Application of Foam-Filled Thin-wall Structures in High Speed Impact Penetrator

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Abstract. High speed impact penetrators need to penetrate into the soil to a certain depth to achieve a specific function. Due to the high penetration speed (about 150 m/s), the inertia force and acceleration response caused by the collision are very large. In order to ensure that the internal PCB circuit will not fail, the design of the energy absorber is indispensable. In this paper, the foamed aluminum filled thin-wall structure is used as an energy absorber. The analysis results show that the foam-filled thin-wall structure is an excellent energy absorber, which has better isolation efficiency and energy absorption capacity, and the foam-filled thin-wall structure with combined density has better energy absorption effect.

Introduction

In recent years, various types of metal foams have developed rapidly and have gradually become a new type of structural functional materials. These porous materials have many excellent mechanical properties such as high specific gravity, high impact energy absorption capacity, extremely light weight, and stable deformation. Therefore, foam materials are widely used in automotive, aerospace, military protection and other fields.

S Hou et al. [1-3] studied the deformation of the foam-filled tube structure and constructed the response surface function of energy absorption and peak crushing force to find the best crashworthiness scheme for thin-walled structures. Isabel Duarte et al. [4] compared the energy absorption effects of foam, empty tubes and foam-filled empty tubes and the foam-filled hollow tube structure has more stable axial collision performance. The results also demonstrate that heat treated aluminum alloy structures ensure high ductility and very good crashworthiness since they deform without formation of cracks during compression, which is a pre-requisite for good and reliable crashworthiness behavior. Dirgantara T et al. [5] described the collisional mechanical behavior of foam-filled single-wall and double-walled columns. And the interaction between the foam core and the column wall will change the deformation mode from one localized fold to multiple propagating folds and lead to the increase of total mean crushing force of the column. Ebrahimi S et al. [6-7] studied the crashworthiness of functionally graded foam filled tubes and analyzed the effects of foam aluminum density versus energy absorption (EA) and peak impact force (PCF). Yanfei Xiang et al. [8] gave five key indicators for energy absorption in thin-walled structures based on axial compression experiments: Effective Stroke Ratio, Nondimensional Load_carrying Capacity, Specific Energy Absorption, Effectiveness of Energy absorption, Undulation of load_carrying capacity.
In this paper, the foam-filled thin-wall structure is used as a buffer energy absorber for high speed impact penetrator. The deformation behavior and buffer energy absorption effect of the buffer absorber during the collision process are deeply studied. The axial compression impact properties of thin-wall, uniform foam-filled thin-wall, and combined foam-filled thin-wall were compared to explore their deformation and energy absorption efficiency.

**Geometric Model**

The penetrator consists of an external protective structure (EPS), a foam-filled thin-wall structure (FTS), a scientific load (SL), and a vibration-damping spring. The scientific load includes a detecting device and its power module. The penetrator lands in a free-falling manner with speed of about 150 m/s and collides with the soil. The inertial force of the scientific load acts on the foam-filled thin-wall structure, so the deformation mode and deformation behavior of the thin-wall structure determine the acceleration response of the scientific load. (See figure 1)

**Aluminum Foam**

Deshpande and Fleck [9] propose a homogenous constitutive model, and the yield criterion for each uniform foam is defined as:

\[ \phi = \dot{\sigma} - \sigma_y \leq 0 \]  
(1)

where \( \sigma_y \) is the yield stress and the equivalent stress \( \dot{\sigma} \) is given as:

\[ \sigma^2 = \frac{1}{[1 + (\alpha / 3)^2]} \left[ \sigma_e^2 + \alpha^2 \sigma_m^2 \right] \]  
(2)

where \( \sigma_e \) is the von Mises effective stress and \( \sigma_m \) is the mean stress. Parameter \( \alpha \) that controls the shape of the yield surface is a function of the plastic Poisson’s ratio \( \nu_p \) given as:

\[ \alpha^2 = \frac{9(1 - 2\nu_p)}{2(1 + \nu_p)} \]  
(3)

The hardening criteria in this material model can be described as:

\[ \sigma_y = \sigma_p + \gamma \frac{\dot{\varepsilon}}{\varepsilon_p} + \alpha_2 \ln\left[ \frac{1}{1 - (\dot{\varepsilon} / \varepsilon_p)^\beta} \right] \]  
(4)

where \( \dot{\varepsilon} \) is equivalent strain, \( \sigma_p, \alpha_2, \gamma, \beta \) and \( \varepsilon_p \) are the material parameters and can be related to the foam density.
\[
\left\{ \begin{array}{l}
\sigma \left( \alpha, \gamma, \frac{1}{\beta}, E_p \right) = C_0 + C_1 \left( \frac{\rho_f}{\rho_{f0}} \right)^k \\
\varepsilon_D = -\ln \left( \frac{\rho_f}{\rho_{f0}} \right)
\end{array} \right.
\]

where \( \rho_f \) is the density of the foam, \( \rho_{f0} \) is the density of the base material, \( C_0 \), \( C_1 \) and \( K \) are constants.

**Aluminum Alloy 6061-T4**

The material of walls is aluminum alloy 6061-T4 [10-11] with the following mechanical properties: density \( \rho = 2700 \text{ kg/m}^3 \), Poisson’s ratio \( \nu = 0.28 \), Young’s modulus \( E = 70 \text{ GPa} \), initial yielding stress \( \sigma_y = 110.3 \text{ Mpa} \), tangent modulus \( E_t = 450 \text{ Mpa} \).

**Indicators for Energy Absorption**

**Isolation Efficiency** \( \eta \). The isolation efficiency reflects the isolation capability and damping capacity of the thin-walled structure. The larger the isolation efficiency is, the smaller the acceleration transmission efficiency is, and the smaller the acceleration of the scientific load is. Isolation efficiency \( \eta \) is defined as follows:

\[
\eta = \frac{A_n - A_m}{A_n} \times 100\%
\]

Where \( A_n \) is the peak acceleration of the scientific load and \( A_m \) is the peak acceleration of the external protection structure.

**Average Acceleration** \( A_0 \) and **Acceleration Unevenness** \( \delta \). Acceleration unevenness is an indicator for evaluating the severity of acceleration changes. \( \delta \) is defined as follows:

\[
\delta = \frac{A_m}{A_0}
\]

Where \( A_m \) is the peak acceleration of the scientific load and \( A_0 \) is the average acceleration of the scientific load.

**Energy** \( E \). The absorbed energy \( E \) [12] is calculated as:

\[
E = \int_0^d Fdx
\]

Where \( F \) is the crash force and \( d \) is the deformation distance.

**Results and Discussion**

The foam-filled thin-wall structures are coded: the thin-walled structure, the foams are denoted as S and A, respectively, and the thickness of the thin-walled and the density of the foam are distinguished by numbers. For example, S1.0A0.3 represents a combination of a thin wall of 1.0 mm and a density of 0.3 g/cm\(^3\).

**Deformation**

During the collision process, the deformation of the empty thin-walls is very large (see Figure 2), indicating that the thin wall is easily deformed and is suitable as an energy absorber. The deformation of the foam-filled thin-walls is more stable, and the amount of deformation is closely related to the foam density. When the thickness of the thin wall is the same, the amount of deformation of the thin-wall filled with foam of 0.3 g/cm\(^3\) is the largest, and the amount of deformation of the thin-wall
with foam of 0.5g/cm³ is the smallest, that is, the amount of deformation shows a negative correlation with the density of the foam. At the same time, the thickness of thin-walls also affects the distance of structural deformation. An increase in thickness will improve the stiffness of the energy absorber and inhibit excessive deformation. Therefore, an appropriate combination of foam density and thin-wall thickness can ensure the amount of deformation of the energy absorber.

**Figure 2.** The final densification state of energy absorbers.

**Acceleration Response**

The EPS is firstly impacted when the penetrator is in contact with the soil. According to the acceleration-time curve obtained from the simulations, the maximum acceleration of the EPS exceeds 10,000 g, and the acceleration rapidly decreases in Figure 3.

**Figure 3.** Acceleration response curve of EPS.

In Figure 4(a), the peak acceleration of the SL and the fluctuation of the acceleration are both large, indicating that the energy absorbing efficiency of the energy absorbing device is very low, and the acceleration unevenness is large, which directly leads to the failure of the SL.

**Figure 4.** Acceleration response curves of SL.
The isolation efficiency of FTS with a foam density of 0.3 g/cm$^3$ is very sensitive to wall thickness. Peak acceleration of SL and the unevenness of the acceleration are very large when wall thickness is small, as shown in Table 1. FTS with a foam density of 0.4 g/cm$^3$ and 0.5 g/cm$^3$ performs well in terms of peak acceleration, acceleration unevenness, and isolation efficiency. The peak acceleration of SL is relatively small, the isolation efficiency is about 80%, the acceleration is relatively stable, and the unevenness is about 2.2, as shown in Table 1. FTS with combined density has the highest isolation efficiency and the lowest acceleration unevenness, indicating that the combined density performs better than the uniform density.

### Table 1. Results of average acceleration, acceleration unevenness, and isolation efficiency.

<table>
<thead>
<tr>
<th>FTS</th>
<th>$A_{m}$/g</th>
<th>$\eta$/%</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1.0/1.2/1.4</td>
<td>10040/100200/4869</td>
<td>45.0/82.8/77.8</td>
<td>6.7/2.0/2.3</td>
</tr>
<tr>
<td>S1.0A0.3/0.4/0.5</td>
<td>5610/1755/2260</td>
<td>84.1</td>
<td>1.9</td>
</tr>
<tr>
<td>S1.2A0.3/0.4/0.5</td>
<td>4236/1830/1855</td>
<td>58.5/82.1/81.8</td>
<td>5.2/2.1/2.2</td>
</tr>
<tr>
<td>S1.2A0.3/0.5</td>
<td>1452</td>
<td>85.8</td>
<td>1.7</td>
</tr>
<tr>
<td>S1.4A0.3/0.4/0.5</td>
<td>1657/1941/2303</td>
<td>83.8/81.0/77.4</td>
<td>2.4/2.2/2.9</td>
</tr>
<tr>
<td>S1.4A0.3/0.5</td>
<td>1608</td>
<td>84.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

### Energy Absorption

S1.0A0.4, S1.2A0.3, and S1.4A0.3 are the best energy absorbers with wall thicknesses of 1.0mm, 1.2mm, and 1.4mm, respectively, which indicates that lower density foams help to increase the energy absorption of the absorber (Figure 5).

![Energy Absorption](image)

**Figure 5.** Effect of foam density, wall thickness on dynamic absorbed energy.

### Conclusions

In this paper, the foam-filled square thin-wall is applied to the high-speed impact penetrator. The research shows that the structure has good energy absorption efficiency and isolation capability under high speed collision. The deformation behaviors of thin-wall, uniform foam-filled thin-wall and combined foam-filled thin-wall are simulated. There are many indicators to evaluate the performance of the energy absorbers, such as isolation efficiency, acceleration unevenness, and the total absorbed energy. The following conclusions can be drawn:

1. The isolation efficiency and total absorbed energy of the foam-filled thin-walls and are better than that of the thin walls, acceleration of the scientific load are also lower than that of the thin wall, which indicate that the foam is favorable for buffering and energy absorption.

2. Combined foam-filled thin-walls perform better than uniform foam-filled thin-walls in terms of isolation efficiency and acceleration unevenness. The optimal results of the isolation efficiency and the acceleration unevenness are 85.8% and 1.7, respectively.
(3) When isolation efficiency, total energy absorption and acceleration unevenness, $S_1.2A^{0.3-0.5}$ is the best design among all the energy absorbers.

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References


