Materials and Design 84 (2015) 351–358

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/jmad

Energy absorption of graded foam subjected to blast: A theoretical approach

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ARTICLE INFO

Article history:
Received 26 January 2015
Received in revised form 5 May 2015
Accepted 18 June 2015
Available online 28 June 2015

Keywords:
Energy absorption
Blast
Cladding
Foam
Graded foam
Density gradient

ABSTRACT

Energy absorption of graded foam subjected to blast is investigated, in which the high velocity crushing of foam is modeled with shock theory and rigid-perfectly-plastic-locking idealization. The characteristics of a typical blast are taken into account when determining the foam density profile. Different from the homogeneous foam, the graded foam density variation is designed largest at the loading end and smallest at the supporting end, with an exponential decay in between. It is found that, subjected to the same blast load, the total input energy, in fact the energy to be dissipated by the cladding, decreases with increasing density gradient. The final foam deformation with larger density gradient is smaller.

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1. Introduction

With an increasing number of man-made blast hazards and industrial accidental explosions, blast mitigation manifests itself as a multi-disciplinary field requiring great attention. The conventional method for structural damage alleviation against blast is strengthening the potentially threatened structural members with higher strength and rigidity. However, if damaged, retrofit of such strengthening is not only labor and cost intensive, but also time-consuming which greatly reduces the resilience of the structure. Cellular materials and structures exist widely in nature, such as certain grass stems and trabecular bones [1,2]. It is the natural selection that balances the weight and mechanical properties, i.e. bending and buckling resistances. These foam-like or honeycomb-like materials and structures are light and sufficiently strong to survive typical external loads from the environment. The merits of cellular material have been realized and this bio-inspired material finds its applications in various fields and industries due to the advantages over its solid counterpart, in aerospace, automobile, nuclear and defense. Specifically, with the exceptional energy absorption capacity, a blast mitigation philosophy of attaching sandwich cladding with cellular solid core to the exterior of protected structure emerged. When subjected to a blast load, the cladding itself absorbs a large amount of energy and lowers down the incident load to the protected structure, by undergoing large plastic deformation (thereafter shortened as “deformation”, referring to plastic deformation unless otherwise stated). After the blast, the damaged/sacrificed cladding can be replaced with a new one to quickly recover its protection capacity, which greatly improves the resilience of the structure. In particular, the cellular solid core (for instance, foams) plays a major role in the cladding and was investigated experimentally, numerically and analytically [e.g. 3–12]. Different crushing modes were observed. To understand the observation, some analytical models were proposed. Amongst, one-dimensional shock theory with rigid-perfectly-plastic-locking (RPPL) idealization effectively delineates the crushing process of low density cellular solid (relative density, defined as the density ratio of the cellular solid to base material, smaller than 0.2) under high velocity dynamic load [13]. Not only single layer cladding, but also double layer cladding subjected to a blast load was investigated [14]. Further, the protection efficiency of a system consisting of a blast mitigation cladding with metal foam core and protected structure subjected to a blast load was examined [15,16]. Full scale tests of aluminum foam cladding protected concrete structures subjected to blast were conducted and reported [17,18]. It is worth noting that with metal foam claddings attached to the protected structure under a blast load, the load exerted on the protected structure is not necessarily reduced; in some cases, the stress level on the protected structure is even higher than that in the case without a cladding [19], called negative mitigation effect. Following the observation of the effect, one believed major cause is that subjected to the blast load, the face plate preventing the foam

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http://dx.doi.org/10.1016/j.matdes.2015.06.124
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Nomenclature

h_b	thickness of the face plate, m
s	shock front location, m
L	original thickness of the foam core, m
Δm	mass per unit area of the densified foam, kg m^{-2}
P_0	peak load on the face plate, Pa
$P(t)$	load time history on the face plate, Pa
T_d	blast duration, s
u	displacement of the face plate, m
x	coordinate from the initial interface location between the face plate and foam core, m
β	gradient of the foam density, dimensionless
ρ	foam density, kg m^{-3}
ρ_0	foam density at the loading end, kg m^{-3}
ρ_b	density of the face plate, kg m^{-3}
ρ_L	foam density at the supporting end, kg m^{-3}
ρ_s	density of the base material from which the foam is made, kg m^{-3}
σ_D	densification stress of the foam, Pa
σ_{pl}	plateau stress of the foam, Pa
σ_{ys}	static yield strength of the base material from which the foam is made, Pa
ε_D	densification strain of the foam, dimensionless
λ, C_1	material constants of the foam, both dimensionless

from disintegrating is dished (deformed like a dish) with double curvatures, which may lead to increased transferred impulse and energy. Other possible causes are also mentioned, although their effects on the negative mitigation are believed to be insignificant [19].

Careful examination of the characteristics of the naturally existing cellular materials reveals that some of them exhibit gradient rather than homogeneous. For instance, the foam cell size of the outer layer of certain grass stem is significantly smaller than that of the inner layer [1]. The relatively stiffer outer part of smaller cell size provides higher resistance to external loads such as bending and buckling while the less dense inner part of larger cell size reduces its total weight. Recently, a few studies on graded cellular solids have been carried out, showing that they may have some merits when employed appropriately [20–26]. However, the underlying mechanism of high velocity crushing remains not reasonably understood.

In particular, the sandwich structures with cellular solid core and two solid face plates (in fact, hollow sandwich structures such as lattice trusses cladding have similar behavior) for protection purpose can be roughly categorized into two groups: on one hand, sandwich structure is used to replace certain part of monolithic structure, such as components of high speed train and land/air/water vehicles. It is found that the sandwich structures outperform the traditional monolithic structure with the same weight in terms of deformation when subjected to the same load. In this situation, the back plate of the sandwich structure is indispensible in controlling the overall deformation. There is no other object adjacent to the back plate thus the deformation of the sandwich structure is not constrained from the back.

On the other hand, when it comes to protection of building with sandwich structures, instead of replacing certain monolithic part, the sandwich structure is used as a sacrificial cladding attached to the exterior of the protected structure [e.g. 27,28]. The blast mitigation philosophy by attaching cladding with cellular solid core to the exterior of protected structure is that when subjected to a blast load, the cladding sacrifices: it undergoes large deformation which absorbs a large amount of energy and at the same time controls the load transfer to the protected structure under a controllable acceptable level. After the blast event, a new cladding will replace the sacrificed one. To prevent the protected structure from permanent damage, the thickness and crushing strength of the cellular solid core should be judiciously designed to ensure the protected structure to deform within the elastic limit. The elastic deformation of typical structural members is generally significantly small compared to the cellular cladding crushing, which is relatively large to lower down the transferred load intensity with almost the same impulse input. Therefore in the analysis of the cladding crushing, the deformation of the protected structure is reasonably neglected (assumed as zero) [28]. Obviously, the back plate is not important since it is in contact with the protected structure, whose deformation is always within the elastic limit and small if the sacrificial cladding is properly designed. In fact it can be considered as a part of the protected structure, rather than a part of the sandwich cladding. Therefore in the current study, the unimportant back plate is neglected. Instead, the face plate and cellular solid core are investigated to represent the sandwich cladding. If the standoff distance between the explosion and the cladding is greater than the characteristic dimension of the protected structure/structural member, the blast can be approximated as a plane load. Then one-dimensional model is sufficient to delineate the cladding behavior subjected to blast load [a number of such simplifications, e.g. 14–16,29–31].

In the present study, graded open-cell foam under strong blast induced high velocity crushing is investigated. It is assumed that the blast is sufficiently strong to crush the foam in a relatively high velocity (higher than the critical velocity, which should be experimentally determined in the future) so that the foam is densified in progressive collapse mode.

2. Formulation of continuous graded foam subjected to high velocity crushing

As discussed in the preceding section, the back plate of the sandwich cladding in protecting building is unimportant and neglected. To design and optimize the performance of a blast mitigation cladding consisting of a face plate and graded foam core, the characteristics of the load applied should be taken into consideration. A typical blast load induced by an airburst is a pulse with an instantaneous rise with a rapid close to exponential decrease, often simplified to a triangular load by preserving the impulse and peak pressure, whose intensity is highest initially and decreases linearly with time [32]:

$$P(t) = \begin{cases} P_0\left(1-\dfrac{t}{T_d}\right) & t \le T_d \\ 0 & t > T_d \end{cases} \tag{1}$$

where P_0 and T_d are the peak and duration of the blast load on the face plate, respectively. t is time starting from the arrival of the blast load on the face plate.

Another important aspect is under high velocity crushing, foam undergoes progressive collapse [33,34]. The crushing velocity threshold (termed as critical velocity) for progressive collapse depends on the foam characteristics such as cell size and cell-wall thickness, not fully understood to date. Further, progressive collapse absorbed more energy than quasi-static global crushing when the same foam is deformed to the same final state [30].

A typical blast load induced by an explosion in air is a load with initial simultaneous peak, followed by a close to exponential decay (approximately) in a short duration. One may imagine that if the homogeneous foam is altered to be stronger at one end and weaker at the other, shown in Fig. 1, while keeping the total mass and thickness unchanged, the stronger foam part may provide greater resistance and dissipate more energy than that of the homogeneous foam in the initial stage. In fact, in so doing, the foam strength distribution in space resembles the blast load intensity variation in time. At the loading end, the foam has higher relative density, resulting in higher plateau stress and smaller densification strain while the foam at the supporting end has smaller relative density, lower plateau stress and larger densification strain. The foam in the middle layer has moderate

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