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Study on Assessment Method of Satellite Damaged by Space Debris

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Abstract. The damage assessment model of space debris was established to satellite, included the description of space debris distribution field, the analysis of function and structure of satellite components, the rendezvous analysis between space debris and satellite, the damage criterion and so on. NASA ORDEM model and Shot-line method were used to describe the probability distribution field of millimeter and centimeter debris in space. The equivalent model of satellite was established by energy conservation principle and basic body method. The failure probability of satellite system was calculated under the impact of space debris. Establishing the vulnerability analysis method of satellite target is great significance to the risk assessment of space debris impacting satellite, and provides reference for the optimization design of satellite protection structure.

1. Introduction

Increasingly frequent space activities, the existence of space debris seriously threatens the safety of spacecraft on orbit. Shielded spacecraft can protect debris less than 1.0mm. Space debris with an average size of more than 10 cm can be monitored and warned by ground-based radar and telescope, and the spacecraft can be avoided collision by orbital maneuver avoidance strategy [1]. However, the debris with a diameter of 0.1-10 cm is beyond the observation and tracking capability, and the debris can't be positioned. The spacecraft has no effective maneuver to avoid these debris, which is extremely dangerous to the spacecraft.

For the description of space debris, The NASA's ORDEM database was generated and the space area was meshed. The distribution of debris was calculated by finite element method, and the debris environment was formed according with the observed data [2, 3]. N. Welty and others combined environmental model, ballistic limit equation and spacecraft exposure area occlusion processing algorithm to calculate the structure damage probability of spacecraft under space debris impact.

The basic body method [4] was applied to satellite target description. The basic body method is to simulate the geometric shape of the target with regular basic shapes. Based on the damage tree, the relationship between target damage and component damage is established.

The paper described the space debris based on ORDEM model, established the satellite target with the basic body method, and found the relationship between component damage and target damage with

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the damage tree [5, 6]. A damage assessment model of space debris to satellite target was established, which provides a new solution for the impact risk assessment of unmanned spacecraft such as satellites.

2. Satellite Equivalent Model

2.1. Satellite Description

Top-down analysis was used to determine the key components of a satellite, also known as damage tree method. The physical and functional characteristics [7,8] of the target satellite were acquired. The target functional block diagram and finally the damage tree diagram was made. Satellite public system is a system that any type and purpose of satellite must be equipped with. The structural system is set as an ellipsis event in Figure 1.

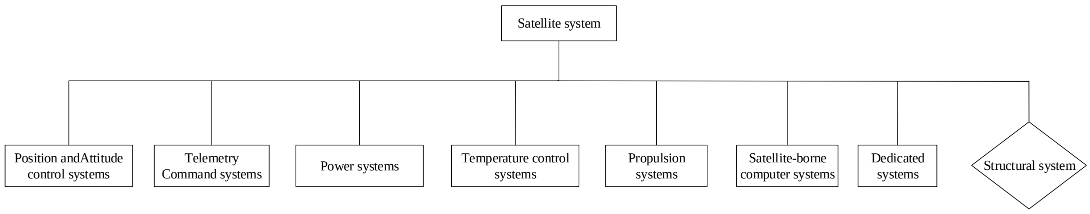

Figure 1. Satellite system structure diagram

2.2. Equivalent Model

The residual velocity of debris penetrating any material target and the equivalent material of the same specification is equal at the same speed and rendezvous mode. In this paper, 2A12 aluminum alloy was used as the equivalent material. The model was established with LS-DYNA finite element software to acquire the residual velocity after the ball penetrated honeycomb aluminum plate.

Three different positions including the hexagonal cell center, the midpoint of the cell wall and the rendezvous of the cell wall, were simulated. The honeycomb aluminum plate was meshed in HyperMesh as shown in Figure 2.

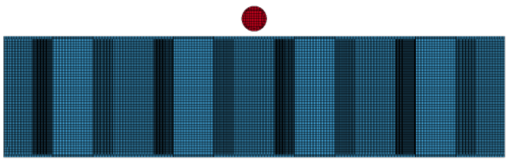

Figure 2. Finite element model

Three groups of velocity curves varying with time were obtained by numerical simulation of ball penetration into honeycomb aluminum at three different positions as shown in Figure 3.

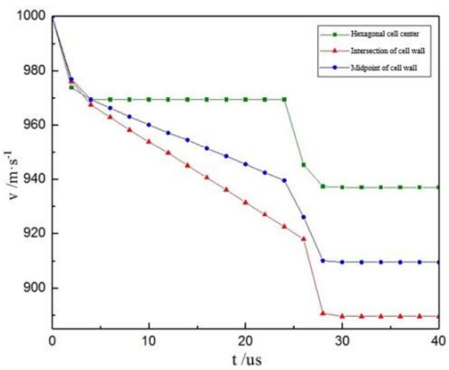

Figure 3. Penetration velocity curve

The average residual velocity was taken as the residual velocity of the ball penetrating honeycomb aluminum. The Von Mises stress of 2A12 aluminum alloy is shown in Figure 4, The velocity of equivalent 2A12 aluminum alloy is obtained by LS-DYNA simulation.

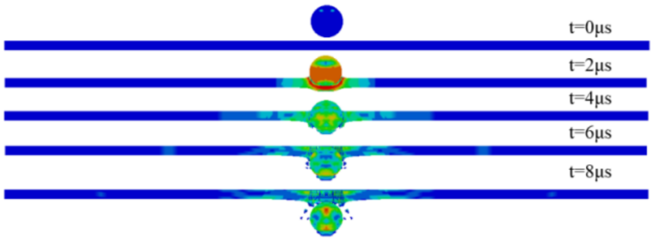

Figure 4. Von Mises stress of 2A12 aluminum alloy

3. Damage Criteria

The interior of these components is made up of many fatal parts, which are destroyed and invalidated only when debris strikes the fatal parts or areas within them. Otherwise, the components will not be damaged, and the key parts in the components are not necessarily tightly arranged. The damage probability of such components can be calculated by the following formula:

$$P_{k/h} = \frac{A_v}{A_p} = \sum_{i=1}^{n} \frac{A_V^{(i)}}{A_P^{(i)}} \tag{1}$$

Where A_v is the total vulnerable area of components, A_p is the total rendering area of components, *n* is to consider the incident direction of debris. For a two-dimensional region, the ratio of the vulnerable area to the rendered area; for a three-dimensional component, such as a satellite computer, the ratio of the total rendered area to the total rendered area in each direction, or the volume of the vulnerable part to the total volume of the component as shown in Figure 5.

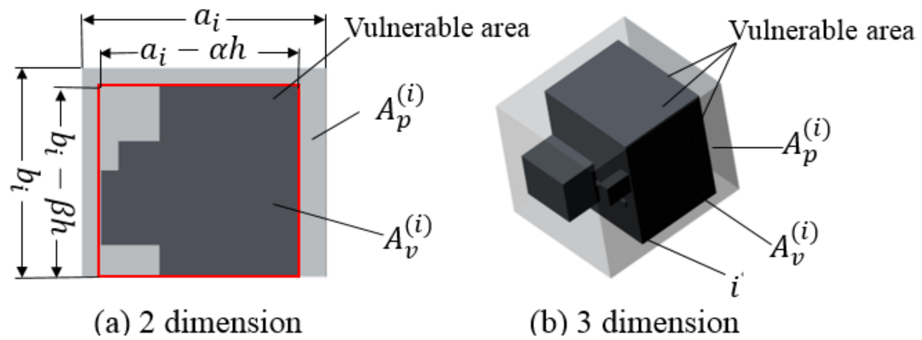

Figure 5. Parts vulnerable area and presentation area

The following formula can be used to calculate the damage probability of components when the internal precise structural parameters can't be determined:

$$P_{k/h} = \frac{\sum_{n=1}^{n}(a_i - \alpha h)\times(b_i - \beta h)\times\zeta_i + \sum_{m=1}^{m}\pi\times(r_m - \lambda h)^2\times\xi_m}{\sum_{n=1}^{n}a_i\times b_i + \sum_{m=1}^{m}\pi\times r_m^2}, \quad (m+n=6, 0\le n\le 6, 0\le m\le 6) \tag{2}$$

where a_i and b_i are the length of area of presentation from the incident direction, ξ and ζ are shape coefficients, r_m is the radius of area of presentation from the j incident direction. α, β and λ are coefficients, *h* is equivalent thickness.

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4. Damage Assessment

4.1. Rendezvous Analysis of Space Debris And Satellite

Whether the debris breaks through the target satellite, the number of debris hit the satellite target (based on breakdown) and the target damage probability. The Shot-line method is simple and image, which can well handle the multilayer penetration of debris and the problem of mutual shielding between components as shown in Figure 6.

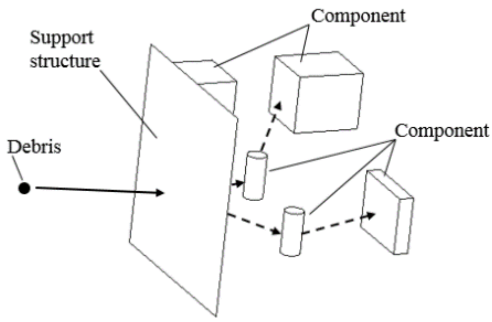

Figure 6. The diagrammatic sketch of Shot-line method

The impact process is Calculated between debris and satellite target, and which parts may be hit by the debris. The coordinates of the impact point and the impact angle can be obtained by calculating the rendezvous of the debris and the components Whether the component structure of satellite target can be broken down or not, the single-layer trajectory limit equation [9] is adopted.

$$t = 4.082 \times d\left(\sigma / \sigma_t C^2\right)^{-0.227}\left(\rho_p / \rho_t\right)^{0.503}\left(V / C\right)^{0.56} \tag{3}$$

where d is debris diameter, V is debris velocity, ρ_P is debris velocity, ρ_t is equivalent aluminum plate density, σ is equivalent aluminum plate yield limit, t is the thickness of the equivalent aluminum plate.

The debris penetrates the component structure of the satellite target, assumed that the motion direction of the debris remains unchanged during the rendezvous process. Characteristic parameters such as residual velocity, residual mass and deflection angle of debris are calculated by THOR equation [6,10] after the rendezvous of debris and satellite components.

$$\begin{aligned}
V_{ijr} &= V_{ijs} - 0.3048 \times 10^{c11} \times \left(61023.75hA_{ij}\right)^{c12}\left(15432.1m_{ijs}\right)^{c13}\left(\sec\theta_{ij}\right)^{c14}\left(3.28084V_{ijs}\right)^{c15} \\
V_{ijo} &= 0.3048 \times 10^{c21} \times \left(61023.75hA_{ij}\right)^{c12}\left(15432.1m_{ijs}\right)^{c23}\left(\sec\theta_{ij}\right)^{c24}\left(3.28084V_{ijs}\right)^{c25} \\
m_{ijr} &= m_{ijs} - 0.3048 \times 10^{c31} \times \left(61023.75hA_{ij}\right)^{c32}\left(15432.1m_{ijs}\right)^{c33}\left(\sec\theta_{ij}\right)^{c34}\left(3.28084V_{ijs}\right)^{c35}
\end{aligned} \tag{4}$$

where V_{ijr} is debris residual velocity, V_{ijs} is debris impact velocity, V_{ijo} is ballistic limit velocity, h is target material thickness, A_{ij} is debris impact area, m_{ijs} is debris initial mass, m_{ijs} is debris residual mass, θ_{ij} is the angle between the velocity direction and the target normal, c11 ~ c35 is material constant or coefficient [10].

4.2. Damage Calculation of Components

During the rendezvous operation between debris and target satellite, each impact between debris and target is considered as an independent event. During each rendezvous, each event uses the initial state of the satellite to calculate the path. It's ignored the damage effect of previous debris on satellite targets, in the rendezvous operation of debris and target satellite. The damage to the satellite target caused by debris and debris is independent of each other. The damage probability of the satellite target is calculated by n hits in Eq. (5).

$$P_{K/H}^{(i)} = 1 - \left(1 - P_{k/h}^{(i)}\right)^n \tag{5}$$

where $P_{k/h}^{(i)}$ is the kill probability of a single debris hitting the component, n is Times of being impacted by the debris.

4.3. Target Damage Calculation

The damage to the satellite was divided into five levels: Damage of position and attitude control system (W level); Damage of communication system (T level); Damage of power system (D level); Damage of functional system (G level) and satellite damage (K level). The damage of the target can be calculated by component damage as shown in Figure7.

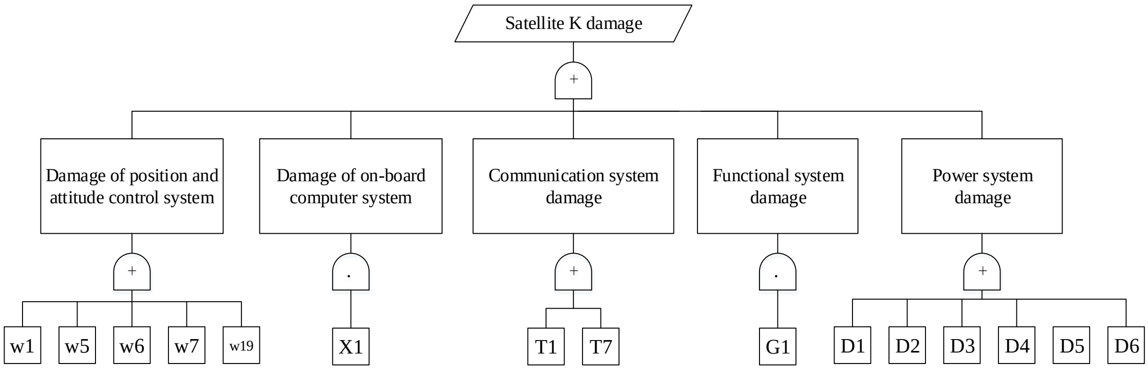

Figure 7. K damage tree for satellite (part)

where W1 is Earth sensor damage, W5 is Sun sensor damage, W6 is Gyroscope damage, W7 is Flywheel damage, W19 is Propulsion system damage, X1 is On-board computer damage, T1 is Damage of Telemetry Command System, T7 is Communication subsystem damage, G1 is Functional damage, D1 is Solar wing A damage, D2 is Solar wing B damage, D3 is Power control equipment damage, D4 is Battery damage, D5 is Power converter damage, D6 is Power distribution and cable net damage.

The relationship between components in damaged tree is "or", and the formula for calculating combined damage probability is shown in Eq. (6).

$$P_{K/H} = 1 - \prod_{i=1}^{n}\left(1 - P_{K/H}^{(i)}\right) \tag{6}$$

The relationship between components in damaged tree is "and", and the formula for calculating combined damage probability is shown in Eq. (7).

$$P_{K/H} = \prod_{i=1}^{n} P_{K/H}^{(i)} \tag{7}$$

where $P_{K/H}$ is component damage probability, n is component number under the damage tree, $P_{K/H}^{(i)}$ is component damage probability under the damage tree.

5. Summary

The damage assessment method of space debris to satellite considers the distribution of space debris, the structure of satellite key components and satellite components, and the equivalent of satellite components with finite element method proposed in this paper. It has important reference value for the impact risk assessment and the satellite protection optimization design of the current spacecraft. So the damage of satellite temperature control system is ignored in debris impact satellites. Further research is needed to quantify the damage criterion of temperature control system.

Acknowledgments
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