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PAGE	ISSUE/ REV.	PAGE	ISSUE/ REV.	PAGE	ISSUE/ REV.	PAGE	ISSUE/ REV.	PAGE	ISSUE/ REV.	PAGE	ISSUE/ REV.
1-16	1/0										

Table of contents

1. REFERENCE DOCUMENTS

RD1. ASTRIUM SAS, CISAS-UPD, PHS Space. TN1: CRITICAL REVIEW EXISTING DATA AND MODELS FOR IMPACTS OF SPACE DEBRIS ON SPACECRAFT. ASTRI.TCN.772717.ASTR. 2013.

RD2. ASTRIUM SAS, CISAS-UPD, PHS Space, J-CDS. TN2: Simplified models: description and justification. ASTRI.TCN.773521.ASTR. 2013.

RD3. ASTRIUM SAS, CISAS-UPD, PHS Space, J-CDS. TN3: Simplified models: evaluation and validation

RD4. AN ENGINEERING MODEL TO DESCRIBE FRAGMENTS CLOUDS PROPAGATING INSIDESPACECRAFT IN CONSEQUENCE OF SPACE DEBRIS IMPACT ON SANDWICH PANEL STRUCTURES. A. Francesconi, et al., in proc. IAC2014

RD5. AN ANALYTICAL METHOD FOR THE PROPAGATION TOWARDS INTERNAL COMPONENTS OF DEBRIS CLOUDS ORIGINATED BY SPACE DEBRIS IMPACTS ON SPACECRAFT WALLS. A. Francesconi, et al. , in proc. IAC2014

RD6. A NEW METHOD TO PREDICT THE CATASTROPHIC DESINTEGRATION OF SPACECRAFT UPON COLLISION WITH LARGE ORBITAL DEBRIS. M. Zaccariotto, et al. , in proc. IAC2014

RD7. AN APPROACH TO INTEGRATE SIMPLIFIED MODELS FOR SPACECRAFT VULNERABILITY ASSESSMENT IN ESA'S CONCURRENT DESIGN FACILITY. M. Bieze, et al. , in proc. SECESA2014

2. INTRODUCTION

All spacecraft in Earth orbit are exposed to the risk of impact with Micrometeoroids and Orbital Debris (M/OD). Because of the large collision velocities, Hypervelocity Impacts (HVI) with M/OD may cause significant damage to various subsystems and components up to mission failure.

In particular, space debris are man-made objects which include collision and/or explosion fragments, other fragments resulting from surface degradation, mission related elements (e.g. lens covers, launch adaptors, etc.), out-of-life satellites and launchers upper stages. Space debris mass is therefore extremely variable, from fractions of milligrams to few tons, and the consequent impacts on operational spacecraft can have very different effects that are broadly classified into two distinct categories:

- **Non-catastrophic impacts**, in which a small piece of debris can eventually cause a local perforation of the spacecraft hull. In this case, a debris cloud is ejected into the vehicle and can produce damage to internal equipment and/or lead to a failure of critical components.
- **Catastrophic impacts**, in which the debris mass (and hence impact energy) is large enough to produce the complete shattering of the spacecraft (or a relevant part of it).

These two issues are considered only partially by most Risk Assessment (RA) tools, which make it possible to predict the number of impacts that are to be expected on each spacecraft surface throughout its orbital lifetime as a function of the M/OD size, speed and direction, but still provide only raw estimations of the damage produced by such events:

- Concerning non-catastrophic impacts, RA tools normally assess the probability of perforation of the spacecraft shell, but most are still not able to perform failure analyses which consider the vulnerability of internal equipment as failure criterion. Rather, critical damage is usually related to the occurrence of structural breech, and this often results in excessive overestimates of the impact risk.
- Concerning catastrophic impacts, RA tools generally employ a classical rule stating that any impact exceeding an Energy-to-Mass Ratio (EMR) of 40 J/g is severe enough to cause the whole spacecraft disintegration, regardless of its configuration and impact point, and hence no consideration is given to impact energy propagation and dissipation through major spacecraft parts.

In addition to these two limitations, current RA tools refer to very specific spacecraft configurations which are already the results of preliminary trade-offs, and are not adequate to compare alternative architectures in the early design phases, when the choice of different solutions (e.g. spacecraft shape, materials, internal layout, redundancies, shadowing by appendages, etc.) often lead to important consequences to the system design.

3. STUDY ORGANIZATION

The study organization reflects the following logic:

- WP1 dedicated to the critical review of data and models is split in four WPs, each led by an expert in this field:
- WP2 dedicated to the development of simplified vulnerability models:
- WP 3 is dedicated to the evaluation and validation:

4. REVIEW OF DATA AND MODELS

Considering the context described in introduction; the objective of WP1 is to provide an exhaustive review of the available knowledge on both non-catastrophic and catastrophic impacts. Such review will serve as starting point to define adapted methodologies for the development and upgrade of simplified (i.e. adequate for future implementation in the CDF framework) vulnerability models addressing the limitations of current tools.

Hence, the activity of WP1 has been conducted on two different but complementary study levels (columns in Fig. 1-1): on one hand, it includes a survey of state-of-the-art information about impact effects on spacecraft (non-catastrophic as well as catastrophic) and the current procedures to deal with them (WP1.1 and WP1.3, led by PHS); on the other hand, it contains a review of methods that could be employed for the development of original and simplified vulnerability models during the prosecution of this Study (WP1.2 and WP1.4, led by CISAS). The outcomes of these studies are detailed in [RD1].

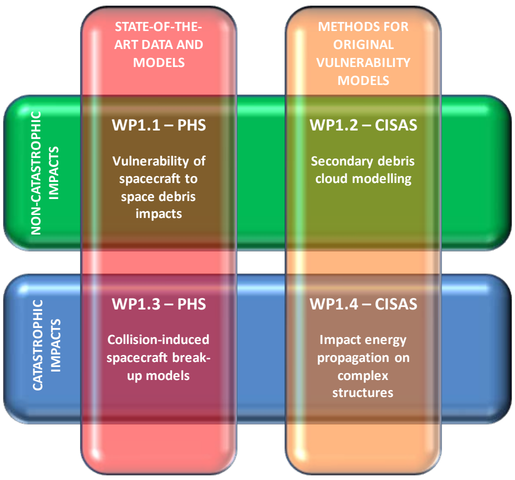

Figure 4-1. WP1 activity organization

5. DETAILED METHODOLOGY FOR SIMPLIFIED VULNERABILITY MODELS

5.1 Internal components vulnerability

The procedure to evaluate the vulnerability of spacecraft internal components to micrometeoroid and orbital debris is based on the computation of the damage caused on equipment hit by secondary debris clouds originated after perforation of the vehicle's hull.

The idea behind the proposed simplified impact risk assessment procedure is to evaluate the damage on internal components due to a new debris environment generated inside the spacecraft in consequence of perforations of the vehicle's hull (Figure 5-1). Starting from where an initial M/OD flux computed by available models (e.g. MASTER or ORDEM), such new environment is the superposition of all secondary debris clouds resulting from primary M/OD impacts that penetrate the spacecraft external surfaces.

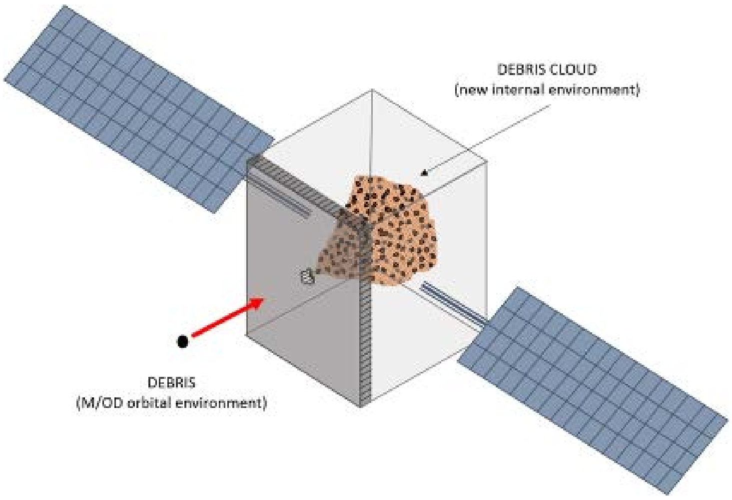

Figure 5-1: Internal components vulnerability: procedure's concept

Secondary debris clouds are assumed to be independent and not-interacting, that is reasonable since the contemporary occurrence of two or more penetrating impacts on the same vehicle is highly unlikely.

Internal components are modelled as simple plates representing the equipment's cases and damage equations for simple plates are finally used to predict the equipment failure.

From a scientific point of view, the key feature of the proposed procedure is the evaluation of damage due to debris clouds propagating inside the spacecraft, and this provides several advantages:

- Impact risk assessment is based upon a general approach employing a true physical analysis of the interaction between debris and spacecraft components, through debris cloud modelling. Moreover, debris cloud models could be regularly improved as soon as new test data become available, continuously adding generality to the method;
- Spacecraft structural configurations, geometries and internal equipment's layout are not limited to those evaluated by HVI testing, whose results cannot be easily and reliably extrapolated outside the

experimental configuration and range. This is particularly limiting in early design phases, when it is worth to explore solutions that might largely differ from historical ones;

- Failure on internal components can be computed with reference to the damage on their cover faces using damage equations for plates, whose reliability is high because of the large databases on which they are based. Furthermore, failure criteria different from "perforation of the equipment case" can be adopted if necessary (e.g. damage area above a certain threshold, even below the ballistic limit);
- Mutual shadowing between components (and hence protecting effects related to different equipment layouts) can be accounted for automatically by propagating debris clouds inside the spacecraft.

On the other hand, from the point of view of the tool implementation, the proposed procedure requires only limited computational burden, since it is based on a simplified formulation using only explicit analytical formulas for both debris cloud models as well as their propagation inside the spacecraft, with no ray-tracing but only minimum knowledge of the spacecraft 3D geometry requested to this aim.

In summary, the core of the proposed procedure incorporates two principal elements of innovation, i.e. the debris cloud models (which generate the new debris environment inside the vehicle) and the algorithm to propagate the clouds towards whatever inner component. These two crucial ingredients have been published in two articles [RD4] and [RD5].

5.2 Catastrophic impact prediction

This section summarized the procedure developed in this Study to predict catastrophic impacts, i.e. large energy events that result in global spacecraft shattering with consequent release of numerous fragments. To this aim, the main driving requirement was to account for the dependence of catastrophic disintegration from the impacted surface, based upon its structural properties and position in the vehicle.

The idea behind the proposed procedure is to partition the input energy due to HVI among a limited number of macroscopic spacecraft elements (e.g. main body walls, solar panels, antennas, etc), and then verify which part of the vehicle eventually exceeds its individual disintegration threshold.

On one hand, the energy distribution in the system depends on the impact position and the structural properties of the impacted element, and can be estimated starting from considerations on energy dissipation and propagation along structural components. On the other hand, it's important to remind that different elements could have different disintegration threshold, and also the consequences of different parts' disruption on the global vehicle's integrity could be much different.

The procedure to calculate the impact energy distribution within spacecraft is based on the Statistical Energy Analysis (SEA) method, whose mathematical framework is discussed in reference [RD1] and is recalled in a published paper [RD6].

6. DST PROTOTYPE WITHIN CDF

6.1 Spacecraft Vulnerability in the CDF process

The spacecraft vulnerability support tool will be integrated in the current CDF process. This means that it will gather some of the required inputs from the other CDF study participants via the OCDT framework. The CDF software support tooling (i.e. the OCDT ConCORDE client tool and Microsoft Excel) act as an interface for each domain to describe their respective part of the design. In some cases results need to be gathered from external tooling, like CATIA, STK etc. These are called Domain Specific Tools (DST). DST's are integrated using either direct software interfacing, or through an intermediate approach using Excel worksheets as user interface.

6.2 Spacecraft vulnerability tool architecture

Within the OCDT, Excel Workbooks are the primary interface to work with and update the design model. During a Concurrent design session all study participants interface with the OCDT Server to read and update the parametric design.

Communication with the OCDT is facilitated by the ConCORDE user client application. ConCORDE is an Excel Add-in which allows the user to interact with the data model.

The Vulnerability domain workbook is used to interface the vulnerability assessment DST with the OCDT. Using dedicated DST worksheets within the workbook, a sub set of the OCDT design model values can be collected and analysis results shared back to the team. The DST reads the DST input worksheet as inputs for the analysis tool. Analysis results are written by the tool to the DST output worksheet. From here it could be linked to the OCDT data using the ConCORDE interfacing facilities, which takes care of submitting the value.

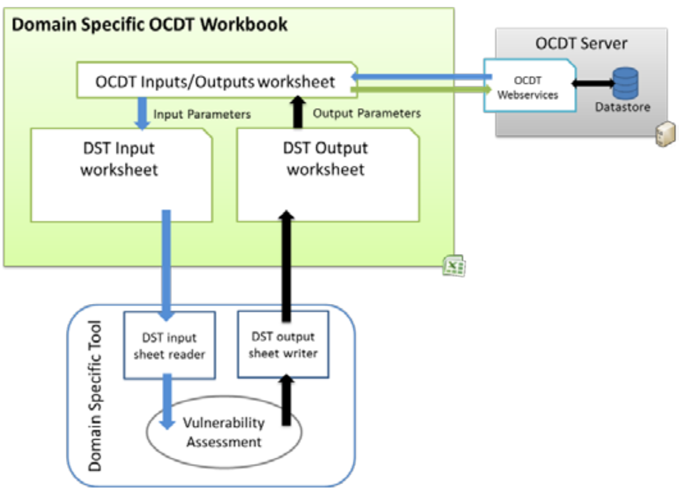

Figure 6-1: Domain Specific Tool integration in the OCDT

Using user configurable DST input and DST output sheets, relevant subsets from the OCDT data model can be gathered to interface with the DST. Details on the tool architecture may be found in [RD2] and in a published paper [RD7].

7. APPLICATION OF DST

7.1 Comparison with Shield3 software

A comparison of results with SHIELD3 has helped to judge the accuracy of the techniques implemented in the prototype Simplified Vulnerability Model tool. In particular, differences in the results between SHIELD3 and the SVM have been highlighted and some explanations offered. Broadly speaking, the number of penetrations predicted by the SVM lies within an order of magnitude of the SHIELD3 results, and in most instances it is much less than this. Given that the development of a high-fidelity cloud model was not the focus of the current study then this can be considered a very satisfactory result. It is certainly a solid base upon which to build. Further work should be undertaken to refine the cloud modelling elements of the SVM and investigate in more detail the main discrepancies with the SHIELD3 results. This is essential if the CDF is to use the SVM tool with a high degree of confidence.

Following this study and the results obtained with the SVM prototype during a mini CDF session, updates of the debris cloud models have been implemented in the prototype. Details of this change are detailed in [RD3].

7.2 Industrial case

The tool has also been used to compute an industrial case, first in the frame of the study itself, then in the frame of a mini-CDF session organised by ESA.

The model was developed from a given step file. By using the available data found in the step file some properties have been extrapolated when possible. The other parameters have been provided through OCDT access. The results obtained for the numbers of impacts/penetrations on the external elements are shown on Figure 7-1.

In addition of these results, it is possible to get a 3D visualization of the P.N.P. as shown on Figure 7-2. It can be noticed on this figure that the component located behind the honeycomb on the rear face of the satellite seems to be more exposed (coloured in green). Another feature of the tool allows seeing from where the perforating debris comes from (cf. Figure 7-3). Applied to this component, it can be noticed that the flux come from the lateral faces composed of MLI and impact the top of the component. As this component has a larger area compared to others component placed behind the honeycomb, it explains the larger number of penetrations and thus the lower PNP.

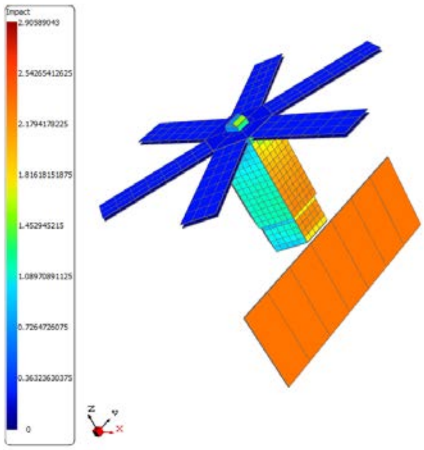

Figure 7-1: Number of impacts (1/m²/yr) for the developed tool

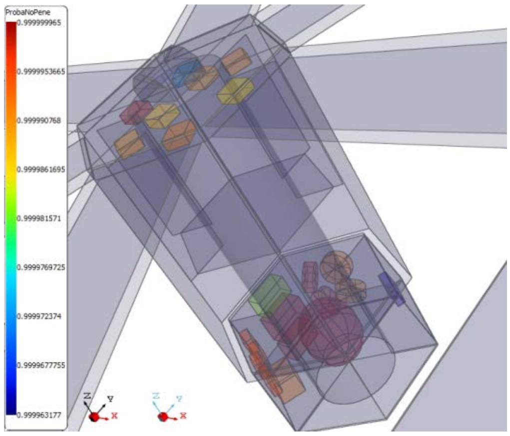

Figure 7-2: P.N.P. of the internal component

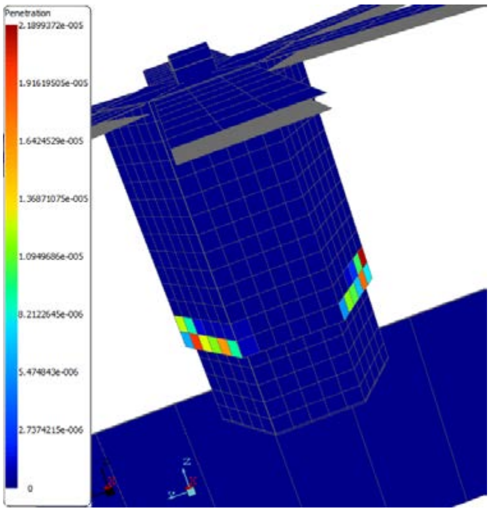

Figure 7-3: Number of penetrations impacting a selected element (top of the battery2)

8. SYNTHESIS AND ROADMAP

8.1 Non catastrophic impacts

The overall process of computation based on the modelling of secondary debris cloud generated after the first impact has the advantage to be relatively generic. Indeed, as soon as the models used are correct, the approach is not limited in terms of geometrical configurations.

Due the constraints of having a tool usable in the context of a CDF session, it was necessary to implement a simplified approach to model the debris cloud and to evaluate the interaction of the cloud with the internal surfaces. This approach based on the computation of the Modified View Factors (MVF) has the advantage to be relatively efficient (as it avoids performing a ray-tracing of the secondary debris) in terms of computation time but is a simplification.

Regarding the computation of the MVF and the way the geometry is handled, the main limitations are the following:

- The accuracy of the MVF computation depends on the meshing of the external surfaces
- The surfaces are treated either as:
    - Shadowing: all the impinging debris are stopped by the surface
    - External: source of the debris cloud
    - Internal: surface on which the penetration will be computed

  This may lead to some limitations in some configuration.

The current approach relies on debris clouds models that are used to model:

- The angular distribution of debris after the first impact
- The mass and velocity distribution of the secondary debris

The models that are implemented in the Vulnerability tool are based on the available data and thus, their validity are limited as soon as the configuration is different than the test data. In particular, the main limitations of the debris cloud models are the following:

- Debris cloud model are based on data for aluminium. Their use for other materials (CFRP, MLI…) may lead to some inaccuracies.
- Due to the lack of data, the angle dependency of the debris cloud model is crude, particularly at grazing incidence.
- The impact of MLI (covering a honeycomb or a single plate) is not taken into account in the cloud model.
- The honeycomb model is basically deduced from a “cascade” model based on the simple plate model. The impact of internal cells has still to be assessed.

Besides the limitations listed above, the other identified limitations are:

- The model computes the probability of penetration inside an internal surface. No model of failure is currently implemented in the tool.
- The impact of pressure (that could concern components) is not taken into account.
- Spacecraft attitude is supposed to be constant during the simulation.

The proposed recommendations come from the identified limitations. They can be split in three main topics: the debris cloud model, the vulnerability software prototype and the debris impact models.

The accuracy of the simulation strongly depends on the models that are used to model the impact of debris on a surface. The validation and test cases performed during the study have shown that improving the debris cloud models is key to improve the accuracy of the vulnerability simulation. More precisely, the main subjects, we recommend to work on:

- Modelling of sandwich panels:
    - Mass distribution data
    - Impact data on panels covered by MLI
    - Panels with composite face-sheets
- Modelling of simple plates:
    - Impact angle dependency
    - Impact data on panels covered by MLI
    - Data on composite materials

Development of updated models could be based on available data from test. Moreover, simulation with Smoothed-particle hydrodynamics (SPH) could complete the experimental data and could support the extrapolation at high speed.

As explained in the previous chapter, the vulnerability software has some limitations. Recommended improvements concern:

- The modified view factors computation in order to improve the accuracy.
- The way to handle the spacecraft geometry: in particular the distinction between shadowing, internal and external surfaces could be improved in order to overcome the limitations / complexity of the current approach.
- The computation of failure to complete the existing computation of penetration.
- Performances: if the chosen approach allows modelling the debris cloud in a reasonable time, computation could probably be improved in the context of CDF session.

Debris impact models (BLE and debris clouds models) are usually based on tests. In order to improve the existing models (see above) and to validate the implementation of the models in the Vulnerability tool, it is recommended to realize hypervelocity tests. Tests should have two objectives:

- To support the improvements of models and particularly cloud models
- To validate the proposed approach and its implementation for some “complex “configuration: e.g. penetration of an equipment protected by a wall In the case of oblique impact.

8.2 Catastrophic impacts

If the Statistical energy analysis method has well established bases and has successfully been applied in many technical domains, its application to model the impact of large debris as well as its implementation in the context of the CDF is new. Validation and test cases performed during the study allowed identifying several limitations of the current approach.

The main limitations are listed below:

- Calculation of Coupling Loss Factors (CLF) and Damping Loss Factors (DLF) is based on assumptions that have to be validated.
- The type of junctions that are currently available in the Vulnerability tool is limited to point junction (a beam connected to a surfaces) and line junction (junction between two surfaces).
- The physical junction between two elements is currently not modelled. It means that it is not possible to simulate the breakout of the structure in its main pieces.
- The energy transmitted to the system is assumed to be performed without loss. This is a relatively crude assumption as we know that a part of the incident energy will be dissipated in the cloud of secondary debris.
- The threshold used to evaluate if a component of the spacecraft is fragmented is 40 J/g. This is a very crude assumption.
- The method and developed tool does not compute the number of fragments generated during an impact.
- The impact of secondary debris generated after the impact and their potential effects are not taken into account.

The proposed recommendations come from the identified limitations.

- Define an algorithm to simulate high-energy “cascade” impacts (i.e. large debris penetrating the hull and continuing its travel inside the spacecraft). Use debris cloud models and energy partition, and combine them.
- Perform testing:
    - To validate CLF calculation approach
    - To create a CLF database
- Review data/perform testing to provide different failure criteria for different spacecraft parts (e.g. pressure tanks would likely require << 40 J/g)
- Develop a model to evaluate the number of debris generated during a catastrophic collision.

Distribution list	OVERALL DOCUMENT		SUMMARY
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