ESTIMATING THE PNF OF INTERNAL SATELLITE COMPONENTS

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ABSTRACT

As a consequence of the debris environment and its growing severity, the quantification of the risk posed to a satellite and its mission is becoming more desired not only from space agencies but also from satellite manufacturers. This paper looks into the use of ESABASE and how it can be used to assess the probability of no penetration (PNP) of a satellite's internal components, providing a more representative probability of no failure (PNF) of the entire satellite and the actual risk imposed on the mission. This improved modelling and analysis methodology increases the knowledge of which areas are the most vulnerable by considering component failures and not just the number of impacts or perforations of the structure walls. This information can then be used for assessing different mitigation measures, whether it is relocating the component, thickening the component walls or implementing additional shielding.

1 INTRODUCTION

Over the years the consideration of the space debris and meteoroid environments has increased within the design and definition phase of satellites and their mission. Several tools such as ESABASE and BUMPER have been developed to consider various environmental models and ballistic limit equations (BLEs) to access the PNF of a spacecraft.

Currently, most satellite projects do not consider the probability of failure due to debris or meteoroids in the reliability assessment of the spacecraft. With the debris environment becoming more problematic in certain orbits the inclusion of such assessments is becoming more important.

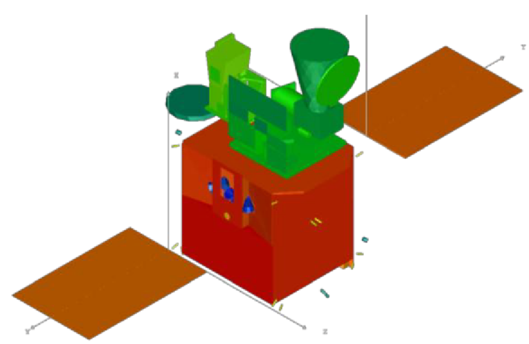
2 METHODOLOGY

The most common way to access the PNF of a spacecraft is to assume that every penetration or spall detachment is a failure. For unmanned spacecraft this leads to conservative estimations of the PNF, which leads to results that are not representative and often mitigation measures that are too demanding to implement. Many improvements have been made with the definition of new BLEs as more hypervelocity impact (HVI) tests are performed, providing more knowledge on how spacecraft and their components react under impact conditions, and ultimately providing more representative results.

Despite improvements in BLEs and environmental models, the existing tools have currently only been used to model the external walls of a satellite. This leads to a PNF that is not realistic because the penetration of a structure wall will not necessarily lead to a satellite failure. As a result, a new method to model the internal components of a satellite has been developed. The following methodology has been developed using ESABASE as an evaluation tool and therefore certain aspects may not be applicable to other impact analysis tools.

2.1 Modelling

To improve the impact analysis results, the internal components of the spacecraft must be modelled and therefore the structural walls must be omitted from the model. Within ESABASE, particles are not propagated once they have made an impact with a surface regardless if the particle penetrates the surface, therefore any object shielding results in an impact flux of zero.



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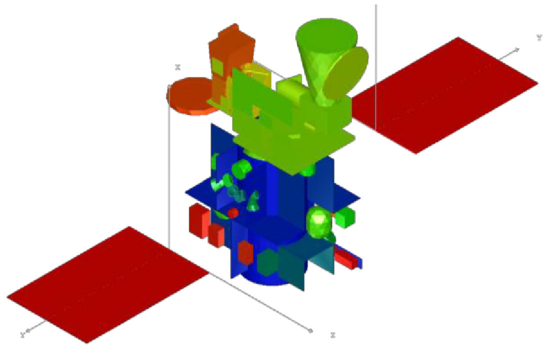

Figure 1: MTG external and internal ESABASE models

In the absence of the structure walls in ESABASE the input parameters of the BLE must be modified such that they represent the component as if the bumper wall (e.g. structure) is there. This can be achieved by adjusting the different spacing and thickness values for each side of the component. This becomes problematic when the component has varying distances to the bumper. This can be overcome by modelling each component as multiple objects in ESABASE. For typical electronic units, each side is modelled as a single object and therefore the appropriate spacing can be implemented. This has a complimentary side affect, which is an improved visibility of the flux direction and its magnitude. This additional information can be extracted from the ESABASE results because each object corresponds to a particular side. This is beneficial because in ESABASE the results for an object are an average of all sides and therefore the side of concern cannot be deduced solely by the PNF or impact results. Normally, the 3D debris results are used to get an indication of which is the most vulnerable side of an object, however there is a loss of precision in this approach. For components which cannot be divided as easily, the shortest distance is taken to ensure more conservative results are obtained.

2.2 BLE Implementation

Despite advances in BLEs, the application of BLEs to internal components remains difficult. Significant progress has been made with the testing campaign used to determine the Schäfer-Ryan-Lambert (SRL) BLE [2] among others, however due to the variations in component material, shape and configurations, only the most common set-ups have been analysed. As the SRL BLE is relatively new, the BLE is not available in ESABASE and therefore it must be manually input or another BLE used.

For this investigation BLEs existing in ESABASE were used. For multi-wall configurations the modified ESA Triple Wall (ETW) BLE [1] was used as it is the basis of the SRL BLE and it is commonly used throughout the industry. Due to restrictions in ESABASE the implementation of this BLE must be done using only single wall spacing. Therefore, depending on how the component wall is oriented with respect to the bumper the following simplifications were made to conservatively align the results with the SRL BLE, for the MTG configurations.

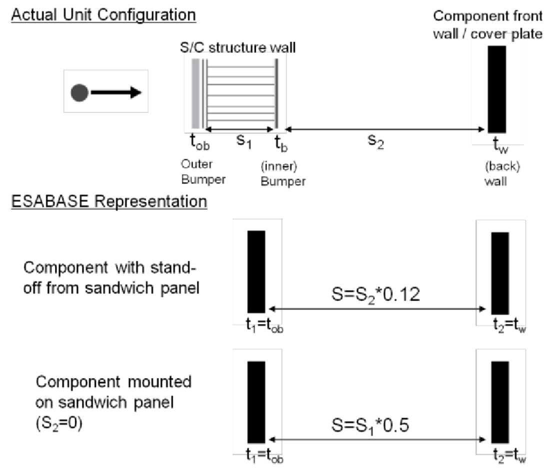

Figure 2: Representation of ESA Triple Wall simplified representation in ESABASE

The representation of the BLE is critical as the definition of a failure, perforation or spall is determined based on the BLE. Therefore, the incorrect representation of the component will result in invalid results. The implemented variations of S, and t_{ob} or t_{w}, have only been compared for the configurations that are seen on MTG. Due to these simplifications, it is seen that the ballistic velocity regime provides slightly more conservative results for the modified ESA Triple Wall represented as a double wall equation. However, as MTG is in GEO and the majority of impacts are in the hypervelocity regime due to meteoroids this is acceptable.

2.3 Lethal Diameter

Another relatively new technique that can be used to increase the knowledge of the results and improve their interpretation was to implement a lethal diameter limit. The lethal diameter represents the particle diameter that will result in a collision with enough energy to cause a satellite failure. A first assumption was made in the P2-ROTECT study that a LEO satellite that is impacted by a 1 cm particle at approximately 12 km/s (average impact velocity in LEO) would have a satellite failure. The corresponding energy-to-mass ratio is 0.05 J/g.

In comparison, it is widely accepted that a particle impact with a ratio of kinetic energy at impact to target mass of 40 J/g will result in the catastrophic breakup of the satellite [4]. The 40 J/g ratio corresponds to an 8.5 cm particle impacting a satellite similar to MTG at 12 km/s and therefore it is safe to assume that an impact with far less energy can cause a satellite failure. For the MTG satellite and orbit the lethal diameter limit was calculated using the 0.05 J/g threshold and was found to be:

- Debris: 1.93 cm
- Meteoroids: 0.76 cm

The application of the lethal diameter was found to be best applied by separating the ESABASE analyses, generating a non-lethal and lethal simulation. Through this, it can be assumed that any perforation in the lethal simulation will result in a satellite failure and those in the non-lethal run can use an additional scaling factor if desired.

3 AN MTG EXAMPLE

Using the methodologies described in Chapter 2, the vulnerability of MTG was assessed. MTG is a meteorological satellite that will operate in a geosynchronous orbit for a lifetime of 8.5 years with an expected launch date in 2019. An additional consideration for the evaluation of the satellite vulnerability is an operational mode change that occurs every 6 months resulting in a spacecraft yaw manoeuvre, changing the side exposed to the velocity direction.

3.1 Input Parameters

The debris and meteoroid environment models used in the ESABASE analysis are detailed below. The values used for impact velocity are slightly conservative with respect to the average impact velocities seen in GEO.

Table 1:Average environment description, GEO

	Debris	Meteoroids
Model	MASTER 2005	Grün
Epoch	May 1st, 2005	May 1st, 2005
Density	4 g/m³	2.5 g/m³
Impact Angle	45 deg	45 deg
Impact Velocity	4 km/s	20 km/s

For the BLEs the internal components were modelled using a multi-wall equation and the external components were modelled using single wall. The multi-wall equations that were used were the Modified ESA Triple Wall equation configured for sandwich panels with aluminium face sheets with an aluminium core and CFRP face sheets with an aluminium core depending on the bumper walls [3]. Comparing the two equations for sandwich panels with a face sheet thickness of 0.4 mm (aluminium equivalent) and a failure criterion of no detached spall, it can be seen that the sandwich panel with CFRP face sheets perform worse.

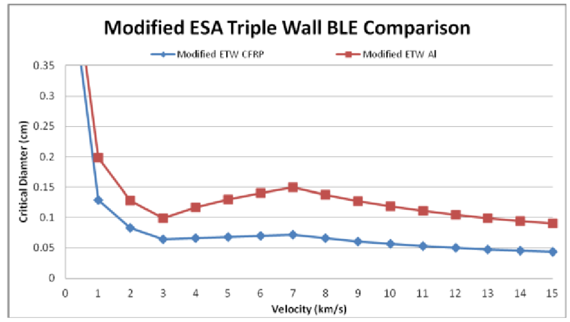

Figure 3: Comparison of Modified ETW BLE for Al and CFRP sandwich panels

Due to the large variation in the critical diameter for CFRP and aluminium sandwich panels, additional analyses are required to model the CFRP sandwich panels with the correct BLE. This can be evaluated on a case by case basis, but as MTG is in a geosynchronous orbit the majority of impacts will occur in the hypervelocity regime where a significant difference is seen between the two BLEs.

3.2 Results

For the MTG analysis to have the best understanding of the results it is best to separate all of the runs. The following chart depicts the different simulations that need to be performed in order to properly access the vulnerability of the satellite. These simulations must be done for both the external and internal model, however for the purpose of this example only the internal simulations were performed.

Table 2: Breakdown of MTG analysis

	Internal Satellite Model			
	Debris		Meteoroids	
Analysis	Al	CFRP	Al	CFRP
Lethal				
Non-lethal				
Full Range	√	√	√	√

In addition, the different operational modes must also be analysed and therefore the analyses identified in Table 2 must be performed with the different satellite orientations (changing RAM face). To demonstrate the method described in this paper, the analysis will focus only on the internal satellite model and the full range of particle sizes. For the analysis the failure criteria used is detached spall and it is assumed that any perforation (spall) corresponds to a failure.

The following images depict the impact flux received by MTG for a given year in a particular orientation.

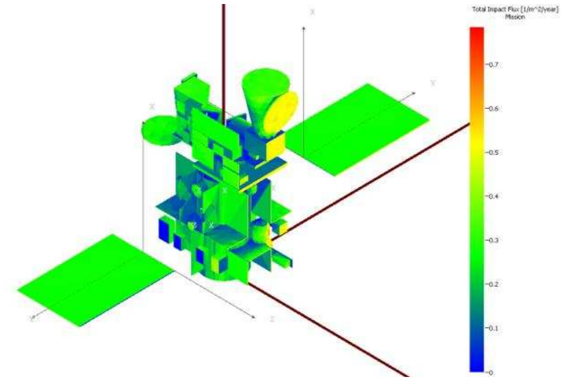

Figure 4:ESABASE2 Impacts/year/m² - Debris (+X)

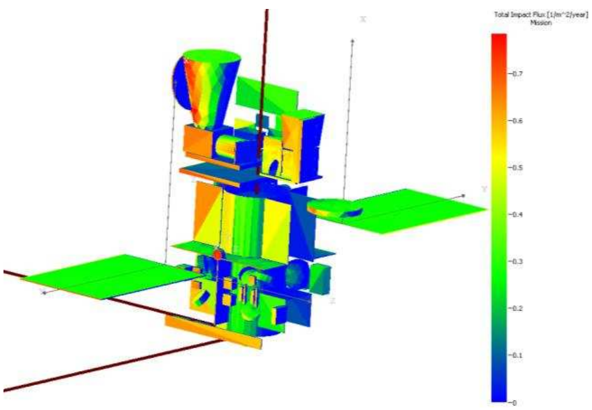

Figure 5:ESABASE2 Impacts/year/m² - Debris (-X)

It can be seen that for the debris environment, the MTG satellite experiences most of the impacts in the +X (RAM) and +Y side. It can also be seen that in comparison to the meteoroid environment, not only is the impact flux significantly smaller but the location of the impacts is more evenly distributed around the satellite when the RAM side is excluded.

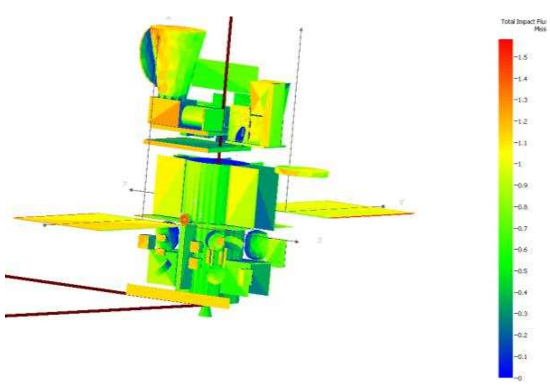

Figure 6:ESABASE2 Impacts/year/m² -Meteoroids (+X)

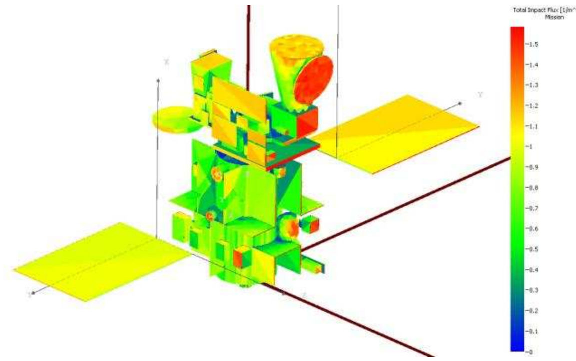

Figure 7: ESABASE2 Impacts/year/m² - Meteoroids (-X)

For the assessment of the debris and meteoroids impacts, the satellite was also assessed in a 180° roll to change the satellite side exposed to the velocity direction.

Based on the evaluation of the different ESABASE analyses the overall satellite result was approximated. The combination of the different runs was done based on the applicable case for the component (Aluminium or CFRP). It can be seen that the model contains some components that are external, however the results of these components will not be investigated.

Table 3: Results of internal components

Component	Impacts / year	No. Failures (/year)	PNF (mission)
AOCS CR A	0.3721	3.806E-06	0.99997
AOCS CR B	0.3497	4.741E-06	0.99996
Gyro e-box	1.3208	1.805E-05	0.99985
STR e-box A	0.7097	1.360E-05	0.99988
STR e-box B	0.8488	1.319E-05	0.99989
APME	1.7632	1.479E-05	0.99987
PCDU	9.4959	8.386E-05	0.99929
SADE	3.8433	4.730E-05	0.99960
SADM North	1.1741	1.142E-02	0.90746
SMU	7.2865	6.073E-05	0.99948
S-band TRX A	0.9258	9.639E-06	0.99992
S-band TRX B	0.9836	8.866E-06	0.99992
WDE e-box	2.6283	2.631E-05	0.99978
Battery A	2.6430	5.487E-05	0.99953
Battery B	4.3160	8.590E-05	0.99927

Component	Impacts / year	No. Failures (/year)	PNF (mission)
DDU	1.7968	1.524E-05	0.99987
RW A	1.3172	4.365E-06	0.99996
RW B	1.6021	5.386E-06	0.99995
RW C	0.9385	6.086E-05	0.99948
RW D	1.4147	6.294E-05	0.99947
RW E	1.0309	3.336E-06	0.99997
SADM South	1.1631	1.133E-02	0.90817
EPC B	0.4326	4.451E-05	0.99962
EPC A	0.4995	4.193E-05	0.99964
K-band Filter A	0.2749	3.283E-06	0.99997
K-band Filter B	0.2751	2.300E-06	0.99998
K-band switch	0.0863	1.941E-06	0.99998
RDM A	0.7569	8.089E-06	0.99993
RDM B	0.8728	7.843E-06	0.99993
TWT 1	0.2611	6.001E-06	0.99995
TWT 2	0.3339	7.920E-06	0.99993
HE-tank A	2.6923	1.645E-04	0.99860
HE-tank B	2.7678	8.902E-05	0.99924
MMH tank	0.4773	2.679E-05	0.99977
MON tank	4.2841	1.651E-04	0.99860

Through this investigation it can be seen that the internal components have a good PNF for MTG. It can also be seen that some components which are not completely shielded by the satellite structure are the most vulnerable as they act as a single wall. This is particularly noticeable for the SADMs.

An overall PNF of the satellite is not provided as all components are not accessed. In particular, the external components have been excluded and as seen with the SADMs, it is more likely that the external components will be critical in accessing the overall satellite PNF.

4 CONCLUSION

Through this paper it has been seen that the internal components of a satellite can be modelled in ESABASE and a confident PNF of the component can be achieved. It has also been shown that the internal components typically have a very good PNF due to the protection of the structure walls, however this is not always the case.

Unlike the internal components the external components are for the most part represented as single walls and therefore are the most critical with respect to the satellite PNF. Despite the external components being the most critical, the analysis of the internal components is still recommended in order to identify if there are any additional vulnerable areas on the satellite.

By modelling the internal components a higher degree of confidence can be achieved in the satellite design with respect to potential failures due to debris and meteoroids. Although this corresponds to additional simulations that must be performed, the detail of the satellite assessment can be evaluated on a case by case basis. To recall, the suggested improvements to MOD analysis are;

- Independent analyses for internal and external components
- Use the SRL BLE for internal components if mounted to structure walls.
- Separation of a component into multiple objects (i.e. represent electronic unit as 6 individual objects – 1 per side)
- Introduction of a lethal diameter, with a kinetic energy at impact to target mass energy ratio of 0.05 J/g.

Through the implementation of these improvements the additional information is gained from the MOD analysis, improving the results and increasing the confidence in the analysis. Ultimately, this can lead to more precise shielding and protection measures, increasing the potential for mass and cost savings.

5 REFERENCES

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4. Johnson, N.L., et al. (2001). NASA's New Breakup Model of EVOLVE 4.0, *Advanced Space Research, Vol.28 No.9:1377-1384.*