METHODS TO REDUCE UNCERTAINTIES IN SPACECRAFT VULNERABILITY PREDICTIONS

Bunte, K. D.(1), Farahvashi, E.(2), Miller, A.(1)

(1) *etamax space GmbH, Frankfurter Str. 3D, 38122 Braunschweig, Germany, E-mail: k.bunte@etamax.de*
(2) *TU Braunschweig, Institute of Space Systems, Hermann-Blenk-Str. 23, 38108 Braunschweig, Germany, E-mail: e.farahvashi@tu-bs.de*

ABSTRACT

As a method to predict the vulnerability of the satellite internal components and thus the probability of the satellite failure due to impacts of meteoroids and orbital debris, a penetration debris cloud model was implemented into ESA's damage assessment tool ESABASE2/Debris. The new model is based on characteristic distribution functions of the clouds mass and velocity to significantly reduce the processing time compared to hydrocode simulations and to overcome the limitations of approaches which are purely based on multi-wall damage and failure equations. The results of the cloud model approach were compared to alternative methodologies as implemented in the existing component damage assessment tools SYSTEMA-DEBRIS and PIRAT. The comparison shows that uncertainties in the vulnerability predictions remain. Recommendations for further improvements are given.

1 INTRODUCTION

Although not necessarily required by the relevant space debris mitigation standards, spacecraft operators and designers have an interest in the prediction of the survivability of their satellite over the mission duration. Besides the usual estimation of the system failure probability due to component failures by means of quality assurance methods, the assessment of system failures due to space debris or meteoroid impacts became more and more important in the last years, making its consideration a relevant requirement. For this purpose so called "impact risk assessment codes" are available, some of which are operational for decades (e.g. NASA's BUMPER and ESA's ESABASE2/Debris).

However, due to limitations in the exiting tools and models, the method applied for impact risk analyses usually considers the probability of penetrations of the outer spacecraft walls only. The resulting quantity for the spacecraft survivability is the "probability of no penetration" which assumes that such penetration would lead to a loss of the satellite. This method obviously overestimates the risk posed to satellites by space debris, since the criticality of the affected spacecraft components as well as the shielding of inner components against the penetration cloud generated after the perforation of the structure hull is not considered. In the end, such overestimation of the risk often leads to higher shielding needs and thus an increased satellite mass.

As the loss of a spacecraft is not determined by the number of penetrations of its outer structure, but on the loss of the functionality of certain components mostly located inside the satellite, two approaches were introduced to determine the satellite's "probability of no failure" based on damage assessments of these internal components [1]. One approach is the application of empirical multi-wall Ballistic Limit Equations (BLE). Due to their nature, these equations provide a realistic and accurate output for the wall configurations from which they were derived while for more complex configurations the uncertainties increase.

To overcome the problems with the methods which consider the combination of both outer and component walls by means of multi-wall BLEs, it is suggested to track particle cloud particles generated by a wall penetration and to assess the damage they cause on component walls by means of appropriate BLEs. This second approach offers the advantage that the propagation of the resulting fragment cloud automatically adapts to the internal components configuration regardless of its complexity [1].

The work described in this paper focuses on the implementation of a simple existing cloud model into ESABASE2/Debris and the generation of first preliminary results rather than the development of an accurate penetration cloud model.

2 RISK AND DAMAGE ASSESSMENT WITH ESABASE2/DEBRIS

ESA's ESABASE2 space environment analysis software tool allows to predict various effects of the space environment on a 3D spacecraft model. It provides a build-in geometry editor for generating 3D spacecraft models and allows to import models from other tools, e.g. CAD software, via its STEP interface. ESABASE2's 'Debris' application is widely used in both industry and academia to assess the risk and damage caused by meteoroids and orbital debris (M/OD) impacts. These analyses are based on M/OD environment models such as MASTER [2] and ORDEM [3] and a

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variety of particle/wall interaction models covering a wide range of application cases.

Currently, ESABASE2/Debris does not contain a direct approach to analyse the failures of internal satellite components after the perforation of the external structure. However, an engineering solution can be applied to perform risk assessments of the internal components with the help of multi-wall BLEs. In this approach, the structure panels of the satellite are removed from the model to expose the internal components to the M/OD environment as shown in Fig. 1 and Fig. 2.

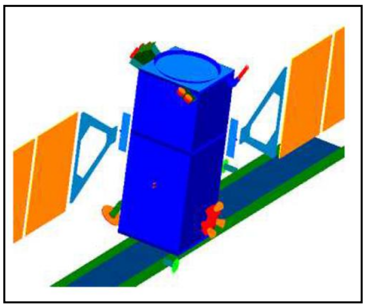

Figure 1. Satellite model with external structure [4]

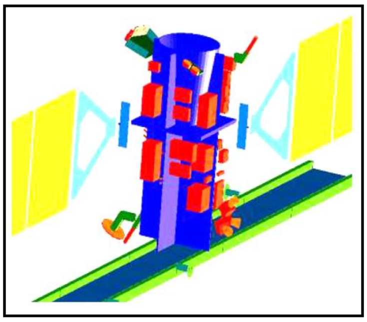

Figure 2. Exposing the internal components [4]

To correctly consider the shielding properties of the outer structure, multi-wall BLEs are applied to the component walls. Appropriate values of the structure wall thicknesses as well as the stand-offs between outer walls and components have to be specified and are used in the applied multi-wall BLEs. With increasing complexity of the structure/component configuration in question, the need for simplification arises. Consequently, the parameters are defined conservatively which again leads to an overestimation of the failure probability of the satellite components and subsequently of the spacecraft.

This problem is inherent to all approaches based on the application of multi-wall BLEs to a combination of both outer structure and inner component walls.

3 PENETRATION CLOUD MODEL

3.1 Cloud Model

The developed preliminary penetration debris cloud (PDC) model is entirely based on characteristic distribution functions derived and adapted from available publications [5], [6] for perforating impacts in the ballistic and shatter regime. The functions consider the typical impact conditions such as impactor mass, velocity and impact direction as well as the structure wall properties in order to represent the typical characteristics of the resulting penetration cloud. For the model, the three characteristic functions for velocity, mass and spatial distribution are used to generate rays which represent the penetration cloud fragments. Moreover, the rays are used to project the cloud fragments on the internal satellite components via the ray-tracing tool in ESABASE2. Fig. 3 illustrates, as an example, the cumulative mass distribution function implemented for the model which is generated based on the interaction between the impactor and the structure wall. It provides the contribution of the cloud particle masses to the overall cloud's mass.

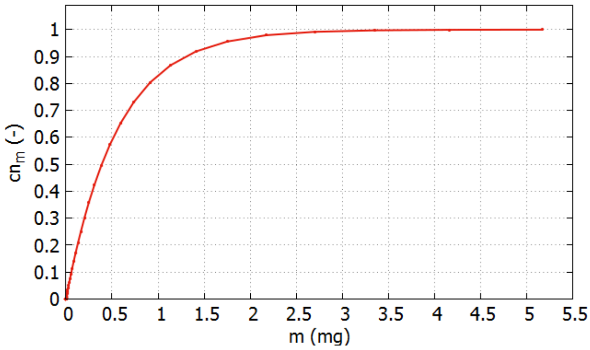

Figure 3. Example of a cumulative mass distribution function

The PDC model distinguishes between perforating impacts in the ballistic velocity regime ($v_{imp} < 3$ km/s) as well as in the shatter and hypervelocity (HV) regime ($v_{imp} > 3$ km/s). For the ballistic regime, it is assumed that the impactor remains almost intact after perforating the structure wall while in the shatter/HV regime the fragmentation of the impactor takes place. It has to be mentioned that for perforating impacts in the HV regime ($v_{imp} > 7$ km/s), the distribution functions of the shatter regime are extrapolated due to lack of available distribution functions for the HV regime. This leads to considerable uncertainties in particular for HV regime, since the resulting penetration cloud overestimates the existence of large fragments [2].

In case of structure perforation after a ballistic impact, a single ray is generated representing the residual largest fragment with a particular mass and velocity vector. In case of a shatter or HV impact, numerous rays are computed carrying the information about the size, quantity, velocity and directionality of the cloud fragments. Both the typically generated "in-line" cloud fragments as well as the "normal" cloud fragments are considered for the cloud computation as illustrated in Fig. 4.

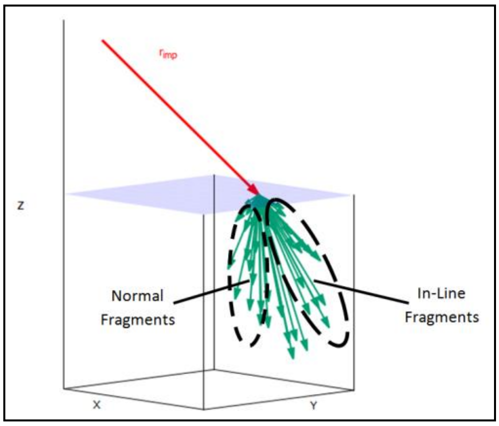

Figure 4. In-line and normal fragment distribution with 50 rays for an oblique impact

There are some limitations of the PDC model:

- The cloud model described in [6] is valid for the penetration of single walls only.
- One static representative mass distribution is used for all penetration cases due to the absence of appropriate publicly available information.

It also must be mentioned that the accuracy of the cloud model approach depends on the number of rays describing the PDC. As for each penetration of the outer spacecraft wall a penetration cloud is generated and analysed, this could lead to very high computation times in case of complex spacecraft models.

3.2 Validation

Prior to the implementation of the model into ESABASE2/Debris, a series of test cases were performed in order to validate the spatial distribution of the cloud fragments. The test cases showed that the computed cloud fragment distribution has the typical behaviours of an actual penetration cloud with respect to various impact conditions. In addition, a time factor was applied to the velocities of the ray fragments to compute their expansion over time. Subsequently, the profile of such simulated cloud was compared to a real penetration cloud for the same timestamp and the same impact conditions as illustrated in Fig. 5. It can be seen that the computed cloud shows a good correspondence to the real penetration cloud in terms of longitudinal and latitudinal fragment expansion.

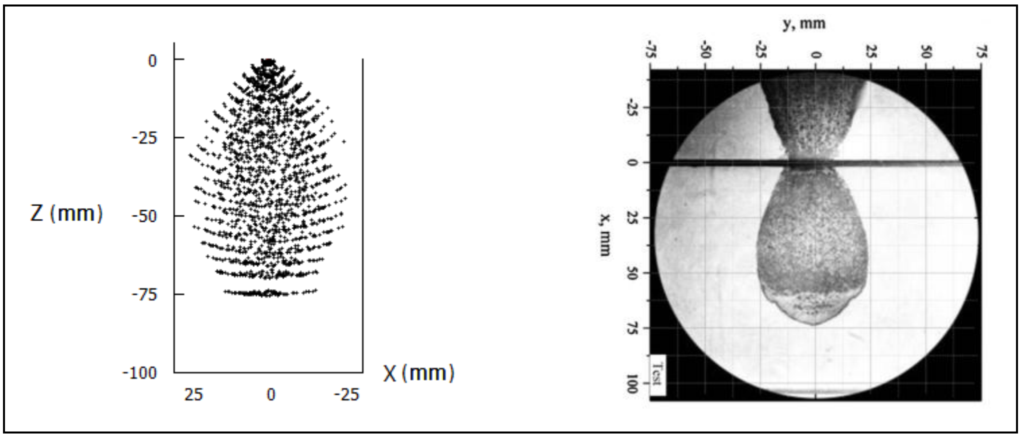

Figure 5. Comparison of the fragment distribution of the computed cloud (left) with a penetration cloud shadowgraph (right [6]) at t=15.6 µs for identical impact conditions

4 ESABASE2/DEBRIS IMPLEMENTATION

4.1 Overview

The developed PDC model was integrated into ESABASE2/Debris by means of several FORTRAN subroutines. Each distribution function is implemented as an individual subroutine to ensure that they can be easily exchanged in case improved distribution functions become available.

The model is wrapped into three main subroutines. The first subroutine generates a random perforating impactor from the applied environment model. The second subroutine generates the resulting penetration cloud rays based on the impactor and structure wall properties. The last subroutine projects the generated rays towards the internal components with the help of the ray-tracing module and passes the ray data to the internal damage analysis subroutines in ESABASE2/Debris for assessing the damage on the struck components.

4.2 Verification

Several test cases were set up to verify the implemented PDC model in ESABASE2/Debris. For this purpose various impact conditions as well as geometrical configurations were applied. In general, the simulation results demonstrated that in ESABASE2 the impactor and the perforated wall properties are correctly taken into account for computing and propagating the resulting debris cloud fragments. In combination with the raytracer, the projection of the cloud fragments adapts to the location, orientation and the geometrical shape of the internal components. Fig. 6 provides an example to demonstrate the consideration of position and shadowing effects of the components on the projected cloud fragments. In this test case, a spherical geometry was placed in-between a target and a witness plate, varying the stand-off of the sphere. A single impactor was fired on the target plate (indicated by a red arrow) to analyze the spatial distribution of the resulting penetration cloud fragments on the witness plate.

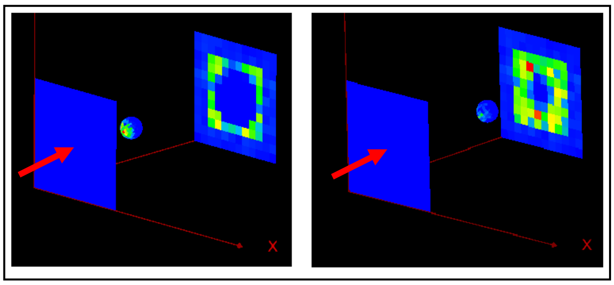

Figure 6. Adaption of the penetration cloud's projection according to the target's component configuration

As shown, the cloud's projection on the witness plate adapts accordingly to the location and geometry of the sphere. Moreover, the number of impacts on the sphere increases, the closer it gets to the cloud's emission point.

5 COMPARISON WITH OTHER TOOLS

5.1 Available Tools and Vulnerability Assessment Methods

Recent developments such as PIRAT (by Fraunhofer EMI) or SYSTEMA-DEBRIS (by Airbus Defence and Space) employ multi-wall BLEs to estimate the failures of internal components. Generally speaking, the tools track the flight direction of the perforating impactor inside the satellite model to determine the struck components while taking shadowing effects into consideration. Subsequently, the parameters of the target wall, component's walls and the spacing in-between are fed into multi-wall BLEs to determine the failure of the component in question. As a result, these methods consider the effect of fragments located at the centre of the cloud cone only [7].

To evaluate the application of a penetration cloud method, the vulnerability results achieved with the developed PDC model were compared with the mentioned tools based on simplified satellite geometries which are described in the following sections.

5.2 Basic Comparison

As a baseline for the comparison, a cubic external structure as described in the IADC Protection Manual was considered for a basic comparison of the tools regarding their damage assessment behaviour. The applied simulation parameters are presented in Tab. 1.

Table 1. Overview of the simulation parameters applied for the basic comparison test case

Mission	Duration: 01/05/2017 - 02/05/2017
	Altitude: 400 km
	Inclination: 51.6 deg
Orbital Debris	Environment model: MASTER-2009
	Analysis type: Debris only
	Particle size range: 0.1 mm to 0.1 m
Structure Geometry Model	Cube, dimension: 1 m × 1 m × 1 m
	Leading panel: +x, Zenith panel: +z
	Wall Thickness: 1 mm
	BLE: Cour-Palais [8]
	Failure factor: 1.8 (perforation)

The obtained simulation results by ESABASE2/Debris, PIRAT and SYSTEMA are presented in Fig. 7 for the number of impacts and in Fig. 8 for the number of failures on each structure panel.

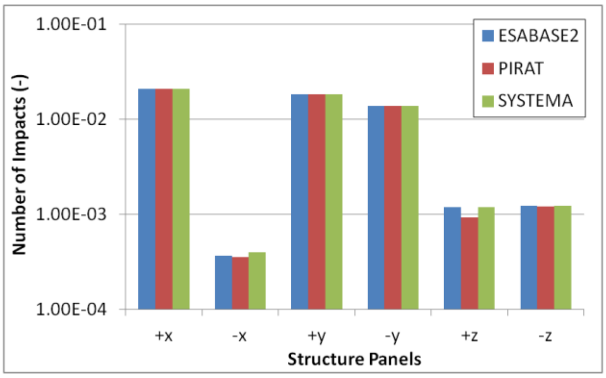

Figure 7. Comparing the number of impacts on the IADC benchmark structure on structure panel level

As can be seen, all tools show a good correspondence in the number of impacts on the structure, while the obtained numbers of failures show quite strong deviations (see Fig. 8). As the numbers of impacts are very similar and the applied shielding parameters and BLEs are identical, these deviations can be caused only by the different utilisation of the impactor parameters used internally by each tool.

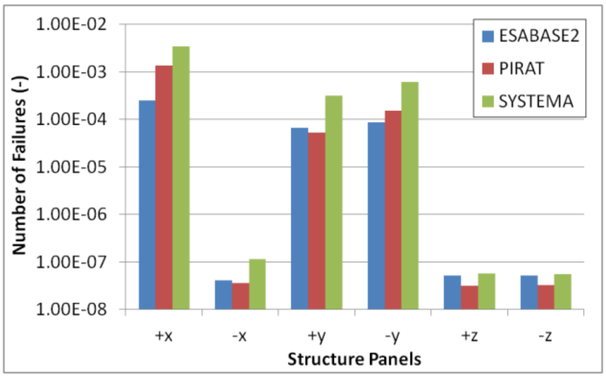

Figure 8. Comparing the number of failures on the IADC benchmark structure on structure panel level

A similar comparison was performed between ESA-BASE2/Debris and NASA's BUMPER tool based on the environment models MEMr2 (meteoroid environment model, release 2) and ORDEM3.0 [9]. In case of MEMr2, an excellent correspondence of both the numbers of impacts and the number of failures could be achieved. On the other hand, for ORDEM3.0, the comparison demonstrated the same tendency as reported above: The numbers of failures in some cases show a deviation of up to 40% although the correspondence of the numbers of impacts is excellent again.

The results of the comparisons by means of the so called "IADC benchmark cases" indicate that on the one hand, the risk assessment tools follow the same global methodology for determining the impact fluxes. On the other hand however, each tool applies an individual methodology to compute the numbers of penetrations. There seems to be the need to agree on the correct interpretation of the environment model output in the damage assessment.

5.3 Component Vulnerability Comparison

The simulation results of the PDC model were compared with those of the tools PIRAT, ESABASE2-IM (current component vulnerability assessment approach of ESABASE2; cp. section 2) and SYSTEMA-DEBRIS. A simple satellite model consisting of eight equidistantly distributed components as illustrated in Fig. 9 was established using the geometry editors of the respective tools. This particular model was chosen to analyse the effects of shadowing and positioning on the vulnerability of the components.

To ease the result comparison between the tools, the components were given a specific ID with respect to their position relative to satellite's orbital pointing as shown in Fig. 9.

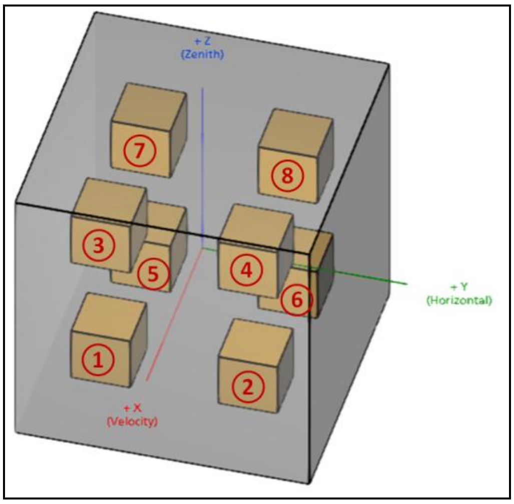

Figure 9. Satellite model for component vulnerability assessment

For the comparison, the same mission, orbital debris and structure properties were applied as presented in Tab. 1. To assess the damage on the components, the Whipple Shield BLE [8] was applied for the multi-wall approach in SYSTEMA, PIRAT and ESABASE2-IM and the single wall Cour-Palais BLE [8] was considered for the component walls in the PDC approach. It is noteworthy that for ESABASE-IM the NASA ISS BLE was used which is the equivalent BLE of the Whipple Shield in ESABASE2/Debris. The component parameters are summarized in Tab. 2. It should be mentioned that the ESABASE2-PDC simulation was executed with fairly low accuracy parameters in order to keep the simulation time reasonable.

Table 2. Overview of the component parameters applied for component vulnerability assessment

Component Geometry Models	Dimension: 0.2 m × 0.2 m × 0.2 m
	Wall Thickness: 1 mm
	Multi-Wall BLE: Whipple Shield [8] (for ESABASE2-IM, SYSTEMA & PIRAT)
	Single Wall BLE: Cour-Palais [8] (for ESABASE2-PDC)
	Failure Factor: Perforation (for the single wall Cour-Palais BLE)

Fig. 10 shows the simulation results for the failure flux on the components in a 3D representation. Here, the results for PIRAT are illustrated in form of the number of penetrations, since the tool currently does not directly show the failure flux. It has to be mentioned that in Fig. 10 the SYSTEMA results are not illustrated since the tool currently does not provide 3D results for the number of impacts and failures on the internal components.

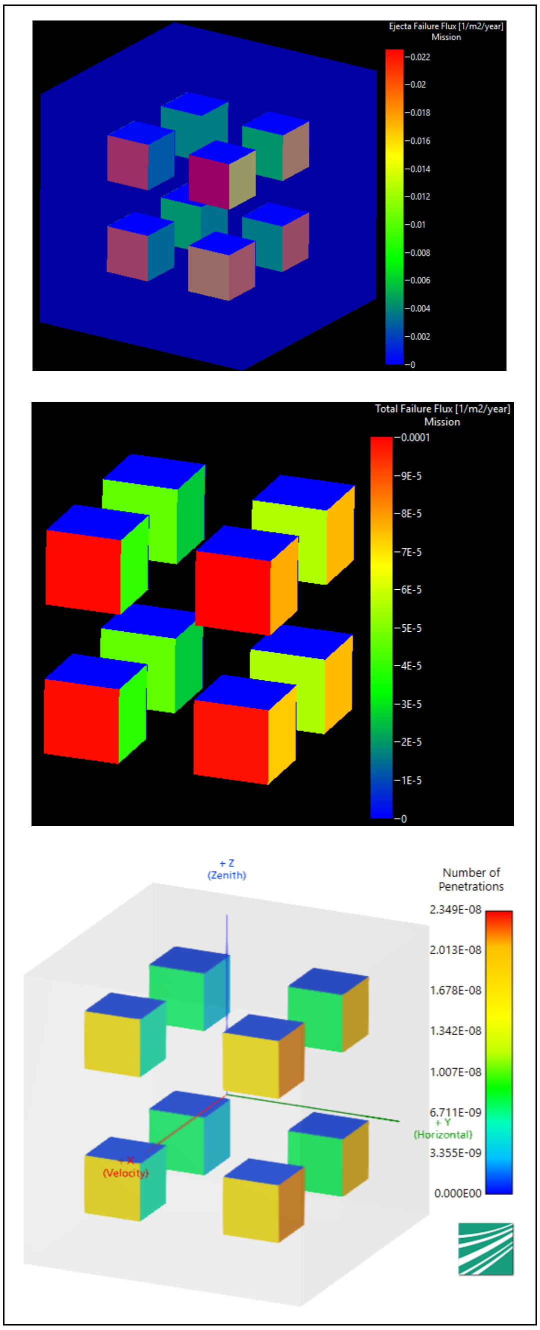

Figure 10. 3D simulation results for component vulnerability in ESABASE2-IM (top), ESABASE2-PDC (middle) and PIRAT (bottom)

As can be seen in Fig. 10, all approaches are capable of taking shadowing effects into consideration. The loads on the component surfaces represent the threat direction due to perforation of the structure.

Fig. 11 and Fig. 12 provide a more detailed view of the distribution of the number of impacts and of the number of failures on component level. However, in Fig. 11 only the numbers of impacts for PIRAT and ESABASE2-PDC are given, since SYSTEMA only provides the number of failures on the components. Moreover, it is not possible to extract the true number of impacts on the components in ESABASE2-IM due to the applied methodology.

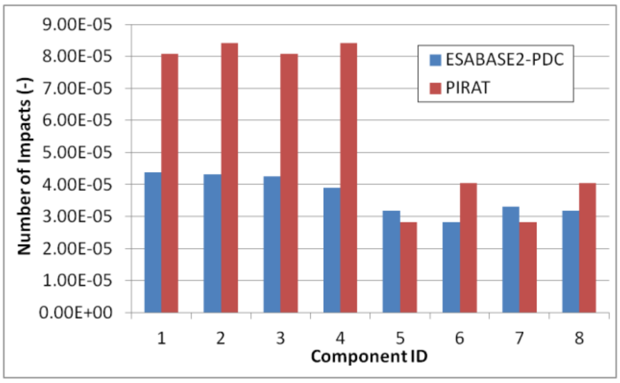

Figure 11. Comparing the number of impacts on component level

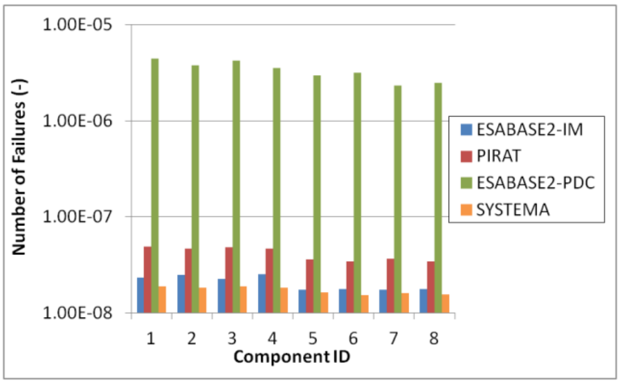

Figure 12. Comparing the number of failures on component level

Fig. 11 and Fig. 12 show that the loads in SYSTEMA, ESABASE2-IM and PIRAT are symmetrically distributed for components which are positioned in the same x-z-plane such as for example the components '1' and '3' or '6' and '8'. In contrast, the ESABASE2-PDC approach shows a stronger variation of the loads on components positioned in the same plane. Further analyses showed that this variation is reasonable and that it represents the distribution and superposition of the cloud fragments inside the structure. Fig. 11 indicates a higher number if impacts on most components in PIRAT compared to ESABASE2-PDC. Particularly the components mounted behind the leading structure panel (component ID's '1' to '4') show a higher number of impacts in PIRAT. Taking Fig. 8 into consideration, it becomes clear that in PIRAT the leading structure panel (+x-panel) has a 10 times greater penetration rate than the ESABASE2 structure which will inevitably result in greater numbers of impacts on the components. However, the numbers of impacts on components in PIRAT are only about two times greater than in ESABASE2-PDC. This indicates that the PDC approach is releasing a significant amount of fragments per perforation.

The most prominent result shown in Fig. 12 is that the numbers of failures determined with ESABASE2-PDC are significantly higher compared to the multi-wall BLE based approaches. The reason is that the perforations of the structure in these simulation cases are mainly caused by HV impacts with an average impact velocity of 10 km/s. As outlined above (section 3.1), the implemented simple PDC model is not suitable for assessing HV perforations due to the lack of distribution functions for the HV regime and the static mass distribution function, i.e. the cloud model is not applicable to the majority of these impacts. In summary this leads to an overestimation of the component failures by about two orders of magnitude. It is expected to achieve much more realistic results, once an enhanced penetration cloud model will become available.

6 SUMMARY AND CONCLUSIONS

To reduce the uncertainties in spacecraft vulnerability predictions at early design phases, a new model was developed to assess the component loads during spacecraft missions based on modelling the penetration debris clouds via characteristic distribution functions. The model was used as proof-of-concept to demonstrate the capabilities of such models as an alternative to the common multi-wall ballistic limit equations which are limited in their application to complex configurations due to their empirical nature. The spatial distribution of the generated cloud fragments was validated by comparing the cloud profile to an image of an actual penetration cloud. Subsequently the model was implemented into ESA's ESABASE2/Debris software tool for assessing the vulnerability of internal components based on 3D spacecraft models.

The obtained results were compared to those of the tools PIRAT and SYSTEMA which perform damage assessments via multi-wall ballistic limit equations. The comparison shows that the new model is capable to determine the cloud fragment impacts on the components with high accuracy while taking positioning and shadowing effects into consideration. However, it was not possible to compare the failure of the components since the simple model is not applicable to the hypervelocity regime above 7 km/s.

Therefore, it is required to establish an enhanced penetration cloud model covering the entire velocity range of meteoroid and space debris impacts and considering different cloud particle mass distributions for different impact velocity regimes.

Furthermore, the comparison demonstrated the necessity of suitable benchmark cases for the damage assessment of internal components and for an agreement on the methodology to utilise the environment model outputs for the damage assessment. Nonetheless, the new model demonstrated that the application of an appropriate penetration debris cloud model could be very promising in terms of simulation accuracy, where the latter is the precondition for a reduction of uncertainties in the spacecraft vulnerability assessment.

7 ACKNOWLEDGEMENTS

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