Assessment Method of Spacecraft Survivability in the Space Debris Environment

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Abstract:

During on-orbit operations, spacecraft are constantly threatened by space debris impacts, particularly from tens of billions of sub-1cm-sized debris particles. Current mitigation strategies focus on enhancing protective structures to improve spacecraft resilience against such impacts. Through survivability assessment and analysis, targeted measures—such as reinforced shielding or layout modifications—are implemented to maximize on-orbit safety at minimal economic cost. The spacecraft survivability evaluation process encompasses impact susceptibility analysis, component vulnerability analysis, and system-level survivability assessment. This paper systematically outlines the logical framework of spacecraft survivability assessment, analyzes fundamental requirements for each evaluation phase, and provides foundational insights for developing survivability assessment systems.

1 INTRODUCTION

Space debris and spacecraft coexist in orbital space, with relative impact velocities ranging from 0 to 16 km/s and an average collision speed of 10 km/s[0]. Micrometeoroids, typically traveling in solar orbits, exhibit even higher velocities, with relative speeds to spacecraft ranging from 3 to 90 km/s and an average speed of 20 km/s[2]. The hypervelocity impacts generate shockwaves and debris clouds, resulting in damage zones far exceeding the size of the impacting particles. This can lead to structural damage, functional degradation or failure of components, and even spacecraft disintegration, directly jeopardizing mission success and crew safety.

As of March 2023, the International Space Station (ISS) has performed 35 debris avoidance maneuvers[3]. In 1998, the Space Shuttle *Discovery* (STS-91 mission) returned with 45 impact craters larger than 1 inch (approximately 2.54 cm) on its surface[4]. On December 15, 2022, the Soyuz MS-22 spacecraft docked to the ISS experienced a coolant leak, rendering it incapable of crewed return. ROSCOSMOS concluded that the radiator's perforation was likely caused by a micrometeoroid impact at 7 km/s[5].

Facing the impact threats posed by micrometeoroids and space debris (MM/SD), spacecraft can adopt distinct protective measures based on the damage potential of different debris sizes. As shown in Figure 3: For trackable debris (5~10 cm) and cataloged debris (>10 cm), real-time monitoring and early warning systems enable collision avoidance via orbital maneuvers. For sub-1 cm debris, spacecraft typically employ enhanced shielding structures to protect critical components. Debris in the 1~5 cm range currently poses a unique challenge: neither effective tracking nor sufficient shielding is technologically feasible. However, sub-1 cm debris dominates the population of space debris. Notably, 80% of debris larger than 5 mm falls within the 5–10 mm size range[6]. Consequently, the primary collision threat to on-orbit spacecraft originates from sub-1 cm debris, with passive shielding remaining the predominant countermeasure.

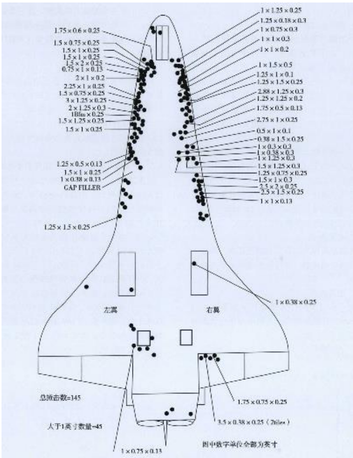

Figure 1 Distribution of impact craters on the surface of space shuttle after mission STS-91

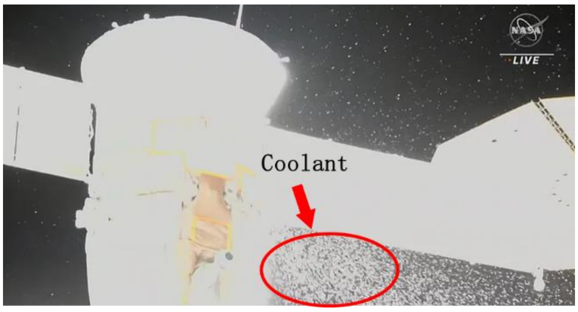

Figure 2 Coolant leakage accident caused by impact of "MS-22

However, the addition of protective structures introduces a dual burden: increased spacecraft mass and elevated construction costs, with the added mass further driving up launch expenses. Therefore, during the design phase, critical decisions—such as determining the extent of shielding, components to prioritize for protection, and optimal orbital trajectory selection—must be carefully weighed. By conducting survivability assessments, rational optimization of spacecraft shielding design can be achieved. This approach not only reduces construction

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and launch costs but also enhances on-orbit survivability throughout the spacecraft's operational lifespan.

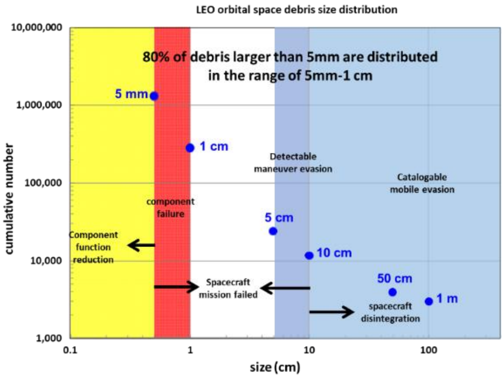


Figure 3 Distribution of quantity with varying sizes of space debris in Low Earth orbit(LEO)[6]

2 TECHNICAL ROUTE FOR SPACECRAFT SURVIVABILITY ASSESSMENT

Survivability assessment technology for spacecraft in the space debris environment focuses on evaluating the probability of survival (P_S)—the likelihood that a spacecraft system avoids functional degradation or failure—when exposed to space debris as the primary impact hazard. This methodology treats the spacecraft as the core subject of analysis, with space debris serving as the stochastic risk source. As illustrated in Figure 4, the overarching framework for spacecraft survivability assessment involves:

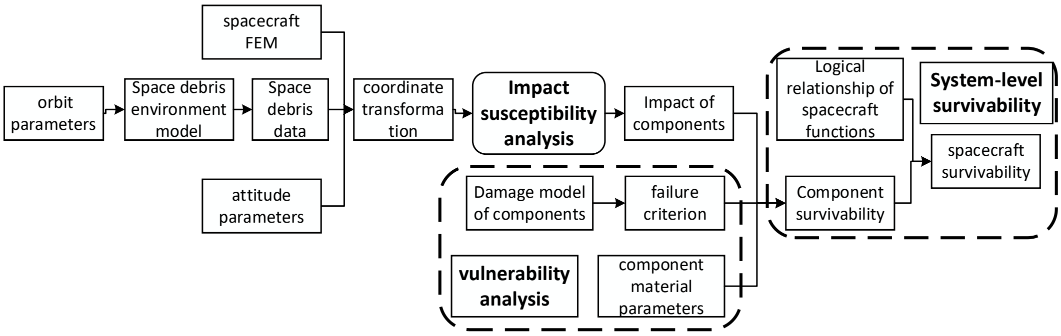


Figure 4 General idea of spacecraft survivability assessment

The geometric models of spacecraft are highly complex and diverse, with potential mutual shielding effects between components. To enable granular assessment of space debris impact exposure across different spacecraft regions, a "divide and conquer" discretization approach is adopted. This involves decomposing the spacecraft geometry into fine mesh elements, as illustrated in Figure 5.

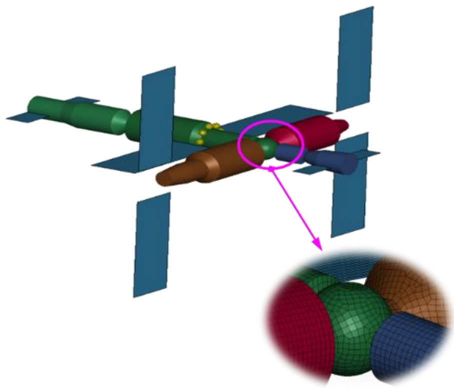


Figure 5 Spacecraft geometric model

Space debris environment data is defined in the flow-aligned coordinate system relative to the spacecraft's on-orbit state. To analyze debris impacts, both the spacecraft and debris trajectories must be aligned within a unified coordinate system. As shown in Figure 6, this involves transforming the spacecraft's coordinates into the orbital frame based on its attitude parameters. For each mesh element, impact analysis focuses on internal component vulnerability—the critical factor determining system survivability.

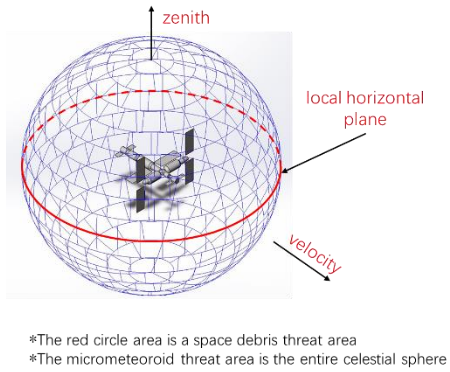


Figure 6 Spacecraft model in space debris environment

Due to shielding effects between internal and external spacecraft components, components positioned forward can protect rear components from debris impacts in specific debris flux directions—either by fully blocking the debris or requiring debris to penetrate the fore components before damaging shielded areas, as illustrated in Figure 7. The overall technical framework for spacecraft survivability assessment depends on the vulnerability analysis methodology applied to internal components. Current methods for analyzing component vulnerability under hypervelocity space debris impacts fall into two categories:

a. Ballistic Limit Equation (BLE) Method

This approach treats all components along the debris trajectory as an integrated shielding stack, focusing on damage to the final layer of shielding. Failure is determined using multi-layer BLEs. While computationally efficient, it cannot assess secondary damage caused by hypervelocity-induced debris clouds. Representative models include: BUMPER[9], PIRAT(Particle Impact Risk and Vulnerability Analysis Tool)[10].

b. Debris Cloud Modeling Method[8]

Each component along the debris path is analyzed individually. Secondary debris clouds—generated after hypervelocity penetration of each structural layer—are characterized by their velocity, size distribution, and propagation direction. These secondary debris are iteratively tracked until they either exit the spacecraft or meet predefined failure criteria. Although this method enables detailed internal damage assessment, it suffers from high computational costs. Representative models include: ESABASE2/Debris[11], HIVAM[12] (Hypervelocity Impact Vulnerability Area Model), TVAS (Target Vulnerability Analysis Software)[8].

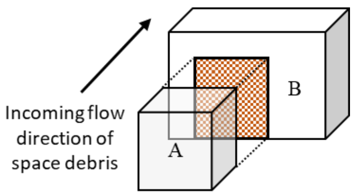


Figure 7 Schematic of shielding

2.1 Fundamental Principles of the BLE Method

The BLE method determines whether functional degradation or failure occurs in internal spacecraft components by utilizing the impact limit equation of multi-layer plates. It defines the cover plate of internal components as the final target layer, using its penetration as the failure criterion for these components. A shadowing algorithm is employed to analyze the shielding relationships between internal and external components, thereby identifying the BLE parameters required for vulnerability assessment of internal components.

During the analysis, the spacecraft's finite element model serves as the analytical subject to establish shielding relationships between surface elements. As shown in Figure 8, surface element **a** shields surface element **b** along the trajectory of space debris impact. When analyzing the vulnerability of surface element **b**, it is combined with surface element **a** to form a double-layer plate structure. The failure of surface element **b** is then determined by evaluating the BLE of this double-layer configuration.

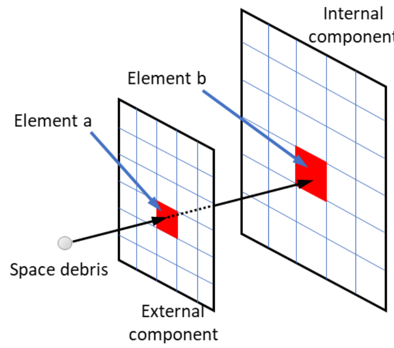


Figure 8 Schematic of BLE method

The determination of shielding relationships between surface elements can be achieved through mature algorithms in computer graphics, typically using a simple region scanning method. As illustrated in Figure 9, if the projection d of the center α of surface element **a** along the debris impact velocity direction onto the plane of surface element **b** lies within the area of surface element b, then surface element a is considered to shield surface element **b**.

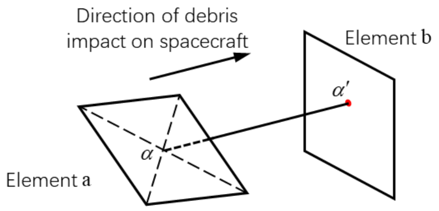
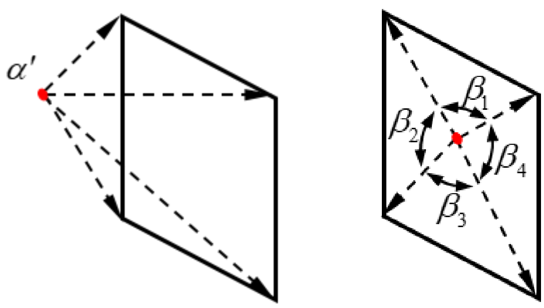


Figure 9 Schematic of judging panel shielding

Whether the projection point α' lies within the region of surface element **b** can be determined using the angle summation check method. As illustrated in Figure 10, the angles (β_1、 β_2、 β_3、 β_4) formed between the projection point α' and the adjacent vertices of surface element **b** are calculated. If the sum of these four angles equals 360°, the projection point α' is located within the region of surface element **b**; otherwise, it lies outside the region.



(a) Not in the panel *(b) In the panel*

Figure 10 Relationship diagram between center point projection and panel

As shown in Figure 8, in the BLE method, space debris causes "point damage" to internal components, specifically affecting only the internal components corresponding to surface element **b**. However, during actual impact events, after penetrating external components, space debris may generate a secondary debris cloud. This cloud can induce "area damage" within the spacecraft, potentially compromising multiple internal components

In the BLE method calculation process, the damage caused by secondary debris clouds to internal components is neglected, leading to discrepancies between evaluation results and actual scenarios. However, this approach offers relatively high computational efficiency. Therefore, it is generally adopted during the preliminary survivability assessment phase of spacecraft design to assist designers in initial layout planning or protective design optimizations

2.2 Fundamental Principles of the Debris Cloud Model Method

The Debris Cloud Model method simulates damage caused by secondary debris generated from hypervelocity impacts on internal spacecraft components. As illustrated in Figure 11, when space debris hypervelocity impacts penetrate the spacecraft's protective structure, they generate a conical-shaped debris cloud that disperses inward. This cloud poses threats not only to components along the original debris trajectory but also to surrounding areas. Consequently, employing the Debris Cloud Model method for internal component vulnerability analysis more accurately reflects the actual damage scenarios compared to traditional approaches.

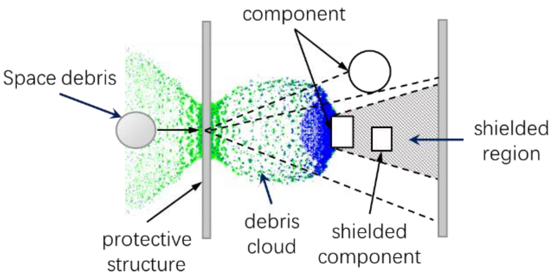


Figure 11 Schematic of shielding analysis based on debris cloud model

When conducting vulnerability analysis of spacecraft internal components using the debris cloud model method, it is necessary to address not only the shielding issues during the impact of space debris on components but also the secondary debris clouds generated by hypervelocity impacts. To facilitate tracking of the impact conditions of space debris and secondary debris on components, the ray-tracing method is generally employed to simulate both space debris and secondary debris particles, where each ray represents a space debris particle or a secondary debris particle.

When simulating space debris impacts on spacecraft components using the ray tracing method, it is necessary to generate rays from the grid centers of components potentially exposed to direct debris impacts and perform shadowing analysis to eliminate grids obstructed by upstream components along the debris trajectory. As shown in Figure 12, the rays generated from components 2 and 3 intersect with other grid cells along their impact paths and are therefore discarded. During the analysis, intersection detection must be performed between rays generated from each grid and all other grids. Rays intersecting with other grid cells along their trajectory are excluded to ensure computational accuracy.

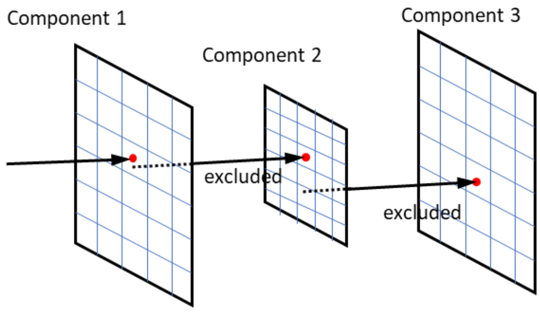


Figure 12 Schematic of initial ray generation

When analyzing secondary debris impacts on internal components, the impact point of the primary space debris serves as the origin of secondary debris rays. The direction vectors of these rays represent the dispersion trajectories of secondary debris, while parameters such as debris size and velocity—derived from debris cloud modeling—are assigned to each ray. Intersection tests between the rays and the spacecraft's geometric model determine whether internal components are struck by secondary debris. The relative shielding order of components is established based on the distance between intersection points and the ray origin, thereby identifying components exposed to debris cloud impacts.

As evident from this process, the debris cloud modeling method differs fundamentally from the BLE method. It captures the area-wide damage inflicted by hypervelocity-induced secondary debris clouds on internal components, offering a more realistic representation of threats in the space debris environment. However, simulating secondary debris via ray-tracing techniques introduces significant computational inefficiencies.

3 SPACECRAFT IMPACT SUSCEPTIBILITY AND ITS CHARACTERIZATION METHOD

The concept of "susceptibility" is derived from target vulnerability in ordnance science, referring to the likelihood of a target being detected by sensors or struck by threatening objects12. In spacecraft survivability assessment, this concept is redefined as "the probability of a spacecraft being impacted by space debris (including human-generated debris and natural micrometeoroids) in the space debris environment.

The degree of spacecraft impact susceptibility depends on three factors:

a. **Environment**: The space debris environment surrounding the spacecraft, comprising both anthropogenic debris and natural micrometeoroids.

b. **Threat**: Hypervelocity impacts from space debris particles.

c. **Spacecraft characteristics**: Geometric configuration, on-orbit duration, attitude parameters, and other operational properties.

3.1 Space Debris Environment Model Data

The space debris environment encountered by on-orbit spacecraft consists of artificial space debris and natural micrometeoroids. Artificial space debris originates primarily from human activities in Earth's orbital space, and thus follows Earth-bound orbits. Micrometeoroids, on the other hand, are natural particles traveling through interplanetary space. Most originate from the disintegration or fragmentation of comets and asteroids, with a minority ejected from collisions involving the Moon, Mars, or other celestial bodies. Consequently, micrometeoroids predominantly follow heliocentric (Sun-centered) orbits. This fundamental difference in orbital mechanics leads to distinct relative velocity vectors when these particles impact spacecraft. As illustrated in Figure 13, artificial debris shares Earth-bound orbits with spacecraft, with most operating in near-circular or low-eccentricity orbits—highly elliptical orbits being relatively rare in practice.

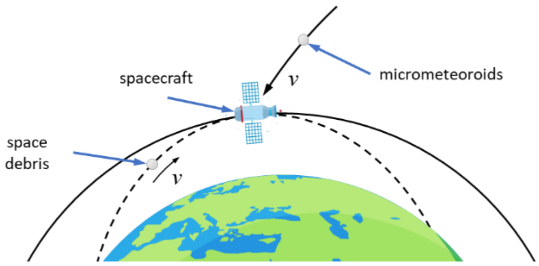


Figure 13 Schematic of debris impact on spacecraft

According to ORDEM[14] calculations, the elevation angles of artificial space debris relative to spacecraft impact velocities are predominantly concentrated within ±15°. Given that space debris environment engineering models typically output elevation angle data at 10° intervals, it is practically reasonable to assume that the impact velocity vectors of artificial debris are parallel to the spacecraft's local horizontal plane in engineering analyses. In contrast, micrometeoroids primarily follow heliocentric orbits and may theoretically strike the spacecraft from any celestial direction. Consequently, impact threats must be evaluated across the entire celestial sphere surrounding the spacecraft.

The space debris environment serves as the operational background for on-orbit spacecraft, with its data acting as the threat source in spacecraft survivability assessments. These environmental data—including fundamental parameters such as particle flux, impact velocity, collision direction, and particle diameter required for survivability analysis—are primarily generated by space debris environment engineering models and micrometeoroid environment models. Currently, the most widely used environmental engineering model software in survivability assessments include: SDEEM2019 (Harbin Institute of Technology), MASTER-8[13], ORDEM 3.1[14]. Each of these three software tools employs its own unique output format for environmental data.

3.2 Coordinate system and its coordinate transformation

The space debris data output from the spacecraft geometric model, motion model, and space debris environment engineering model all define their respective coordinate systems. During the survivability calculation process, the data of each model must be unified into the same coordinate system for calculation. Therefore, before carrying out viability analysis, the definition of each coordinate system must be clarified, and coordinate transformation methods must be used to transform the data under each coordinate system into the same coordinate system to facilitate subsequent calculations.

3.2.1 Definition of coordinate system

(1) The orbit coordinate system

The orbit coordinate system[15] $O\text{-}X_cY_cZ_c$ is defined by the orbital plane, with its origin located at an arbitrary point along the orbit. the X_c-axis is along the intersection between the orbital plane and the local horizontal plane, and points to the forward direction of the spacecraft; the Z_c-axis points to the center of the earth along the local vertical line, and the Y_c-axis is determined by the right-hand rule.

(2) The body coordinate system

The body coordinate system $O\text{-}X_bY_bZ_b$ [15], The origin is located at the mass center of the spacecraft O, and the three axes of the coordinate system are the inertial principal axes of the spacecraft.

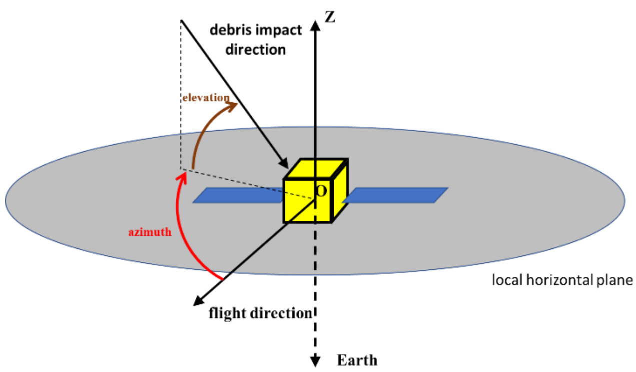


Figure 14 Coordinate system of space debris infow

(3)Space debris flux coordinate system

The space debris particle flux coordinate system[13] defines the directional relationship between incoming particles and the spacecraft. As shown in Figure 14: The azimuth angle of particle impact is defined in the local horizontal plane, with Z direction as normal vector and clockwise as positive; the elevation angle is defined as the angle between velocity vector and local horizontal plane, and the velocity direction pointing to the earth is positive.

3.2.2 Coordinate transformation

In survivability analysis calculations, coordinate systems must be unified through coordinate transformations[16]. As illustrated in Figure 15, let the reference coordinate system be denoted as $O\text{-}XYZ$. Coordinate system $O\text{-}X'''Y'''Z'''$ is derived by sequentially rotating system A about its axes in a specified $Z\text{-}X\text{-}Z$ Euler by angles ψ , φ , θ , respectively.

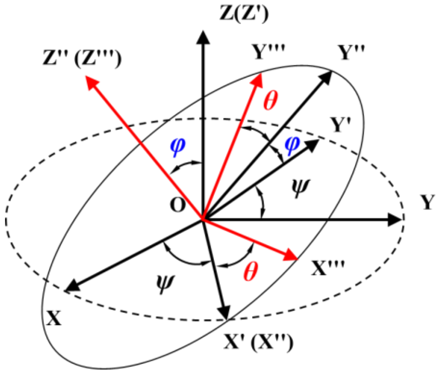


Figure 15 Z-X-Z sequential coordinate transformation

In coordinate system $O-X'''Y'''Z'''$, the coordinates can be expressed as:

$$
\begin{Bmatrix} X''' \\ Y''' \\ Z''' \end{Bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & \sin\varphi \\ 0 & -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix}
$$
$$
= \begin{bmatrix} \cos\theta\cos\psi - \sin\theta\sin\psi\sin\varphi & \cos\theta\sin\psi + \sin\theta\cos\psi\cos\varphi & \sin\theta\sin\varphi \\ -\sin\theta\cos\psi - \cos\theta\cos\varphi\sin\psi & -\sin\theta\sin\psi + \cos\theta\cos\psi\cos\varphi & \cos\theta\sin\varphi \\ \sin\psi\sin\varphi & -\sin\varphi\cos\psi & \cos\varphi \end{bmatrix} \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} \tag{1}
$$

3.3 Characterization method of spacecraft impact susceptibility

Since Kessler and Cour-Palais[17] introduced the concept of flux in 1978, the number of debris particles λ passing through a cross-sectional area S over a time interval t has been expressed as:

$$\lambda = FSt \tag{2}$$

Here, F represents the space debris flux (environmental factor), while S and t characterize the spacecraft system—specifically, its effective cross-sectional area projected along the debris impact direction and its on-orbit mission duration. These parameters depend on the spacecraft's geometric configuration, attitude dynamics, and orbital profile.

The space debris flux[18], output by space debris environment engineering models, quantifies the number of particles within specified size, velocity, and spatial position ranges that pass perpendicularly through a unit area per unit time. As illustrated in Figure 16, flux is mathematically defined as:

$$F(\Delta\boldsymbol{r},\Delta\delta,\Delta\boldsymbol{v}) = \partial^2(q(t,\Delta\boldsymbol{r},\Delta\delta,\Delta\boldsymbol{v}))/(\partial S\partial t) \tag{3}$$

Where: D-Space debris flux, unit: 1/m^2/year；

q -Number of space debris particles within specified ranges；

$\Delta\boldsymbol{r}$ -Spatial position interval, defined using orbital elements；

$\Delta\delta$ -Debris size interval, typically discretized into bins；

$\Delta\boldsymbol{v}$ - Velocity interval (magnitude and direction)。

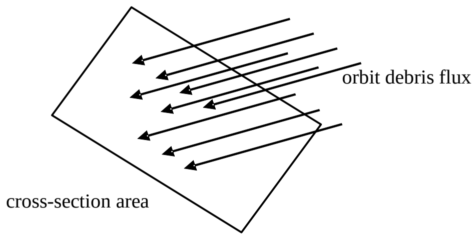


Figure 16 Definition of space debris flux

For spacecraft in orbit, collisions with space debris are statistically independent events, thus satisfying a Poisson distribution[19]. Let $p(N)$ denote the probability of experiencing N impact events. Then:

$$p(N) = \frac{\lambda^N}{N!}e^{-\lambda} \tag{4}$$

Where, λ : Expected number of impacts.

The probability of zero impacts ($N = 0$) is:

$$p(N=0) = e^{-\lambda} \tag{5}$$

Then the probability of at least one impact event occurring is:

$$p(N>0)=1-e^{-\lambda} \tag{6}$$

Substitute equation (2) into (6) to obtain the probability (susceptibility) P_{H_i} of impact.

4 VULNERABILITY OF SPACECRAFT COMPONENTS AND ITS CHARACTERIZATION METHOD

Vulnerability is defined as the degree to which a subject is susceptible to damage or injury, reflecting its inherent fragility and capacity to withstand accidental damage under specific conditions. To facilitate the establishment and application of vulnerability models for spacecraft components, this study defines spacecraft component vulnerability as the capability of spacecraft components and assemblies to resist space debris impacts. This vulnerability represents the "sensitivity" of component damage to damaging factors (space debris), which can be comprehensively described through three integrated aspects: failure modes, damage laws, and damage equivalence models.

4.1 Failure mode of components

Damage to spacecraft components and assemblies includes both superficial structural damage and mission-capability degradation resulting from space debris impacts. Such impacts may lead to functional loss or performance deterioration, manifesting as distinct damage levels or failure modes. The failure types comprise service life reduction, functional degradation, and operational failure, which are collectively termed component failure modes[20].

The classification of failure modes is inherently qualitative and subjective, based on components/assemblies' functional requirements and operational context. Different damage mechanisms induce distinct failure modes, which govern subsequent damage effects — specifically the causality linking failure modes to space debris impact conditions. In this study, components/assemblies under hypervelocity space debris impacts exhibit failure modes reflecting particle impact responses. These responses demonstrate probabilistically quantified inherent randomness, mathematically defined as a functional relationship between the probability of a specific failure mode and given space debris impact conditions.

4.2 Damage rule of components by HVI

Damage to spacecraft components/assemblies from space debris impacts exhibits inherent randomness, quantified through probabilistic metrics. The damage law is defined as the functional relationship between the probability of component/assembly damage (under a specific failure mode) and the characteristic intensity parameters of damaging factors (e.g., space debris), expressed as a probability density function (PDF) or probability distribution function. This law mathematically generalizes the "damage susceptibility" in component vulnerability, reflecting damage response mechanisms — specifically their correlation with space debris. Its mathematical form may adopt continuous or piecewise functions, with the general expression formulated as[21]:

$$P_{k/h}=A\big(M,f(k)\big)\cdot f(k) \tag{7}$$

In the formulation, let $P_{k/h}$ denote the damage probability and k represent the characteristic intensity parameters of the damage-inducing factor (e.g., space debris impact energy). $A(M,f)$ characterizes the response relationship between functional impairment and structural damage in components/assemblies, reflecting the mechanism transferring functional degradation to structural failure. $f(k)$ defines the structural damage response to the damage-inducing factor, dependent on component geometry, material properties, and intensity parameters. The parameter k may be a scalar or vector described by failure criteria (e.g., critical stress thresholds). Depending on the specific form of k, distinct damage law functions apply to different failure criteria. In space debris studies, k typically corresponds to the critical debris particle size or impact velocity.

Commonly used damage law functions include: Bernoulli distribution, linear probability-density functions, and Poisson distribution. For engineering applications, the Bernoulli distribution is typically employed to characterize the occurrence probability of deterministic failure modes in components/assemblies， formulated as:

$$P_{k/h}=\begin{cases}0 & d<d_c\\ 1 & d\ge d_c\end{cases} \tag{8}$$

Given the conditional probability $P_{K_i|H_i}$ (vulnerability) of different failure modes occurring when spacecraft components/assemblies are subjected to deterministic impacts — determined by synthesizing empirical data, engineering judgment, and experimental validation — the damage probability P_{K_i} of components/assemblies in the space debris environment can be expressed as:

$$P_{K_i}=P_{H_i}\times P_{K_i|H_i} \tag{9}$$

4.3 Damage equivalent model of components by HVI

The damage equivalence model for spacecraft components/assemblies is a simplified, regularized, and standardized representation constructed by analyzing their physical/mechanical responses to specific damage factors. It adheres to two principles: geometric-physical similarity to actual systems and functional damage equivalence. This model provides a quantitative framework for studying damage laws, failure criteria, and thresholds. Its primary value lies in enabling computational analysis of complex damage mechanisms through abstraction while retaining critical failure characteristics of real-world engineering systems.

4.3.1 Component Classification Based on Damage Induction Mechanisms

Spacecraft systems exhibit high complexity with diverse components and assemblies. To facilitate the establishment of damage equivalence models, components are classified into two categories based on functionality: structural components/assemblies and functional components/assemblies. Structural components/assemblies refer to parts that maintain the spacecraft's configuration, bear and transfer loads, and ensure specific stiffness and dimensional stability. When subjected to space debris impacts, these structures undergo purely mechanical behavioral changes without compromising their intrinsic functionality or affecting other components/assemblies.

Functional components/assemblies refer to those that fulfill specific functions on spacecraft, which can be basic functional elements within subsystems, or payloads realizing spacecraft mission functions such as remote sensors, antennas, and even astronauts. Vulnerability analysis of functional components/assemblies is more complex, requiring characterization of their functional damage during the analytical process. The core challenge in spacecraft component vulnerability analysis lies in how to characterize the functional damage of these functional components/assemblies.

4.3.2 Damage Equivalence Model for Spacecraft Components and Assemblies

Based on spacecraft component classification, damage equivalence models are categorized into configuration equivalence models and functional equivalence models. The configuration equivalence model, primarily applied to structural components/assemblies, considers only physical damage (e.g., deformation, perforation) without addressing functional degradation. Its purpose is to assess space debris impact effects or component damage resistance by establishing damage criteria or equivalent structural representations using standardized materials, derived from mechanical responses and physical damage thresholds (e.g., critical impact energy). Examples include using impact limit equations for single-layer plates, honeycomb panels, and Whipple shields, while composites and MLI (Multi-Layer Insulation) non-aluminum structures are simplified as aluminum alloy plates with equivalent areal density.

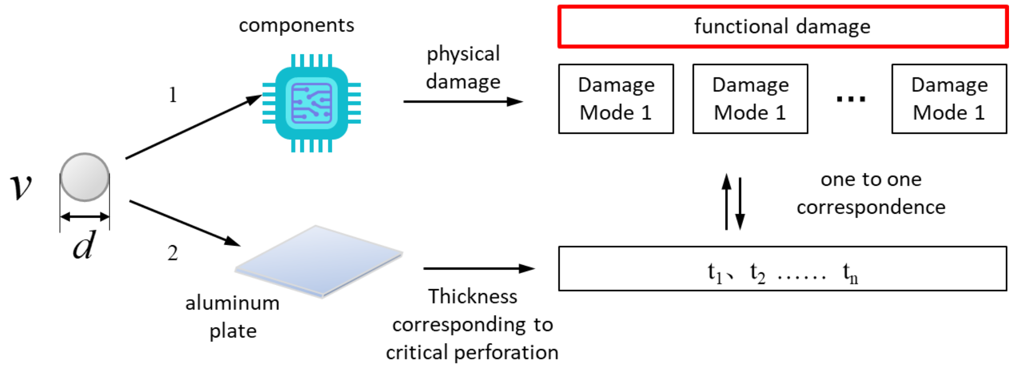


Figure 17 Schematic of damage equivalent model of functional components

The functional equivalence model for spacecraft components/assemblies prioritizes their functional degradation by analyzing the correlation between failure modes and performance impairment. The theoretical modeling process (Route 1 in Figure 17) employs hypervelocity impact experiments to establish a mapping relationship[22] between observed physical damage (e.g., cracks, perforations) and component performance metrics (e.g., power output, thermal resistance). This quantifies the correlation between performance degradation thresholds and physical damage severity, ultimately integrating the physical/mechanical response laws governing component functionality under damage-inducing factors (e.g., debris velocity, impact angle).

For spacecraft with diverse component types, conducting hypervelocity impact tests on every component to study vulnerability presents significant engineering impracticalities. To reduce complexity in survivability assessments, a unified functional equivalence model is adopted for characterizing the vulnerability of functional components/assemblies. Given aluminum alloy's prevalence in spacecraft construction and well-established hypervelocity impact damage laws for aluminum single-layer plates, functional damage is modeled equivalently using the critical penetration thresholds of aluminum plates with defined thicknesses. As shown in Figure 17, space debris particles with specific size, velocity, and impact angle induce physical damage to components/assemblies, subsequently leading to functional degradation.

The functional damage of spacecraft components/assemblies is quantified using the critical perforation thresholds of equivalent aluminum plates. Specifically, aluminum plates with standardized thicknesses define the critical damage thresholds — where plate perforation under given impact conditions directly correlates to component functional failure. This standardized approach enables consistent damage assessment across diverse components, simplifying vulnerability model development for spacecraft systems and enhancing their applicability in engineering survivability analyses.

4.4 **Failure Criteria and Failure Evaluation Methodologies of components**

Failure Criteria are quantitative descriptions of component/assembly failure, encompassing two aspects: first, the occurrence of specific failure modes and their quantitative standards; second, the relationship between the degree of component damage and the intensity of damage-inducing factors acting upon them. Failure Thresholds are critical values determining whether specific failure modes occur, typically expressed using threshold values of damage-inducing factor intensity parameters (e.g., the critical size of space debris).

Section 4.3 establishes damage equivalence models based on component types. For structural components/assemblies, the failure mode under space debris impacts is perforation. Typical structural components (e.g., protective structures or load-bearing supports) are directly characterized through impact limit equations specific to their configurations or equivalently modeled as single-layer aluminum plates described by corresponding plate impact limit equations.

5 SPACECRAFT SYSTEM-LEVEL SURVIVABILITY

The survivability of a spacecraft system is defined as the probability that the failure or functional degradation of its components or subsystems leads to the failure or degradation of the spacecraft system's overall functionality. The steps for assessing spacecraft system-level survivability[23] are as follows: Step 1: Identify the essential functions required for the spacecraft to complete its designated mission. Step 2: Determine the subsystems and components responsible for executing these essential functions. Step 3: Analyze the impact of different failure modes of individual components or subsystems on their ability to perform their essential functions through Failure Mode and Effects Analysis (FMEA). Step 4: Link component or subsystem failure modes to hypervelocity impact damage using Damage Mode and Effects Analysis (DMEA). Step 5: Evaluate the criticality of each damage mode via Criticality Analysis (CA). Steps 4 and 5 can be combined into Damage Mode, Effects, and Criticality Analysis (DMECA). Finally, establish the logical relationship between component damage and system-level damage, typically represented through Fault Tree Analysis (FTA).

5.1 **Assessing System-Level Survivability Based on Fault Tree**

Fault Tree Model[24] is a qualitative model that describes the functional and logical relationships among spacecraft components, subsystems, and the system as a whole, while also capturing fault propagation pathways. In this framework: The top event is defined as the spacecraft system's functional failure. Basic events represent component-level failures or functional degradation caused by hypervelocity impacts. Intermediate events encompass all logical connections between the top event and basic events. These events are represented using standardized symbols (e.g., rectangles for events, AND/OR gates for logic) and interconnected via logic gates to form a hierarchical tree diagram, as illustrated in Figure 18.

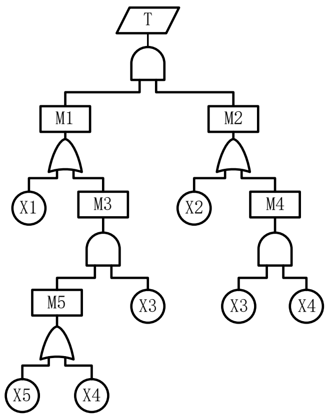


Figure 18 Fault tree diagram

Classification of Events in a Fault Tree:

a. Top Event: The Top Event is located at the top of the fault tree and represents a system-level failure or functional degradation in the spacecraft caused by the failure or functional degradation of one or more components or subsystems. As such, it can only serve as the output of a logic gate and cannot act as the input to any logic gate. In fault tree diagrams, this event is typically represented by the symbol shown in Figure 19a.

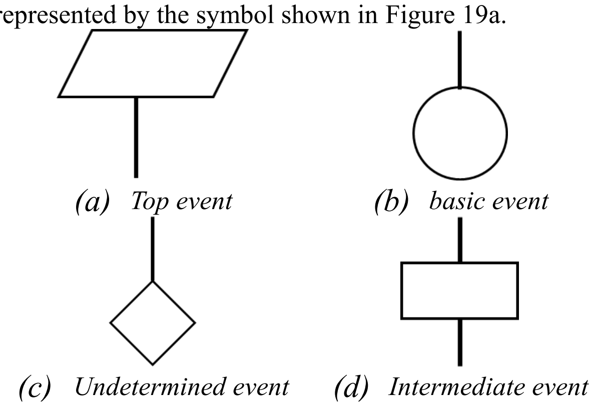


Figure 19 Fault tree event symbol

b. Basic Event: The Basic Event is located at the bottom of the fault tree and typically represents the failure or functional degradation of a component caused by hypervelocity impacts from space debris. As such, it can only serve as an input to a logic gate and cannot act as an output of any logic gate. In fault tree diagrams, this event is generally represented by the symbol shown in Figure 19b.

c. Undeveloped Event: The Undeveloped Event refers to a basic event in a specific fault tree analysis that does not require further investigation into its causes. In fault tree diagrams, it is typically represented by the symbol shown in Figure 19c.

d. Intermediate Event: The Intermediate Event is a resultant event located between basic events and the top event. It typically represents the failure or functional degradation of a spacecraft subsystem or component caused by the failure or degradation of one or more components. Unlike basic or top events, it can act as both an output event (triggered by lower-level events) and an input event (contributing to higher-level failures). In fault tree diagrams, it is usually represented by the symbol shown in Figure 19d.

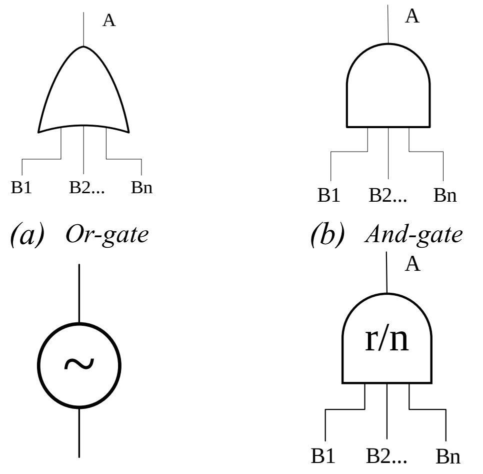
Logic Gates and Their Symbols:

a. OR gate: Indicates that the output event does not occur if and only if none of the input events occur. In other words, if any one or more input events occur, the output event will occur. When n basic events in a fault tree are connected by an OR gate, it is equivalent to n units connected in series in a logic diagram. The symbol is shown in Figure 20a.

b. AND gate: Indicates that the output event occurs if and only if all input events occur. When n basic events in a fault tree are connected by an AND gate, it is equivalent to n units connected in parallel in a logic diagram. The symbol is shown in Figure 20b.

c. NOT gate: Indicates that the occurrence of the output event is the opposite of the input event. The symbol is shown in Figure 20c.

d. Voting gate: Indicates that the output event occurs only if r or more of the n input events occur. The symbol is shown in Figure 20d.



(a) Or-gate *(b) And-gate*

(c) Not-gate *(d) Votie-gate*

Figure 20 Fault tree logic gate symbols

5.2 Construction of Spacecraft Functional Logic Relationships

Fault Tree Construction serves as the foundation of Fault Tree Analysis (FTA) and is critical to the system-level survivability assessment. Fault tree construction can be divided into top-down and bottom-up approaches. The former assumes a component failure and analyzes its consequences, while the latter starts from an undesired top event and traces back to its root causes. For spacecraft system-level survivability analysis, the top-down method is typically employed—beginning with the degradation or failure of spacecraft system functions and systematically investigating downward. The specific steps are as follows:

a. System Analysis and Fault Identification. By reviewing spacecraft documentation or consulting expert knowledge bases, analyze the system's functions, structure, operational principles, failure modes, fault sources, and their impacts.

b. Definition of the Top Event. For spacecraft system survivability assessment, the top event of the fault tree is usually defined as system-level functional degradation or failure that jeopardizes mission success.

c. Fault Tree Development. After defining the top event, identify the subsystems contributing to the functional failure. Further break down the analysis to subsystems, components, and parts until all underlying factors affecting spacecraft functionality are traced. Represent each element (components, subsystems, system) with appropriate event symbols and connect them using suitable logic gates (e.g., AND, OR).

d. Fault Tree Simplification. Starting from the basic events (bottom level), derive logical expressions for each hierarchical event relationship. Apply Boolean algebra to analyze and compute the fault tree structure, eliminating redundant events to optimize the model.

5.3 Implementation of System-Level Survivability Assessment Techniques

The complexity of fault tree construction varies significantly. For relatively simple fault trees, the top event can be directly represented by basic events in an intuitive manner. However, for complex fault trees, it becomes considerably difficult to express the top event solely through basic events. Therefore, minimal cut sets are generally employed for fault tree analysis and computation.

In the process of spacecraft system survivability analysis, basic events typically represent various components of the spacecraft. A cut set refers to a collection of certain basic events (i.e., components) within the fault tree. When all components in a cut set experience failure or functional degradation, the spacecraft system will inevitably fail or undergo functional degradation.

A cut set is considered a minimal cut set when it cannot be further reduced—that is, if the removal of any single component from the set results in the remaining components' failures or degradations no longer causing system failure (the spacecraft system can still function normally). Each minimal cut set represents a distinct failure mode that could lead to the spacecraft system's malfunction.

Let the minimal cut set be denoted as C, and the fault tree contains n basic events (component or electronic unit failure modes) $X_1, X_2, \cdots, X_n$. The j-th minimal cut set is represented as C_j, and the i-th basic event is denoted as X_i, where $C_j = \bigcap_{i \in C} x_i$. Assume the spacecraft system's functional degradation or failure event is T, which consists of N minimal cut sets. Each minimal cut set contains K_j components, $j = 1, 2, \cdots, N$. Let $P_{j,i}$ represent the probability of functional degradation or failure of the i-th component in the j-th minimal cut set, which corresponds to the damage probability of the component in the space debris environment as given in Equation (9). When the probabilities of basic events are sufficiently small, the occurrence probability of the top event can be approximated as:

$$P(T) = \sum_{j=1}^{N} \left(\prod_{i=1}^{K_j} P_{j,i} \right) \tag{10}$$

6 CONCLUSIONS

Spacecraft survivability assessment constitutes an indispensable component during the design and development phases, guiding protective design and structural optimization to enhance mission accomplishment capability during orbital operations, representing a comprehensive systems engineering endeavor that integrates multiple data dimensions including the orbital space debris environment, spacecraft geometric configuration, component vulnerability models, and functional logic relationships across components-subsystems-system hierarchy; this paper systematically examines fundamental elements for constructing a survivability assessment system and analyzes the technical methodology comprising three key phases - space debris impact susceptibility analysis, component vulnerability assessment, and system-level survivability evaluation - with detailed investigations of each segment establishing the foundation for assessment system development and enabling subsequent refined studies, with principal conclusions as follows:

(1) The technical approach for spacecraft survivability assessment is determined by the analysis method employed for evaluating internal component vulnerability, with two primary vulnerability analysis methods available - the BLE method which offers relatively higher computational efficiency but lower accuracy and is typically used during early mission feasibility studies, and the debris cloud model method which conversely improves computational accuracy at the expense of some efficiency and is generally applied during spacecraft mission design and manufacturing phases.

(2) The susceptibility analysis is determined by three key factors - environmental conditions, threat parameters, and spacecraft characteristics - and is mathematically characterized using Poisson distribution, with the environmental data being provided by space debris engineering models and micrometeoroid models that clearly define output data formats to guide data application, while also establishing coordinate definitions and transformation methods for all elements to provide comprehensive data support for the entire survivability assessment analysis.

(3) The vulnerability concept is comprehensively characterized through the integration of failure modes, damage laws, and damage equivalence models in the development and application of vulnerability modeling, where spacecraft components are classified into two main categories - structural-type and functional-type - based on their susceptibility to hypervelocity space debris impacts, with corresponding damage equivalence models established for engineering practicality.

(4) The core of spacecraft system survivability lies in establishing the functional logic relationships among spacecraft components, subsystems and the overall system, which serves as the fundamental modeling basis for the system-level survivability calculations presented in this paper.

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