Minimum weight design of close-celled metallic foam protection for low velocity impact

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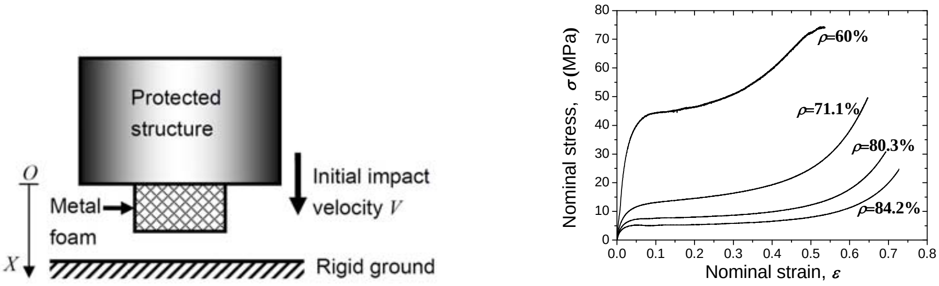
Summary A single-degree-of-freedom colliding model (SDF-CM) for large-mass structures protected by close-celled aluminum foam cushions is developed to minimize the weight of the foam cushion under different constraint conditions. The optimal geometrical dimensions of the foam are obtained for each type of constraint. The results show that the optimal foam weight varies almost linearly with the impact energy and the optimal foam diameter ratio increases logarithmically with increasing impact energy.

MANUSCRIPT PREPARATION

To protect important equipment and fragile objects against impact during transport, a wide range of packaging materials have been exploited, such as polymer foam, soft paper. The energy absorbing capabilities of these materials may be insufficient when the impact energy is intense, such as the landing of recovery space capsules with astronauts or airdrop of heavy civil/military facilities from low height. With the capability to undergo large deformation at an almost constant nominal load, cellular metallic foams with closed cells have found a wide range of energy absorption applications [1-5].

Colliding model description

Consider a closed system consisted of protected structure and foam cushion colliding with rigid base ground, which may be modeled as a rigid body (protected structure in this study) attached to a metallic foam cushion that impacts the rigid ground from a fixed height, as shown schematically in Fig. 1 (a). For simplicity, both the protected structure and the foam cushion are taken as cylindrical so that the problem may be treated as axial-symmetrical. The mass of the structure M is much larger than that of the foam m_f, and the top surface of the foam is glued to the bottom surface of the protected structure. Rebounding of the system is ignored, due to its negligible influence on structure safety. Relevant system parameters are defined as follows: u - compressive displacement of foam, g - gravitational acceleration, R_0 and H_f - initial radius and thickness of foam cushion, $\sigma(u)$ - foam stress, ν - plastic Poisson ratio of foam, μ_1 and μ_2 - frictional coefficients on the top and bottom surfaces of foam cushion.



(a) (b)

Fig. 1 (a) Metal foam-protected structure colliding with rigid ground at initial velocity V; (b) Experimentally measured uniaxial compressive stress versus strain curves of close-celled aluminum foams having different porosities.

The dynamic equilibrium equation of the one-dimensional colliding system is given by [6]:

$$M\ddot{u} - Mg + \pi R_0^2 \sigma(u)(1+\nu\frac{u}{H_f})^2 = -\frac{2}{3}\pi(\mu_1+\mu_2)\nu R_0^3 \sigma(u)(1+\nu\frac{u}{H_f})^2 / H_f \quad (1)$$

which is solved with the following initial conditions:

$$u\big|_{t=0} = 0, \quad \dot{u}\big|_{t=0} = V \quad (2)$$

The weight of metal foam cushion is an important control parameter in the design of cushion materials. An economical designing scheme would be minimizing the weight of the foam cushion on the premise that the dynamic responses of the protected structure meet the safety requirements. In general, the peak acceleration of the protected structure (i.e., $a_{\max}$) must be less than the critical value a_r, so that the impact loading applied to equipment or personnel within the protected structure is contained in the safe range:

$$a_{\max} / a_r \le 1 \quad (3)$$

When the plastic deformation enters the densification stage, the foam stress rises sharply posing serious threat to the safety of the protected structure. Thus, the maximum foam stress $\sigma_{\max}$ should be limited by the critical stress σ_r so as to guarantee structural integrity and security:

$$\sigma_{\max} / \sigma_r \le 1 \quad (4)$$

In practice, the geometrical dimensions of the foam cushion may also be limited, which may be expressed as:

$$0 < H_f / H_r \le m, \quad 0 < D_f / D_r \le n \quad (5)$$

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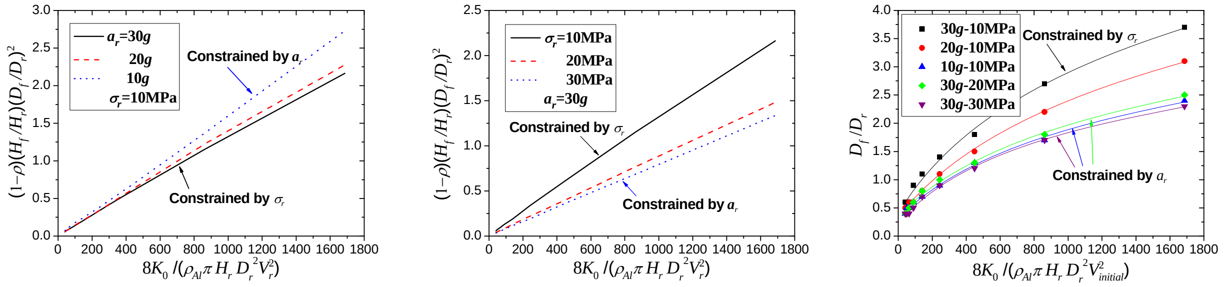
where H_f / H_r and D_f / D_r are the height and diameter ratio of foam respectively (the reference dimensions of the cylindrical foam cushion are selected as: height $H_r = 150mm$ and diameter $D_r = 200mm$). m and n are the allowable geometrical dimensions.

Minimum foam weight under different constraints



(a) (b) (c)

Fig. 2 Minimum weight and geometries of foam plotted as a function of impact energy: (a) influence of allowable acceleration; (b) influence of critical stress; (c) optimal geometrical dimension of foam cushion.

The minimum weight of close-celled aluminum foam cushion with porosity 84.2% of Fig. 1(b) are obtained and shown in Fig. 2 based on colliding model (Eqs. (1) and (2)) and subjected to the constraints of (3), (4) and (5). As shown in Fig. 2, when the impact energy is increased, the minimum weight of the foam cushion increases almost linearly. The dependence of foam weight on impact energy may be expressed as:

$$(1-\rho)\frac{H_f}{H_r}\left(\frac{D_f}{D_r}\right)^2 = \frac{m_f}{M}\left(\frac{V_r}{V_{initial}}\right)^2 \frac{8K_0}{\rho_{Al}\pi H_r D_r^2 V_r^2} \tag{6}$$

This suggests that the structure/foam mass ratio M / m_f remains nearly constant for the specified constraint conditions when the impact velocity is specified. If the constraint range is broader, the optimal mass ratio could become larger.

With the critical stress σ_r fixed at 10 MPa, Fig. 2(a) plots the foam weight as a function of impact energy for selected values of the allowable acceleration a_r. As a_r is increased, the minimum foam weight is seen to decrease, gradually approaching that when the critical stress becomes the main constraint, i.e. Eq. (4), for the minimization.

With the allowable acceleration kept at $a_r = 30g$, Fig. 2(b) plots the foam weight as a function of impact energy for different selections of σ_r. In contrast to the solid black line in Fig. 2(a), when σ_r is increased (from 10 MPa to 30 MPa), the minimum weight decreases and approaches that when the allowable acceleration becomes the main constraint, but the influence of stress constraint on minimum foam weight is weakened.

The dimensionless geometrical dimensions of the foam cushion associated with its minimum weight for different constraint conditions are presented in Fig. 2 (c). It is seen that the dimensionless contacting area (diameter ratio) increases logarithmically with increasing impact energy. By comparing the curves of “10g-10MPa” and “30g-30MPa” in Fig. 2, both constrained by a_r, it is seen that the former is about twice the latter in magnitude. However, the results of Fig. 2 (c) demonstrate that the foam diameter ratios associated with the two cases are almost identical, implying that the foam thickness ratio is the key variable for reducing the peak acceleration of the protected structure. Besides, the foam diameter ratio, increasing with decreasing σ_r, is more sensitive to stress constraint conditions.

CONCLUSIONS

A single-degree-of-freedom colliding model for large-mass structures protected by close-celled aluminum foam cushions has been employed to minimize the weight of foam cushion against impact energy subjected to different design constraints. For each type of constraint, the foam weight varies almost linearly with the impact energy and the optimal foam diameter ratio increases logarithmically with increasing impact energy.

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