zone (L.E.)	0.995 / 10 years	# Dangerous leack of water # Uncontrollable hazard propagation # Critical repair
D4: Power /Data Harness damage	- Perforation of the APM Shell in the Harness allocation zone (L.E.)	0.995 / 10 years	# Uncontrollable hazard propagation

Table 2 - Damage threshold list (Columbus APM)

SELECTED CRITERIA	HOLE DIAMETER [mm]				
	ADIABATIC K=1.4	K=1.3	K=1.2	K=1.1	ISOTHERMAL K=1
Total Pressure Drop	69	71	74	77	80
Depressurization Rate	128	133	139	145	152

Table 3 - Hole diameter versus selected medical criterion and gas coefficient (Internal volume = 192 m^3)

Thermodynamic model

The following assumptions have been made for the behaviour of the air flowing through a hole from a closed volume to the external space environment:

- The expansion of the air that is blowing out of the closed volume is adiabatic.
- The air that remains inside the enclosed volume is treated in a parametric way (the ratio of specific heats varies from 1, isothermal expansion, to 1.4, adiabatic expansion).
- The mass flow rate is corrected by a discharge coefficient *cd* to account for the loss of energy and the contraction of the streamtube section outside the hole (*vena contracta* phenomenon). The value of *cd* has been assumed to be 0.6.

Results

The analysis of a module (APM) fast decompression produced the following results:

* The worst case air loss from inside the module corresponds to an adiabatic expansion (Tables 3 and 4).
* The first medical criterion to be violated is the pressure drop of 300 hPa in 120 s (Table 3).
* The minimum hole diameter endangering the crew survivability is 69 mm (for the APM plus node scenario, Table 3).
* The minimum hole diameter causing a delta pressure of 300 hPa in 120 s as a function of the volume of air available is given in Table 4.
* The evolution of the internal pressure for several volumes of air available assuming a hole diameter of 69 mm is shown in Figure 2 (following page).

4. DAMAGE DESCRIBING EQUATIONS AND DATABASE

Following the identification of a damage threshold, the relationship must be established between the characteristics of the impacting particle (i.e. the mass, velocity, density, etc. of the meteoroid/debris) and the characteristics of the impacted item (configuration, materials, thickness, density, etc.). This means determing a damage describing equation suitable for the damage threshold of interest. Note that the state-of-the-art knowledge does not presently provide a well-suited set of damage equations for every occurrence.

The accuracy of a damage describing equation is very important to determine with some precision the critical damage occurrence. Even a small uncertainty in the predicted value of the projectile critical diameter may imply a rather large uncertainty in the number of damaging impacts (that is, in the probability value).

The activities performed by Alenia in the field of damage formulae are the following.

- Select, from literature survey, the damage equations which are as suitable as possible for the configuration to be investigated.
- Modify and verify the selected formulae against a set of data obtained from hypervelocity impact tests for a configuration similar to the baseline design configuration.

When no formulae are available, new formulae have been derived from analysis of experimental data.

To support the analysis of damage describing equations, a database has been created that collects data from hypervelocity experiments. Originally, the database was developed for the data coming from the ESA funded MDPS-E study (Ref. 7).

SCENARIO	VOLUME [m ^ 3]	DIAMETER [mm]	
		ADIABATIC	ISOTHERMAL
a)	142	60	70
b)	192	69	80
c)	277	83	97
d)	522	114	134

Table 4 - Hole diameter sensitivity with respect to internal volume

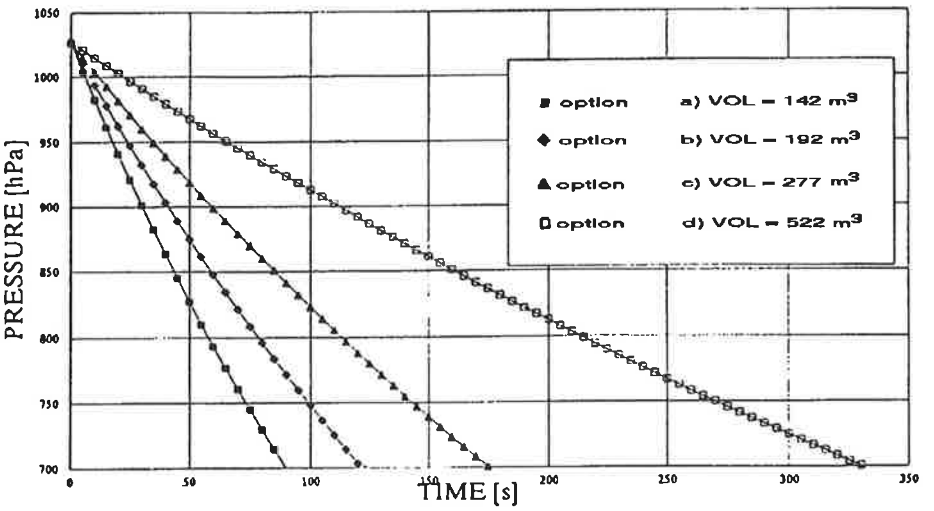


Fig. 2 - Internal pressure as a function of time (hole diameter = 69 mm)

More than 100 shots have been performed against Columbus APM-like configurations. For every shot, parameters for the impacting particle, the impacted target configuration and the damage produced have been inserted in the database.

The software used for the database implementation is Microsoft Excell. Using Excell macro instructions, data is easily updated and transferred to the mathematical package Mathcad, that also runs under the Windows environment.

The parameters of the experiments evaluated have been divided into test parameters and damage evaluation parameters. For the classification of the damage on the back wall, the standard proposed by Cour-Palais and Dahl (Ref. 8) has been used.

Hypervelocity shots are rather expensive, however despite the fact that several hundred experiments have been performed worldwide, data from different sources has seldom been compared. The database aims to collect data from different test campaigns and to provide a basis for their comparison and for their statistical consistency. For the time being, some data available from other sources (Ref. 9) have been inserted in the database. From a preliminary analysis, the ESA and the NASA results do not appear to be statistically comparable. Moreover, it seems that shots with similar parameters cause different degrees of damage.

5. DAMAGE DESCRIBING EQUATIONS ANALYSIS

Three damage equations will be discussed in detail: the first one is to predict the hole diameter in a thin plate. The second and the third equations are to predict the ballistic limit and the hole diameter in the BW of a 2,3-plate structure.

5.1 Hole in a thin plate

Although the data collected in the database is not well-suited to analysis of impacts on a single plate, some comparisons of the experimental data with formulae predicting the hole diameter in a thin plate have been performed. Two formulae have been considered:

General Motors formula (GM) (Ref. 10)

$$hd = d \cdot \left[0.45 \cdot \left(\frac{ts}{d} \right)^{\frac{2}{3}} \cdot v + 0.9 \right] \tag{1}$$

Sawle formula (Ref. 11)

$$hd = d \cdot \left[3.2 \cdot \left(\frac{ts}{d} \right)^{\frac{2}{3}} \cdot \left(\frac{v}{c} \cdot \frac{\rho_p}{\rho_t} \right)^{0.2} + 1.0 \right] \tag{2}$$

Normal impacts

A comparison has been performed with data from the MDPS-E study for:

- Velocities: from about 3 to 8.5 km/s
- Diameters : from 2 to 10 mm
- Projectile densities : 2.7 and 4.5 g/cm^3
- Bumper Shield thicknesses : 0.8 mm and 1.6 mm

In the experimental region, the GM formula Eq. 1 exhibits the correct (linear) growth with the velocity, while the Sawle formula Eq. 2 is erroneously almost flat with the velocity. The values predicted by Eq. 1 are always lower and generally closer to the experimental points (standard deviation between 0.07 and 0.08 cm, for the cases compared) than the value predicted by the Sawle formula (standard deviation between 0.18 and 0.21 cm). Fig. 3 (following page) shows a sample of the comparison between empirical values and experimental points for Eq. 1. From the few shots with titanium projectiles, it seems that the hole does not depend on the density. Eq. 1 fits the experimental data, while Eq. 2 departs even more. However, Eq. 2 is used to limit the increase of Eq. 1 predictions for very high velocities and large diameters.

Oblique impacts

The formulae have been compared with data produced by oblique impacts for:

- Velocities : from about 3 to 7 km/s
- Diameters : from 5 to 8 mm
- Projectile density : 2.7 g/cm^3
- Bumper Shield thickness : 0.8 mm
- Angles of impact : from 30 to 75 degrees

For oblique impacts, the hole produced is elliptical rather than circular, and the maximum and the minimum diameters have been investigated. An inverse cosine factor has been introduced in the empirical formulae to fit the experimental points concerning the major hole diameter.

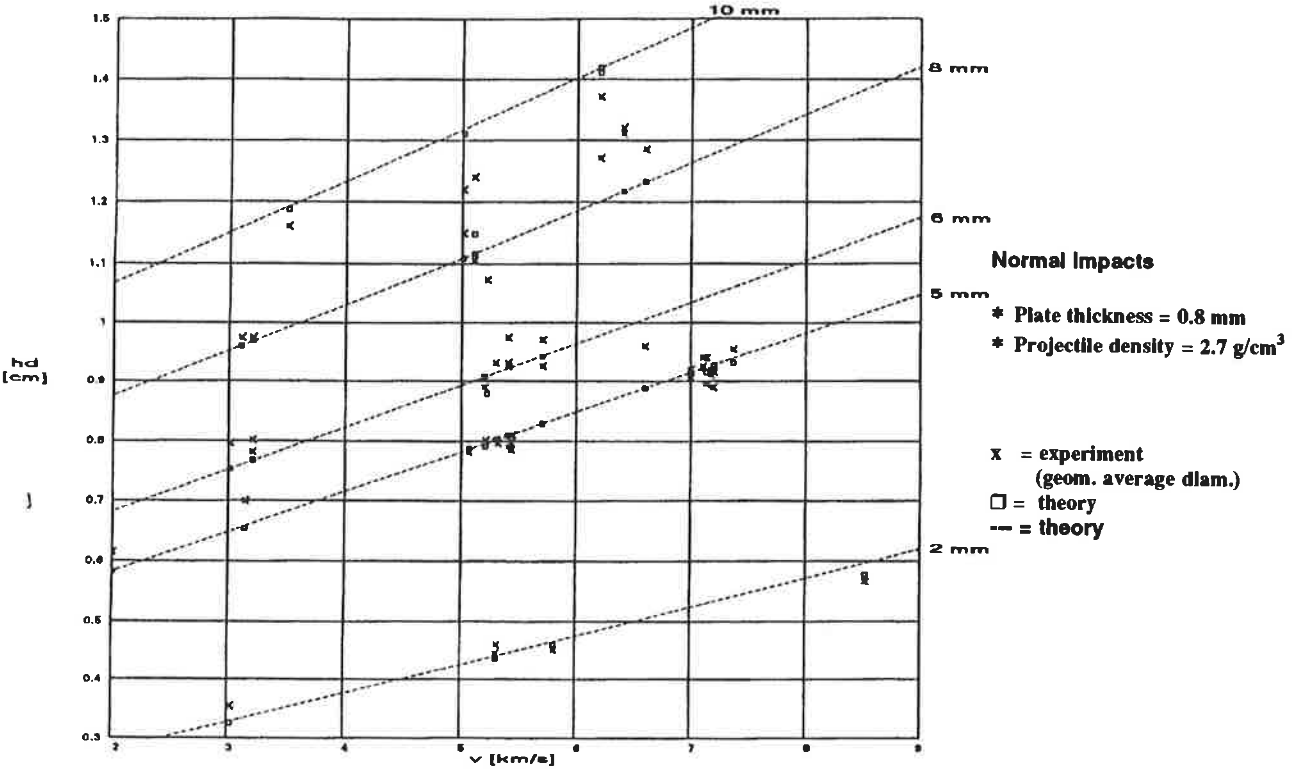


Fig. 3 - Hole diameter versus velocity, GM formula

The GM formula, Eq. 1, still performs better than the Sawle formula. In particular, the linear growth with the velocity is confirmed. The agreement is rather good, except for a few points for highly oblique impacts (60 and 75 degrees) that show large experimental scattering. The minimum hole diameter (i.e., along the direction perpendicular to the flight path) is always larger than the hole diameter obtained for normal impacts with similar experimental conditions. The disagreement between theory and experiment increases with higher angles of impact. A possible explanation is that oblique impacts not only affect the longitudinal dimension of the hole, but in some way also its size along the normal direction. The insertion in the empirical equations of an inverse square root cosine factor increases the fit between theory and experiments.

5.2 Ballistic limit of the BW of a 2,3-plate structure

One of the purposes of the MDPS-E test campaign was to compare the performance of a double plate structure versus the performance of a triple wall configuration.
MDPS-E Study data are compared with several formulae:

- Formula currently used at Alenia (Ref. 12)
  - * Low Velocity :

$$tbt = 0.75 \cdot \left[1.8 \cdot d^{\frac{19}{18}} \cdot \left(\frac{\rho_p}{\rho_t}\right)^{0.5} \cdot \left(\frac{v}{c}\right)^{\frac{2}{3}} - ts \right] \qquad (3)$$

  - * High Velocity :

$$tbt = 8.2 \cdot \frac{m \cdot v}{sp^2} \cdot \sqrt{\frac{\sigma_1}{\sigma_2}} \qquad (4)$$

  - * Intermediate Region : Linear interpolation between low and high velocity formulae.

- ESA/ESTEC Formula (Ref. 13)
  - * Low Velocity :

$$tbt = 0.78 \cdot (0.42 \cdot m^{0.352} \cdot \rho_p^{0.167} \cdot v^{0.667} - ts) \qquad (5)$$

  - * High Velocity :

$$tbt = 0.165 \cdot d^{0.5} \left(\frac{\rho_p}{\rho_t}\right)^{0.167} m^{0.87} \frac{v}{\sqrt{sp}} \cdot \sqrt{\frac{\sigma_1}{\sigma_2}} \qquad (6)$$

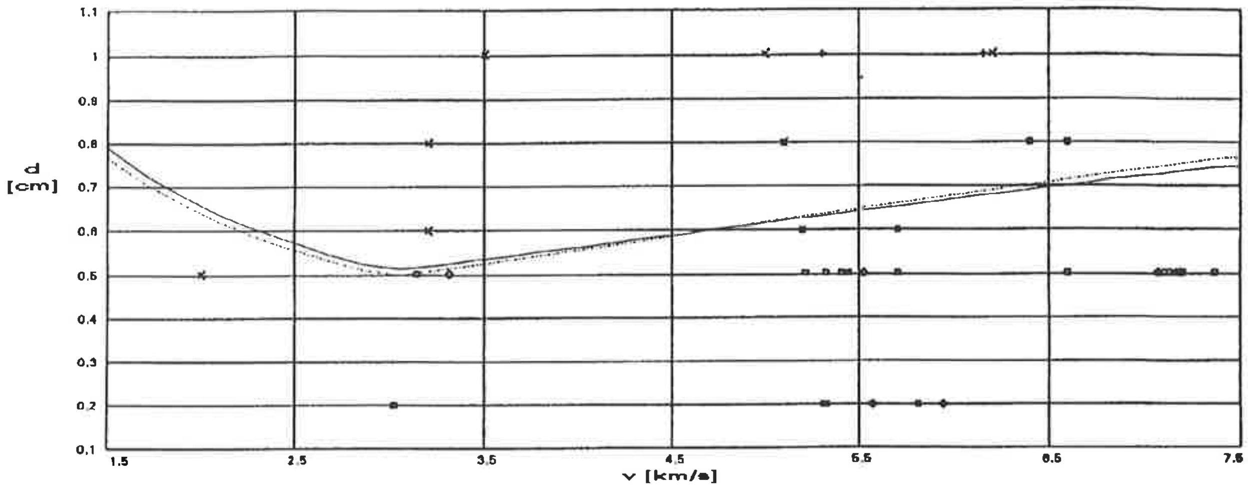
  - * Intermediate Region : Linear interpolation between low and high velocity formulae.

- Two different formulae (one for 2-plate and one for 3-plate structures) are suggested by the Final Report of the MDPS-E study (Ref. 7).

Normal impacts

A comparison has been performed for:
* Velocities: from about 2 to 8.5 km/s
* Diameters: from 2 to 10 mm
* Projectile densities : 2.7 and 4.5 g/cm^3
* Back-up Wall thickness : 3.2 mm
* Two Bumper Shield configurations:
single (SBS) ts = 1.6 mm, spacing = 12 cm
double (DBS) ts = 0.8 + 0.8 mm, spacing = 6 + 6 cm

The formulae Eqs. 3, 4 and Eqs. 5, 6 predict on-set of perforation. The back-up wall is not necessarily airtight after a non-perforating impact (Fig. 4, following page). MDPS-E formulae (Ref. 7) predict no-leakage occurrence and are hence more conservative at low velocities. Moreover, the 3-plate equation gives a larger critical diameter than the 2-plate formula, at low velocities (Fig. 5, following page).



x : experiment, DBS (perforation)
□ : experiment, DBS (crater depth < 3.0 mm)
+ : experiment, SBS (perforation)
✧ : experiment, SBS (crater depth < 3.0 mm)
— : theory, Eqs 3 and 4
··· : theory, Eqs 5 and 6

Fig. 4 - Ballistic limit of the back-up wall, Eqs. 3, 4 and Eqs. 5, 6

From the available experimental data, it is not possible to verify the ballistic limit formulae in the high velocity region.

From the analysis of the experimental data, the SBS configuration seems to perform slightly better at low velocities, (i.e., shots #2216 SBS: very tiny crack; #2193 DBS: well-formed crack).

The DBS configuration performs better at medium-high velocities (i.e., shot #7324 DBS: no perforation; #7373 SBS: perforation). Targets with waffle pattern (i.e., shots #7366 / #7368 / #7372) show fewer deep craters.

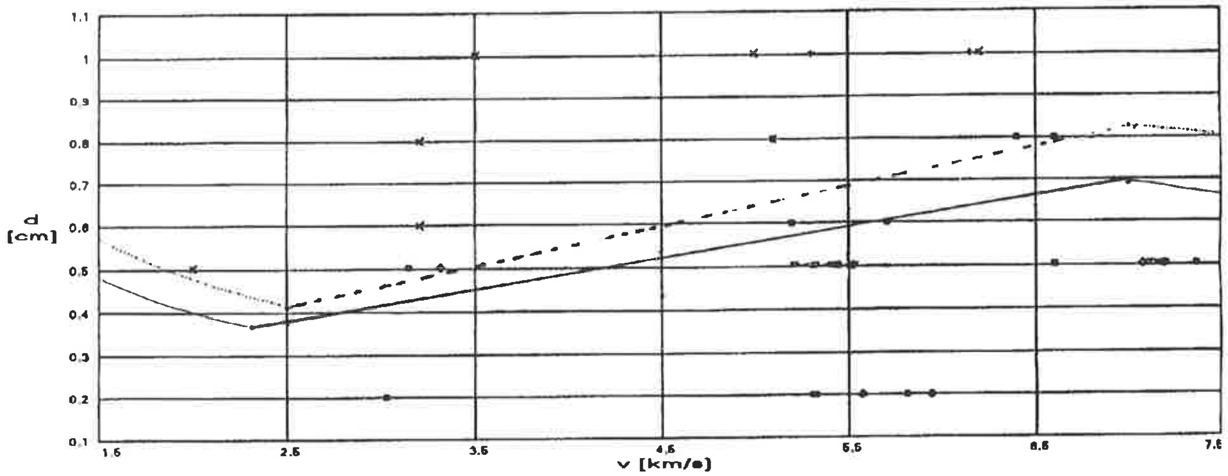
NASA experimental data for 2-plate structures

Data from NASA (Ref. 9) has been inserted in the database for comparison with ESA data and empirical formulae.

The NASA data selected are characterised by the following parameters:

- Velocities: from about 2 to 7 km/s
- Diameters: from about 3 to 9 mm
- Projectile density: 2.7 g/cm^3
- Back-up Wall thickness: 3.2 mm
- Bumper Shield thickness: 1.6 mm
- Spacings: 10 and 15 cm
- Normal impacts

From a comparison with ESA data for spacing of 12 cm (Fig.6, following page), the NASA experimental results seem to be similar or even more severe for a spacing of 15 cm (while it should be the opposite) over the complete experimental range. We are not presently able to explain this discrepancy.



x : experiment, DBS (perforation)
□ : experiment, DBS (crater depth < 3.0 mm)
+ : experiment, SBS (perforation)
✧ : experiment, SBS (crater depth < 3.0 mm)
··· : theory, 3-plate formula
— : theory, 2-plate formula

Fig. 5 - Ballistic limit of the back-up wall, formulae from Ref. 7

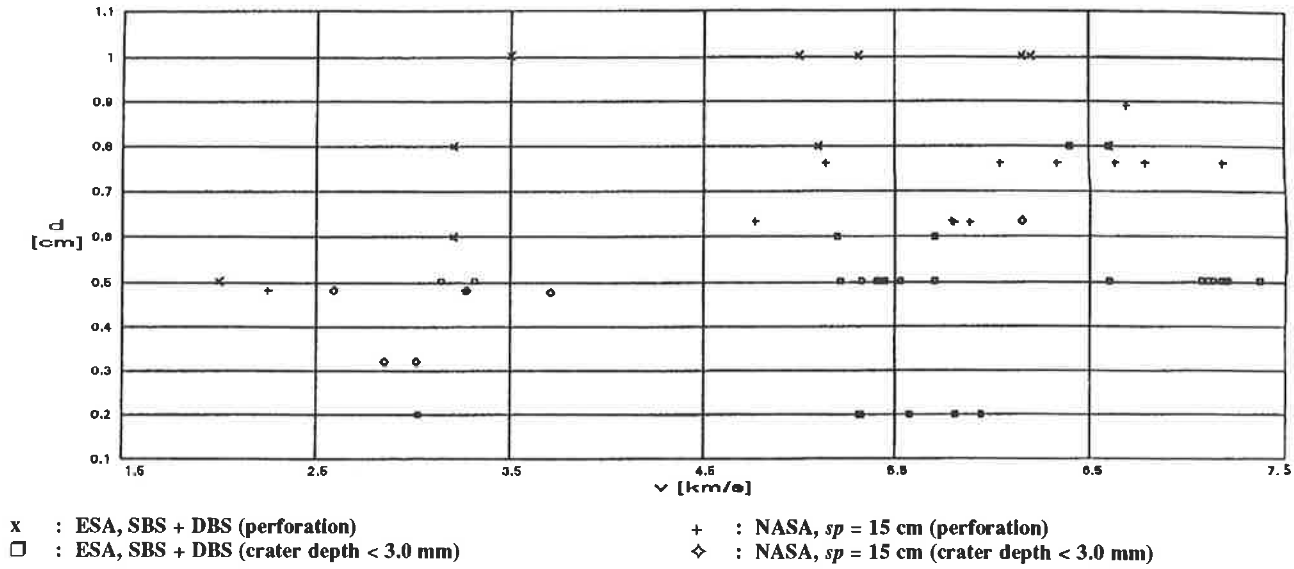


Fig. 6 - Comparison of NASA and ESA data

5.3 Hole diameter in the BW of a 2,3-plate structure

Empirical equations are necessary to predict the hole size in the module pressure wall. The task is made difficult because the holes in the back wall exhibit manifold patterns (from cookie cut holes to petalled holes). For intermediate velocities, the behaviour of the experimental points is similar to that of the *excess of perforation* (i.e., *tbt* - *tb*, where *tbt* is the wall thickness to avoid perforation, given by the ballistic limit equation and *tb* is the actual wall thickness).
Two basic formulae have been analysed:

- Two-step equation (Ref. 12):

$$hd = \begin{cases} 2.5 \cdot d & v < 4 \text{ km/s} \\ A \cdot (tbt - tb)^B & v \geq 4 \text{ km/s} \end{cases} \tag{7}$$

The coefficients $A = 3.0$ and $B = 1.4$ have been obtained through a best fit routine with the experimental data.

- Equation based on the spray angle formula (Ref. 14):

$$\gamma_s = 0.28 \cdot \left(\frac{\rho_t}{\rho_p}\right)^{0.667} \cdot \left(\frac{ts}{d}\right)^{0.25} \cdot \left(\frac{v}{c}\right)^{0.667} \tag{8}$$

Normal impacts

A comparison has been performed with data (from Ref. 7) with:

- Velocities: from about 3 to 7 km/s
- Diameters: from 5 to 10 mm
- Projectile densities: 2.7 and 4.5 g/cm^3
- Back-up Wall thickness: 3.2 mm
- Two Bumper Shield configurations:
  single (SBS) *ts* = 1.6 mm, spacing = 12 cm
  double (DBS) *ts* = 0.8 + 0.8 mm, spacing = 6 + 6 cm

Due to the elliptical shape of the hole produced, the geometric average between major and minor diameters is used. The lack of experimental points, require that the SBS and DBS configuration data be considered together. The spray angle formula Eq. 8 exhibits an incorrect increase with the velocity, while the two-step formula Eq. 7 performs better. However, the spray angle formula is used to limit the increase exhibited by the two-step formula for high velocities and large diameters.

Oblique impacts

The few data available for impact angles of 30, 45, 60, 75 degrees, show that the hole diameter decreases noticeably for oblique impacts, at least in the experimental range. To match the experimental data, the following multiplying factors have been inserted in the two-step formula (Fig. 7):

$\cos\alpha$	for $v < 4$ km/s
$\cos^2\alpha$	for $v \geq 4$ km/s

5.4 Remarks

From this brief review of experimental formulae, there still remain some problems concerning the damage formulae to be solved. For instance, equations to predict the ballistic limit or the hole diameter for the BW of a multi-plate structure are inaccurate for oblique angles, large projectiles and high velocities. This is partially due to experimental limitations and cost. Moreover, the accuracy of a damage describing equation is very important to determine with some precision the probability of damage occurrence. Due to the sensitivity of the M/D flux with respect to projectile parameters such as the mass/diameter, conservative assumptions can lead to a severe design configuration mass penalty.

Even more critical is the situation for the formulae to predict a module burst under M/D impact. Such formulae are absolutely missing and, unfortunately, experiments to support their investigation seem to be very complex and expensive.

APM

DAMAGE THRESHOLD	PROBABILITY (per year)	REQUIREMENT (per year)
PERFORATION	0.9977	0.995
FAST DECOMPRESSION (hd > 69 mm)	0.9998	0.9995
UNSTABLE CRACK PROPAGATION (hd > 52 mm)	0.9997	0.9995

MPLM

DAMAGE THRESHOLD	PROBABILITY (15 months)	REQUIREMENT (10 years)
PERFORATION	0.9977	0.995

Table 6 - APM and MPLM results

6. S/W TOOLS AND IMPACT ANALYSIS RESULTS

A S/W tool (named MDPS-Code) has been developed, in house, to support the numerical evaluation of the damage caused by M/D impacts on orbiting structures. This code has limited geometrical capabilities, some numerical approximations and does not have any graphic interface. On the other hand, it is characterised by a high flexibility and the damage describing equations can be modified and inserted as needed.

The ESABASE Debris Tool (recently developed by ESA and Matra, Ref. 15) has powerful geometric and graphic capabilities and will replace the MDPS Code employed at Alenia Spazio. A validation/comparison of ESABASE is on-going: a good agreement with the MDPS-Code results (as far as debris induced damage and simple structures are concerned) has been obtained. An interface between the Alenia damage routine and ESABASE is under evaluation.

Table 6 reports some results obtained for two major projects (Columbus APM and MPLM) as a sample of the damage evaluation process addressed in this paper. These results are affected by the uncertainties and open areas which are still present in the analysis (for instance, the damage thresholds and the damage describing equations). The APM project, characterised by detailed and complex failure scenarios, is more affected by such uncertainties than the MPLM program, for which only the penetration of the pressure wall is considered. The evaluation for the APM has been performed considering only the year 1998, while for the MPLM the reference year is 2006.

7. CONCLUSIONS

A methodology is under development at Alenia to produce a coherent and exhaustive approach to the M/D impact analysis for pressurised modules. This effort permits identification of the critical areas and the establishment of a priority in the problems to be solved. The definition of appropriate M/D induced damage thresholds requires detailed thermal and structural investigations. A hole with a diameter of 69 mm in the APM pressure wall, has been proved to cause a fast decompression, endangering crew survivability.

Accurate damage equations to predict the hole diameter in a thin plate have been verified, while damage formulae for the ballistic limit of a multi-plate structure require further experimental efforts, that have to cope with cost constraints and experimental limits.

Additional activities are still necessary to render the S/W tools available more accurate for design purposes. Uncertainties present in the analysis still allow acceptable predictions for the MPLM project to be obtained, but are too high to guarantee compliance with the M/D requirements for the APM project at the present time.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to Blaine Sessions and Giovanni Sciorati (Alenia Spazio), and Lucia Mancinelli (SIA) for their support in preparing this paper.

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