PENETRATION CHARACTERISTICS OF METAL HARPOONS WITH VARIOUS TIP SHAPES FOR CAPTURING SPACE DEBRIS

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ABSTRACT

The shape of a metal harpoon tip is considered to greatly influence penetration behavior. It is necessary to design the shape of the harpoon tip appropriately in order to penetrate space debris from any angle. In the present study, we investigate the effects of the shape of the harpoon tip on the penetration behavior through numerical simulation. Four types of harpoon tip, i.e., conical, spherical, flat, and double-bladed harpoon tips, were used, and their penetration behaviors were compared. We gained insight into the penetration characteristics of harpoon tips at various target angles as well as when the target was placed horizontally.

Nomenclature

A : initial yield stress

B : strain-hardening constant

C : strain-rate constant

D : overall damage variable

D_{1-5} : damage constant

m : thermal softening exponent

n : hardening exponent

p : mean stress

T : temperature

T_m : melting temperature of material

T_o : reference temperature

ε_f : equivalent fracture strain

ε_p : equivalent plastic strain

ε_p^* : normalized equivalent plastic strain

σ : equivalent plastic flow stress

1 INTRODUCTION

Recently, a number of satellites that are no longer operational due to failure are drifting in orbit and exist only as space debris. Space debris removal using various systems, such as the electrodynamic tether (EDT)(1) or propulsion systems(2) to decelerate debris, has been studied. These methods require attachment of the mitigation system directly to the debris, for example, by capturing the debris with a robotic arm and using propulsion to make the debris fall out of orbit.(2) However, such designs create the potential for numerous problems, such as the expense and maintenance of complex robotic systems. Simplified methods for orbital debris mitigation systems have been proposed,(3-5) including the lodging of a tethered anchor into a defunct satellite.

The authors previously studied space debris removal using a metal harpoon, as well as the development of corresponding numerical simulation models.(6) The shape of the metal harpoon tip is considered to have a great influence on the penetration behavior. However, the conical harpoon tip has mainly been studied, and other harpoon tip shapes have not been studied sufficiently at present. In addition, few studies have examined penetrating debris oriented at an oblique angle. If the harpoon has a conical tip, then the harpoon will not penetrate into the debris if the tilt angle of the debris exceeds half of the harpoon tip angle. Therefore, it is necessary to design the shape of the harpoon tip appropriately in order to penetrate debris at any angle. However, there is also the potential problem of the anchor passing too far into, or through, the target, leaving the tether vulnerable to being cut by the raw edges of the impact hole made by anchor penetration. Therefore, in the present study, we examine the relationships between metal harpoons with various tip shapes and the penetration behavior under various penetration conditions.

2 BASIC CONCEPT OF CAPTURING SPACE DEBRIS USING A METAL ANCHOR

In capturing space debris using a metal anchor, a tethered anchor is used to harpoon space debris, and a tether will connect the debris removal system to the space debris.

When harpooning a structure using a metal anchor, three major penetration states, i.e., no penetration, penetration, and passing through, were observed in our previous study.(7) Major penetration states during harpooning are shown in Fig. 1. If the anchor passes through the target

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surface, then the tether may be cut on the edge of the hole created during penetration by the anchor, resulting in capture failure. Therefore, we assume that only the penetration state is suitable for capturing space debris.

In addition, force is generated when the space debris mitigation system pulls the anchor and the attached target structure.[8] If the necessary bonding strength cannot be obtained, then the anchor may separate from the satellite structure. Dudziak et al. used a deployable toggle mechanism to increase the pullout strength of the metal anchor.[3] However, deployable toggle mechanisms are complex and pose the risk of not deploying during projection or prematurely deploying before penetration owing to the shock of the impact.

Therefore, the metal anchor used in the present study has been designed to penetrate, but not pass through, satellite structures upon impact and achieve the appropriate fixing conditions necessary to allow for the operation of space debris mitigation systems without any deployment mechanism. The rear end of the anchor was constructed to be the thickest part of the anchor in order to prevent the anchor from passing through the target, and the shaft of the anchor contained a narrow section in order to increase the pullout strength.[7] Four anchor tip shapes, i.e., conical, spherical, flat, and double-bladed tips, were investigated. The spherical tip is advantageous in the case in which the tip impacts a single point on the target at an oblique angle. The flat tip is advantageous in the case in which the entire surface of tip impacts the target, which is oriented horizontally, and the results show what the specific penetration behaviors are. The double-bladed tip is frequently used as a tool for making holes, e.g., hole punchers. Schematic diagrams and the appearances of the metal anchors are shown in Fig. 2. SS400 steel was used to construct the anchors, each of which had a mass of 203.5 g.

In the present study, aluminum alloy, which is widely used in satellite construction, was used for the fabrication of the target structures for penetration. These structures were plates constructed of aluminum alloy Al2024-T3, and the dimensions of the plates were 250 mm × 250 mm × 1 mm. The effects of the tether were ignored in order to focus on the penetration behavior of the structure by the metal anchor.

In addition, a schematic diagram of shooting a metal harpoon into a target is shown in Fig. 3.

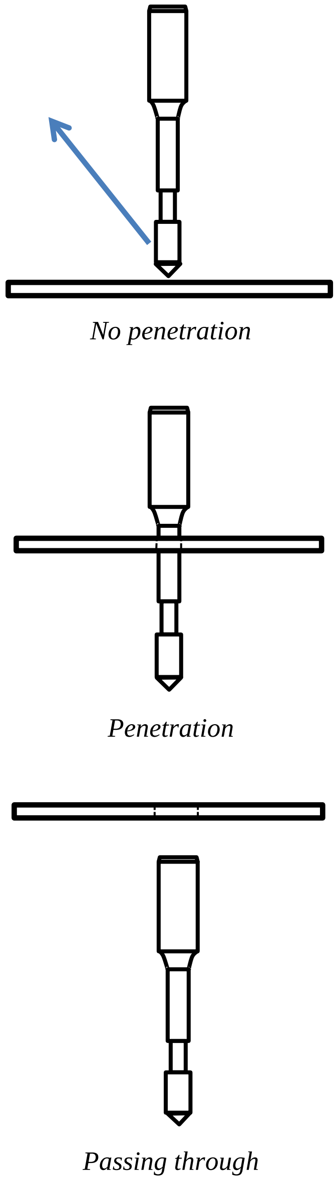
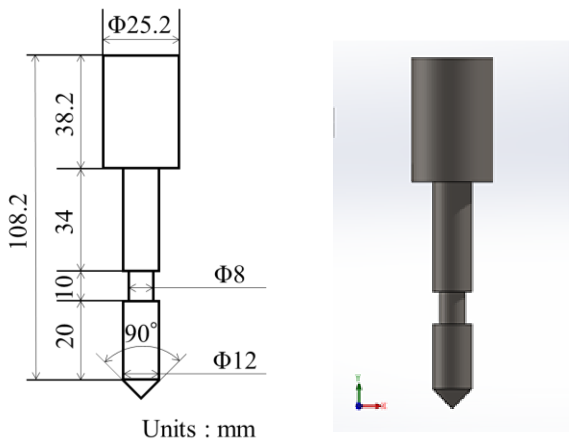
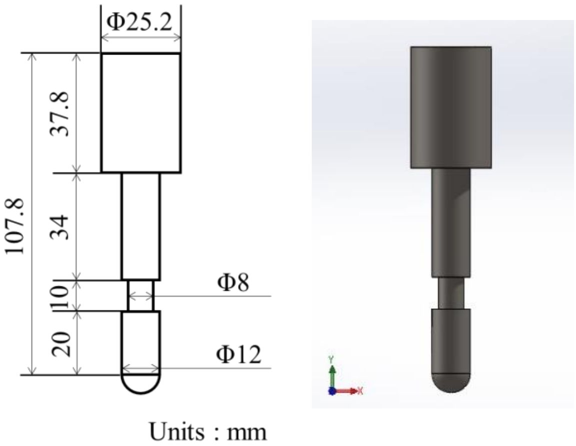


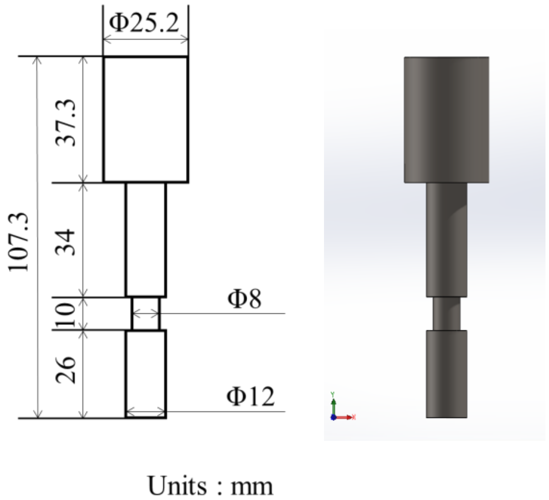
Fig. 1. Major penetration states during harpooning.



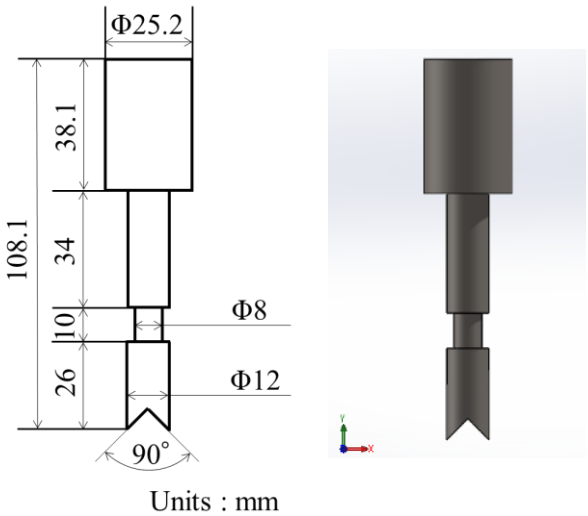
Conical



Spherical



Flat



Double-bladed

Fig. 2. Schematic diagrams and appearances of metal anchors.

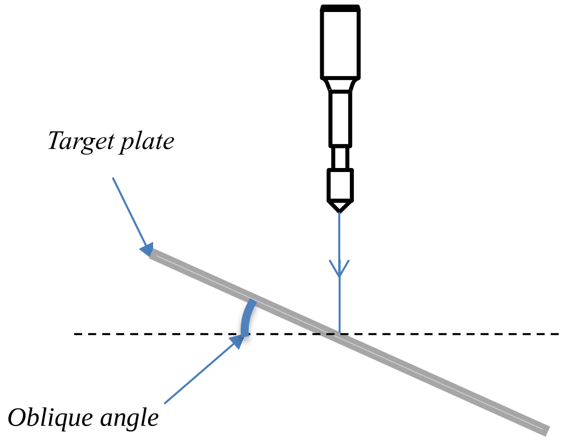


Fig. 3. Schematic diagram of shooting a metal harpoon into a target.

3 NUMERICAL SIMULATION OF SHOOTING A METAL HARPOON

The size of debris in orbit varies, and it is difficult to experimentally investigate the harpooning of debris of various sizes. Therefore, numerical simulations are indispensable for realizing the harpooning method, and an appropriate numerical model is required. In the discussed harpooning method, a metal anchor penetrates the target structure, and numerical models are used to simulate the fracture phenomenon. The Johnson-Cook (JC) model was used as the material model. The JC material model is an empirical constitutive model and has been widely used to model impact-related and penetration-related problems. The material characteristics during penetration can be simulated by the combination of the JC strength model and the JC failure model. The equivalent plastic flow stress σ can be calculated by the JC strength model as follows:

$$\sigma = [A + B{\varepsilon_p}^n][1 + C\ln \dot{\varepsilon_p}^*]\left[1 - \frac{(T - T_0)}{(T_m - T_0)}\right]^m \quad (1)$$

In the present study, the relative equation for the temperature is not considered. The fracture of the structure can be simulated by the JC fracture model. The equivalent fracture stain is obtained as follows:

$$\varepsilon_f = \left[D_1 + D_2\left(\exp D_3 \frac{p}{\sigma}\right)\right][1 + D_4 \ln \dot{\varepsilon_p}^*] \quad (2)$$

$$\left[1 + D_5 \frac{T - T_0}{T_m - T_0}\right]$$

and the overall damage variable *D* is calculated as

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon_f} \quad (3)$$

The material is assumed to be intact until D = 1.0.

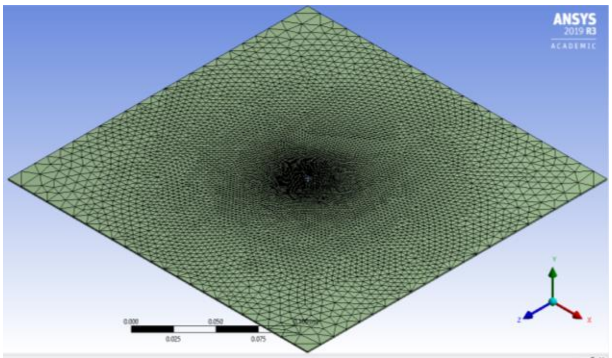
The parameters of the JC material model have been investigated in several studies.[9],[10] However, the parameters of actual materials used in space debris have not been investigated. Therefore, we assume space debris to be composed of Al2024-T3, which is generally used in the construction of spacecraft. We used these parameters in a previous study as well.[6] The parameters of Al 2024-T3 are summarized in Tables 1 and 2. Numerical simulations were performed using ANSYS Workbench (solver: AUTODYN). A triangular prism mesh was used for the finite element method mesh. Furthermore, we investigated the dependence of the anchor penetration on the target plate boundary condition, i.e., peripherally fixed. The numerical model is shown in Fig. 4. In our previous study, the effects of a mesh size of 1 mm were determined to be adequate for analyzing anchor penetration.[7] Therefore, a minimum mesh size of 1 mm is used in the present study as well.

Table 1. Basic physical parameters of Al 2024-T3.

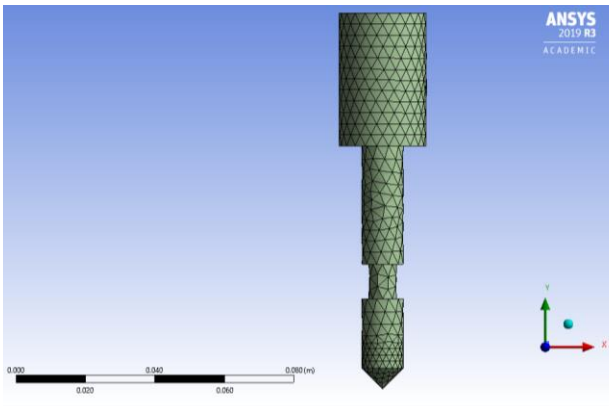
Density (kg/m^3)	Elastic modulus (GPa)	Poison ratio
2,700	73	0.33

Table 2. Parameters of Johnson-Cook models. [9], [10]

A (MPa)	B (MPa)	n	C	M
265	426	0.34	0.015	1
D_1	D_2	D_3	D_4	D_5
0.13	0.13	-1.5	0.011	0



Target plate: *triangular prism mesh*



Metal anchor

Fig. 4. Numerical model.

4 NUMERICAL RESULTS

The numerical simulations were conducted while varying the shape of the harpoon tip, the target angle, and the penetration velocity. We show numerical simulation examples of penetration of a metal harpoon with a conical tip into a target in Fig. 5. The obtained results are listed in Table 3.

The minimum penetration velocity of the double-bladed tip was lower than the penetration velocities of the other tip shapes. Also, a small piece of debris was created during penetration using the anchor with the double-bladed tip. The spherical and flat anchors did not reach suitable docking states at an oblique angle of 45 degrees. The suitabilities of the spherical and flat anchors for docking are shown in Fig. 6. The penetration velocity of the double-bladed tip was lower than the penetration velocities of the other tip shapes because the two blades were assumed to strike the target at the same time. However, the double-bladed tip shape may create new space debris because the tip does not penetrate the target at a single point. The small piece of debris created during penetration using the anchor with a double-bladed tip is shown in Fig. 7.

Table 3. Minimum penetration velocities for anchors. (m/s)

Oblique angle	Conical	Spherical	Flat	Double-bladed
0 deg	13.0	13.0	21.5	15.5
30 deg	16.0	23.5	22.0	15.5
40 deg	35.0	38.5*	31.5*	18.5

* Anchor passed through at the minimum penetration velocity.

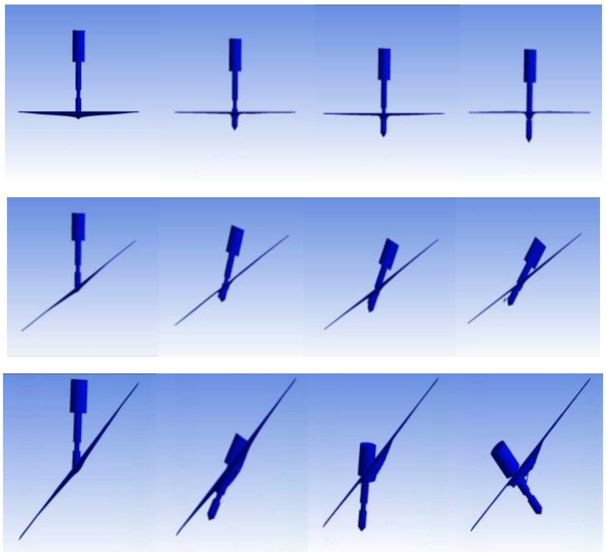


Fig. 5. Penetration by a conical anchor of the target at various oblique angles.

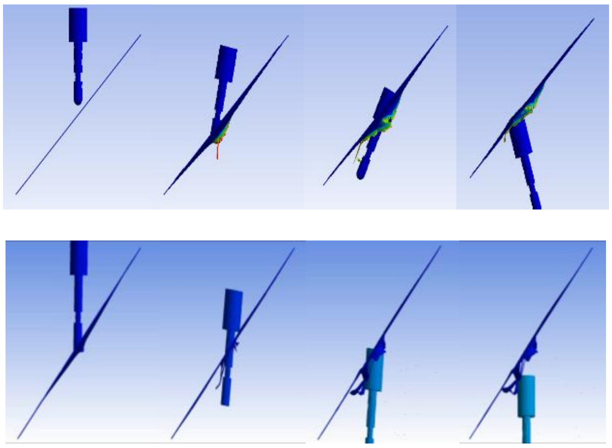


Fig. 6. Docking states of spherical and flat anchors at an oblique angle of 45 degrees.

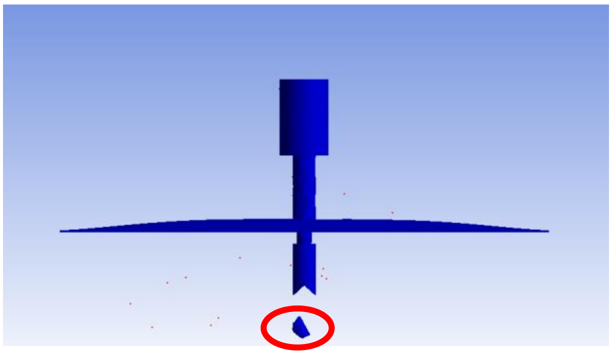


Fig. 7. Small piece of debris created during penetration using the double-bladed anchor.

5 CONCLUSION

We investigated the effects of metal harpoons with various tip shapes on penetration behavior through numerical simulation. The penetration velocity of the spherical and flat tips is higher than that of the conical tip. In addition, spherical and flat tips cannot reach suitable docking states at an oblique angle of 45 degrees, and it is possible to damage the EDT during an actual mission.

The minimum penetration velocity of the double-bladed tip was lower than the velocities of the other tips. However, the double-bladed tip can create new space debris. In addition, the penetration behavior can change depending on the relationship between the number of impact points of the double-bladed tip and the target, which may vary with the impact angle. Thus, it is necessary to investigate this relationship in detail. In the future, we intend to apply numerical simulation to the free-fall condition.

6 ACKNOWLEDGMENT

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