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Structural Damage Prediction and Analysis for Hypervelocity Impact

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Space Debris Surfaces (Computer Code): Probability of No Penetration versus Impact Velocity and Obliquity

N. Elfer*, R. Meibaum*, and G. Olsen†
* Martin Marietta, New Orleans, LA
† NASA-Marshall Space Flight Center, Huntsville, AL

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SPACE DEBRIS SURFACES:
PROBABILITY OF NO PENETRATION
VERSUS IMPACT VELOCITY AND OBLIQUITY

N. Elfer*,t, R. Meibaum*, G. Olsen**,t

Abstract
A unique collection of computer codes, Space Debris Surfaces (SD_SURF), have been developed to assist in the design and analysis of space debris protection systems. SD_SURF calculates and summarizes a vehicle's vulnerability to space debris as a function of impact velocity and obliquity. An SD_SURF analysis will show which velocities and obliquities are the most probable to cause a penetration. This determination can help the analyst select a shield design that is best suited to the predominant penetration mechanism. The analysis also suggests the most suitable parameters for development or verification testing.

The SD_SURF programs offer the option of either FORTRAN programs or Microsoft EXCEL spreadsheets and macros. The FORTRAN programs work with BUMPERII. The EXCEL spreadsheets and macros can be used independently or with selected output from the SD_SURF FORTRAN programs.

Examples will be presented of the interaction between space vehicle geometry, the space debris environment, and the penetration and critical damage ballistic limit surfaces of the shield under consideration.

Space debris probability codes, BUMPERII and Space Debris Vulnerability (SDV), analyze a space vehicle as a faceted geometry. These codes calculate the probability of no penetration for each facet based on the exposure area and the penetration resistance (ballistic limit) to each facet.

* Martin Marietta Manned Space Systems, New Orleans, LA 70189
** NASA Marshall Space Flight Center, Huntsville, AL 35812

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The space debris environment may be modeled as a series of threats from discrete directions. For low earth orbit (LEO), space debris may be assumed to exist in circular orbits. This assumption fixes the orbital velocity. Debris cannot intercept a
spacecraft from more than approximately 10° above or below a plane tangent to the local Earth normal. Otherwise the debris would enter the Earth's atmosphere and be removed as a threat. Therefore, the relative impact velocity in LEO is determined by the orbital velocity, \( V_0 \), and the intersection angle, \( \phi \), of the two orbits. The impact velocity, \( V_1 \), is:

\[
V_1 = 2 V_0 \cdot \cos \left( \frac{180° - \phi}{2} \right)
\]

Figure 2 shows the fraction of the total flux coming from angles relative to the direction of flight. The relative impact velocity for the intersection of 388 km orbits is also shown on the plot.

**Fig. 2. Angular and velocity distribution of flux.**

**Ballistic Limit Surface**

The spectrum of debris sizes, velocities, and obliquities that may impact a shield lead to a variety of penetration mechanisms. Figure 3 illustrates a ballistic limit surface for hypervelocity impact on a multiwall shield. A projectile diameter at a velocity and obliquity above the surface will penetrate the shield. A diameter below the surface will not penetrate the shield. There are several penetration mechanisms which are described in Fig. 3. Changes in shield parameters affect each penetration mechanism differently. Therefore, it is important for the designer to know what penetration mechanism has the greatest effect on the overall probability of no penetration.

**Critical Damage**

It is necessary to understand the consequences of a penetration. A small penetration should be avoided because of potential difficulties in finding and repairing a leak. However, a small penetration does not result in an immediate fatality. Critical damage will be defined as penetrations resulting in rapid depressurization as well as catastrophic crack growth. There is a theoretical threat of bodily injury due to fragments, but this is much less likely and will not be treated in this paper.

For Space Station Freedom, the critical hole size for too rapid depressurization has been estimated as 10 cm in diameter. To get this diameter, either a large projectile or petalling of the hole is necessary. Conservative fracture analyses predict that large petals may lead to catastrophic
rupture rather than simple depressurization.

A critical damage limit surfaces is presented in Fig. 4. At high velocity there is sufficient intermediate thermal blanket/shield to prevent cratering or spall, and the rear wall fails by momentum induced bulging and petalling. This can open a hole or propagate a crack to a much larger size than the initial damage area. The projectile diameter to cause critical damage was estimated to be 50% larger than the projectile diameter to cause penetration. For low velocity penetration the projected area of the projectile, plus a damage zone, is assumed to control critical damage. This is a very rough assumption because there is insufficient data about the momentum deposited in the rear wall. The estimate of the size of the damage zone will not have a strong influence on the overall probability because of the large projectile size.

An alternative high-velocity penetration mechanism may be wide area spall. A larger particle would then be necessary to drive petalling and crack growth in the rear wall, because much of the momentum will be transferred to the spall fragment. To estimate the influence of this failure mechanism, the projectile diameter was assumed to be 225% of the ballistic limit diameter for the following calculations.

Probability Analysis

The probability of no penetration (PNP) from each direction and for each element is based on the Poisson distribution for zero events:

\[
\text{PNP}_{\text{el}} = \exp\left(- \sum_{i=1}^{n_{\text{threats}}} (N_i f_i N_R(d_i)) t \right)
\]

where (with consistent units)

- \(N_i\) = flux that penetrates from each threat direction, \(i\),
- \(f_i = 4 \cdot f_i N_R(d_i)\).
- \(N_R\) = flux on a randomly tumbling plate (specification definition) of diameter \(d\) or larger. \(d_i\) is the diameter to penetrate at the velocity and obliquity of the \(i\)th threat.
- \(f_i\) = fraction of flux from threat direction.

The total PNP is determined by the product of the PNP for each element.

\[
\text{PNP}_{\text{total}} = \prod_{j=1}^{n_{\text{elements}}} \text{PNP}_j
\]

Figure 5 shows the BUMPERII modules and their input and output as they calculate PNP. BUMPERII starts with a SuperTab output file finite element model of the spacecraft.

The GEOMETRY module of BUMPERII calculates the projected area of the elements exposed to each threat direction. A significant part of this calculation is intercomponent shadowing. This can be a very time consuming process for a large model.

The RESPONSE module creates a ballistic limit surface from a menu of user selected penetration equations. The ballistic limit for each shield of interest is stored in a matrix for every 0.25 km/s and 5° obliquity. This is also stored in binary form in the computer. Another BUMPERII code, RPLOT, reads the binary file and puts out a formatted file with the ballistic limit at 0°, 15°, 30°, 45°, and 60° obliquity for 2D plots.

The SHIELD module calculates the PNP for any range of element numbers requested by the analyst. SHIELD also has an option to create a SuperTab file to plot probability contours on the original geometry model.
**SD_SURF Analysis Approach**

To design the most effective shield, the analyst must know which penetration or damage mechanism is predominant. It is the goal of the SD_SURF computer programs to provide this information.

The flux associated with each point on the ballistic limit surface can be weighted by the probability of an impact at that particular velocity and obliquity.

\[ PNP(V, \beta) = \exp[-N(d) - A(V, \beta) - t] \]

where \( A(V, \beta) \) is the total area of the spacecraft that will be impacted at an obliquity, \( \beta \), from a debris particle at velocity, \( V \), and \( N(d) \) is the flux associated with the diameter \( d \) that just penetrates at \( V \) and \( \beta \).

There is a difference in the PNP calculated for a unit area at a single velocity and obliquity versus distributing the area over two bracketing velocities and two bracketing obliquities. This is due to the non-linear relationship between flux and diameter. On the other hand, the analysis of a curved surface is more accurate if the sum of areas is equal to the area reported by BUMPERII.

The A_SURF module puts out both an unformatted file and a formatted file. The unformatted binary file can be read by the P_SURF module. The formatted text file can be used to check the output manually, or it can be read by the EXCEL modules as described in the next section.

The P_SURF module reads in the A_SURF and RESPONSE output files, and uses the same flux routines in BUMPERII-SHIELD to calculate the flux-area-time (NAT) array. A text based contour map is generated, which should be compatible with any FORTRAN platform, and also a text file that may be used with sophisticated graphics packages. Examples of the contour plots will be shown in the examples in the next section of this paper.

The final FORTRAN module is R_PLOT5. It is used to translate BUMPERII-RESPONSE output files to text formatted files. The text formatted file is set up at 0.5 km/s and five-degree increments rather than the 0.25 km/s and five-degree increments used by RESPONSE. Commas are used as delimiters to ease import by the EXCEL modules.

**SD_SURF - EXCEL 3.0 Version**

The EXCEL version can be used both as an alternative or a complement to the FORTRAN version. The EXCEL version is not as fast or as "turnkey" as a FORTRAN application. However, it has the advantages of a spreadsheet: customized calculations and analyses are simple to generate; error checking is very easy; there is quick access to graphing.

The structure of the EXCEL version is shown in Fig. 7. The backbone of the PNP calculation is the facets is smaller than the five-degree increments used on the RESPONSE and AREA SURFACE tables.

**SD_SURF - FORTRAN Version**

The interrelationship of the FORTRAN modules of SD_SURF is shown in Fig. 6. SD_SURF acts as a post-processor of BUMPERII-RESPONSE and GEOMETRY output. It provides additional information not readily obtainable from BUMPERII.

The A_SURF module reads the BUMPERII-GEOMETRY binary output to create the exposed area matrix as a function of velocity and obliquity. Rather than lump the area of one facet at the nearest velocity and obliquity, A_SURF uses the lever rule to distribute the projected area, for one facet and one threat, over the four nearest velocities and obliquities. The sum of the exposed areas is equal to the area reported by BUMPERII.

The A_SURF module puts out both an unformatted file and a formatted file. The unformatted binary file can be read by the P_SURF module. The formatted text file can be used to check the output manually, or it can be read by the EXCEL modules as described in the next section.

The P_SURF module reads in the A_SURF and RESPONSE output files, and uses the same flux routines in BUMPERII-SHIELD to calculate areas on the worksheet:

- Ballistic Limit surface, diameter to penetrate in increments of 0.5 km/s and five degrees of obliquity. (It is created on a Ballistic Limit Template or imported from RESPONSE via R_PLOT 5.)
- Environment definition including year, solar flux level (explicit or calculated), and altitude.
- Flux calculation for each diameter in the ballistic limit surface. (This is a function macro that is defined on the function macro worksheet.)
- Area Surface, \( A(V, \beta) \), created using Area_Maker Macro, or imported from A_SURF.
- Flux - Area - Time, N.A.T, for each \( V \) and \( \beta \). (The summation of these cells is used to calculate the PNP.)

Function macros operate as subroutines and are used to calculate ballistic limits or flux for appropriate input values. Command macros provide control of files and the pasting of named arrays from ballistic limit and area templates to the PNP_Template. Any of the templates may be customized and saved by any name for later use. Hardcoding the names would make it easier for a new user, but the flexibility provided by using general names was deemed to be more important.
Model Generation
- SuperTab
- NASTRAN translator

SuperTab
- Universal File
  - Nodes
  - Elements

GEOM
- Space Debris
- Meteoroids

Geometry Database

Exposed Area by vel. and obl. [binary]

A_SURF
- Area Fraction Table
  - Space Debris

Exposed Area by vel. and obl. [formatted]

P_SURF (FORTRAN vers.)
- Space debris only
- BUMPERII flux subroutines

Response
- Space Debris
- Meteoroids

Ballistic Limit Lookup Tables [binary]

R_PLOTS5 (5 degrees)

PNP by range
Flux-Area-time by vel. and obl.

Ballistic Limit by vel. and obl. [formatted]
The Area Surface maybe created on the Area_Template using the Area_Maker Macro. The analyst selects the geometry desired from a pull-down menu. The standard geometries are shown in Fig. 8. The specific geometry is entered in customized dialog boxes. Each facet is analyzed at each velocity increment. This is effectively 64 threats (at equally spaced velocities), compared to the 45 threat default in BUMPERII.

SD_SURF for EXCEL lacks some of the features of BUMPERII. BUMPERII must be used for shadowing analysis in GEOMETRY, multiyear flux averaging in SHIELD, or the extensive iterations required to run PEN4 in RESPONSE. However, the GEOMETRY and RESPONSE output may be imported via the FORTRAN A_SURF and R_PLOT5 programs. Multiyear flux calculations can be programmed into the EXCEL macros with a corresponding increase in analysis time.

**Probability Studies**

**Effective Area**

The A_SURF program and the Area_Template calculate the effective exposed area at each velocity and obliquity. Figure 9 illustrates the analysis of a flat plate that is oriented edge on to the direction of flight (90 degrees yaw in Fig. 8). The first part of the analysis is the calculation of the projected area relative to each impact velocity direction. Figure 9(b) shows the probability associated with each impact velocity. Figure 9(c) shows the final result after multiplying the projected areas by the relative probability.

A_SURF reveals the coarseness, or granularity, in the spacecraft model and debris threat in the GEOMETRY analysis. The default of 45 threat directions in BUMPER gives only 22 velocities due to symmetry. This will produce gaps along the velocity axis. "Waves" on the surface are an artifact of the coarseness of the modelling. The sphere is an easy shape to analyze since it looks the same from any direction. (That is why it is a separate option in the AREA_Maker macro.) The projected area from any direction is shown in Fig. 10. Also shown is its appearance if it were modelled using facets that cover 15 degrees of curvature. The granularity, or waviness is obvious.

The sphere is also a good representation of the surface area of any spacecraft that is not Earth oriented. It will appear to be randomly tumbling to the debris flux and average out to the oblique impacts on a sphere with the same surface area.

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**Fig. 8 AREA_MAKER Available Geometries**
Since the distributions are not smooth, the analyst must recognize that adjacent cells all with moderately high impact rates can be more significant than a single cell with the maximum impact rate.

**Penetration Analysis**

Figure 11 shows the P_SURF analysis of the effective area in Fig. 9. This is an example of the text-based contour plot. The ballistic limit was the RESPONSE output for a 0.050 inch bumper, four inch standoff, MLI, and a 0.125 inch 2219 aluminum rear wall, using the BUMPERII regression equation and default analysis of Wilkinson momentum failure.

Figure 12 is an illustration of the velocities and obliquities for which most penetrating impacts could occur on one early concept for a space station module. (The same RESPONSE ballistic limit surface is used as in the previous example.) It can be noted that BUMPER analyzed the PNP for one year as 99.88305%, while P_SURF calculated it as 99.88475%. The effective area was identical. But, as mentioned previously, partitioning the area to discrete velocities and obliquities will affect the result, just as assuming a curved surface is represented by a flat facet. The probability of penetration (POP = 1 - PNP) was 0.11695% for BUMPERII to 0.11525% for P_SURF. The percent change between the two is 1.5% of the POP.

**Critical Damage Analysis**

Mathematically the calculations for the probability of no critical damage (PNCD) are no different from the PNP calculations except that a critical damage surface is used instead of the ballistic limit surface for penetration. Use of the previously described critical damage limits gives a
penetration of the baseline design, but collision
References


