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Generic module wall damage prediction equations for habitable spacecraft crew survivability evaluations

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ABSTRACT

The process used to calculate and reduce the consequences of meteoroid and orbital debris penetrations and their link to catastrophic failure has evolved over time. As the threat of the orbital debris population increased in the 1980s and early 1990s, NASA developed a tool to determine what percentage of space station penetrations might be survivable (referred to as the probability of no catastrophic failure, or PNCF) and how to improve that survivability percentage. The quantity PNCF is directly related to the PNP, or probability of no penetration, as calculated by *Bumper*, the code used by NASA to perform MOD risk assessments. Part of the process in determining PNCF involves calculating the size of the holes and cracks caused by any penetrations. A review of the original techniques used to calculate hole size and crack length as well as current equations revealed some serious concerns that needed to be addressed. As a result, a study was undertaken to develop revised models that would address these concerns. In this paper, the features of new generic hole- and crack-size prediction equations, as well as the phenomenology involved in the formation of holes and cracks in habitable space station modules are presented and discussed. By comparing the predictions of the new equations against the predictions of current hole and crack size models as well as against empirical data, we found that (1) the predictions of the new equations fit the empirical data just as well as, if not better than, the current models and that (2) the new equations displayed the appropriate phenomenological response characteristics as the diameters of impacting projectiles increased beyond the ballistic limit diameters. Based on the results, we believe that when the new hole and crack size equations are used in survivability assessments the fidelity of the PNCF calculations and predictions will also increase dramatically.

1. Introduction

The approach of spacecraft designers and operators in computing and reducing the consequences of a meteoroid (and later, an orbital debris particle) penetration and its link to catastrophic failure (defined here as a crew fatality) has changed over time. With earlier, relatively small spacecraft (e.g., Mercury, Gemini, Apollo, Soyuz), computing the likelihood of catastrophic failure was elementary as virtually any penetration of the capsule by a meteoroid would result in loss of its pressurized environment capability. In these analyses, the probability of catastrophic failure was considered as being roughly equal to the probability of penetration.

However, the advent of large space structures such as the International Space Station (ISS) allowed scenarios where many meteoroid and orbital debris (MOD) penetrations could be survivable. The large interior volumes separated by hatches could be independently sealed if found to be leaking, and the continuing presence of a "lifeboat" spacecraft (either the Soyuz or until recently the Space Shuttle orbiter) docked to the ISS may provide escape if necessary. As the orbital debris population (and the associated penetration threat) increased in the 1980s and early 1990s, NASA engineers began to develop a tool that would allow them to determine what percentage of ISS penetrations might be survivable for the crew and the ISS, and how to improve that survivability percentage with improved operations (e.g., sleep locations, internal hatch closure protocols, and spacecraft docking locations) and tools (e.g., repair patches, internal shielding, and leak detectors). Hypervelocity impact (HVI) testing also demonstrated that with improved shielding, penetrations resulted in larger holes in the space station

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pressure wall when they did occur, and that both the potential positive and negative effects of shield improvements needed to be considered as part of a comprehensive assessment of survivability.

Given these developments, NASA developed the *MSCSurv* computer code for quantifying a so-called '*R* factor' – the ratio (*R*) of orbital debris penetrations that would cause either one or more crew losses, or the long term (potentially irrevocable) loss of spacecraft habitability, to all orbital debris penetrations [1]. The overall probability of no catastrophic failure, or PNCF, of the crew or ISS due to impact by MOD particles is then computed using the equation:

$$\mathrm{PNCF} = \mathrm{PNP}^{\mathrm{R}} \tag{1}$$

where PNP, the probability of no penetration, is given by

$$\mathrm{PNP} = \exp(-N) \tag{2}$$

In Eq. (2), *N*, the number of impacts causing penetration, is equal to the sum of the penetrations in each region (N_i) over all regions ($i = 1$ to n) of the spacecraft. As shown in Eq. (3), N for each region is found from the product of the cumulative flux, *F* (number/m^2-year), of meteoroid and orbital debris impacts that exceed the failure limits (or ballistic limits), the exposed area, *A* (m^2), and duration or time exposed to the MOD flux, *t* (year). This equation demonstrates that MOD risk is proportional to the area and time the vehicle is exposed to the MOD threat.

$$N = \sum_{i=1}^{n} N_i = \sum_{i=1}^{n} (\mathrm{FAt})_i \tag{3}$$

PNP is determined using *Bumper*, and is a function of particle flux, module surface area, exposure time, and shield ballistic limit. *Bumper* is the standard code used by NASA, its contractors, and the international partners (Japan Aerospace Exploration Agency, Russian Federal Space Agency) to perform MOD risk assessments [2]. NASA has applied *Bumper* to risk assessments for ISS, Space Shuttle, Mir Space Station, extravehicular mobility units, and other satellites and spacecraft. NASA has expended significant effort [3] to review *Bumper* and benchmark it to other MOD risk assessment codes used by some ISS international partners.

The *R* factor is also a function of these parameters, plus HVI damage, crew operating parameters (such as position, egress characteristics, injury thresholds), and ISS equipment characteristics (such as protection levels, failure modes and effects). The *MSCSurv* tool was designed to quantify and improve the PNCF considering these factors for orbital debris impacts (note that only orbital debris impacts are currently considered within *MSCSurv*). There is no established requirement for the module or ISS level PNCF or *R* from MOD, although an ISS-level PNCF is reported as part of the ISS risk assessment process.

To calculate *R*, *MSCSurv* performs the following steps:

1. randomly generate a large number (e.g. billions) of spherical, aluminum orbital debris particles (size, velocity, and approach direction) based on selected NASA orbital debris environment models;
2. select an impact location for each particle generated, based on exposure of the ISS from this approach direction;
3. determine which of these particles penetrates the shields based on the interacting particle and configuration parameters;
4. predict the resulting damage from each particle that penetrates;
5. compare the predicted damage from the impact to critical levels required to induce loss of one or more crew members, considering the location and exposure of the crew to these damage levels, and their ability to escape from the damage and/or hazards; and
6. quantify *R* for each module and the module cluster taken as a whole, averaged over millions of simulated penetrations (billions of impacts).

To perform Step 3, *MSCSurv* uses ballistic limit data from *Bumper* to insure consistency with *Bumper* when quantifying the number of orbital debris particles that will penetrate the spacecraft shields. Step 4 requires use of HVI damage prediction equations to determine hole size, crack length, and penetration depth into the interior of the module. While Steps 3 and 4 are related to HVI phenomenology, Step 5 requires other assumptions regarding the capability of the ISS to tolerate damage and the reactions of the crew and their physical capability to withstand and escape harm. The details of *MSCSurv* have been documented in the *MSCSurv* User's Guide [4].

Once completed, these calculations determine an *R* factor prediction for each module based on each of seven failure modes, including:

1. critical external equipment failure,
2. manned module critical cracking (or unzipping),
3. critical internal systemic equipment failure,
4. critical internal payload equipment failure,
5. crew hypoxia during escape or rescue,
6. fatal fragmentation injury to crew, and
7. critical thrust from a penetration causing high angular velocity (occurring only when key guidance, navigation, and control (GN&C) equipment is damaged) preventing safe escape vehicle departure.

In addition to the above seven failure modes identified that may cause an "immediate" loss, *MSCSurv* also conducts a longer term probabilistic assessment of the condition of the ISS and its crew when an immediate loss does not occur, including the following three conditions:

1. fragmentation or secondary factors causing non-critical injury,
2. loss of ISS control, and
3. critical module depressurization.

By altering the input parameters regarding crew operations, internal arrangement of the ISS modules, and other design factors, an analyst can compare the safety of various existing or proposed modes of ISS operation. This comparison can also be used to identify changes that could be made to lower overall probability of crew loss.

To calculate the value of *R*, *MSCSurv* must consider numerous assumptions regarding crew and ISS response to an impact. Some of the most important of these include:

1. hole and crack size given a penetration, for different shield types,
2. depth of penetration into the interior of the modules and external critical equipment (e.g., pressurized tanks), taking into account:
   2.1. protection offered by the interior and exterior equipment, and

2.2 penetration equation for multiple material types, and

3. crew response to HVI (e.g., alarm response, wakeup time, egress speed, time to check pressure, time to close hatches, time to find wounded crew, time to egress ISS, and hypoxia level prior to loss).

In this paper, we focus on the first of these, that is, the manner in which *MSCSurv* calculates module pressure wall hole diameters and