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Protection Against Blast Load with Cellular Materials and Structures

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The protection of buildings and structures against blast loads has long been of significance and attracted continued attention of research and industrial communities. Rather than strengthening the structures themselves, possible application of attaching cellular materials and structures to the exterior of structures to alleviate load on them is reviewed. First the properties of cellular solids under typical loading conditions, i.e., quasi-static compression, low to moderate rate compression, as well as high velocity compression, are briefed. Then the dynamic behavior of the composite structures containing cellular materials subjected to blast loads is introduced. The emphasis is placed on the dynamic response of blast mitigation cladding and their protection efficiency. Amongst, the analysis methods in terms of energy absorption and impulse transfer are surveyed and the fundamental problem of whether attaching cladding with cellular solid core to the exterior of protected structure can effectively mitigate blast load is discussed. Throughout the review, merits and drawbacks of the existing models and applications are examined and discussed. Some possible future directions on structure blast mitigation with cellular solid cladding are presented, inclusive of blast mitigation cladding with gradient cellular solid cores of specific density variations, active protection cladding rather than the traditionally studied passive protection methods.

Keywords: Blast mitigation, Structure protection, Cladding, Cellular material.

1. Introduction

To protect key buildings against industrial accidental explosions and terrorist attacks, a traditional way is strengthening them with thicker structural members. The drawback of such strengthening is costly, labor-intensive and time-consuming in construction and retrofit if damaged; in addition, with the same blast load induced by an airburst, due to fluid-structure interaction, the load experienced by the strengthened structures may be higher than that of the un-strengthened ones due to increased structural rigidity. During the past decades, a new philosophy of

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structure protection against blast load emerged- by attaching a cladding with cellular material core to the exterior of a structure, the load experienced by the protected structure is mitigated to a relatively lower level and a large amount of energy from the explosion is absorbed by the cladding. The mechanism is that the cores of the cladding, made of cellular material or structures, undergo large deformation when subjected to blasts, transforming load on the protected structure from a pulse with an extremely short duration and a high amplitude to a pulse with relatively longer duration and lower amplitude.

In the present survey, research works on structure protection against blast load has been briefly reviewed and the effect of protection is examined. Some issues in metal foam crushing and protection efficiency by using cellular solids are discussed. Further, some possible future research fields are presented.

2. Cellular Solid as A Blast Mitigation Material

Cellular solids are a kind of material with struts and plates interconnected as networks and cellular structures are structures formed with thin-walled plate or struts regularly stacked [Gibson and Ashby, 1997]. Compared to the normal solids, cellular solids have exceptional properties such as low thermal conductivity and being lightweight. These advantages over its solid counterpart make it versatile in industrial applications: thermal insulation, vibration isolation and packaging, bio-compatible components, filters, structural construction, sound suppression and energy absorption. Among various properties of cellular solids, the most important one is the relative density, defined as the ratio of cellular solids to the base material from which it is made. In fact, other features such as Young's modulus, yield strength, plateau stress, and densification strain are directly dependent on the relative density. Conventionally, only cellular solids with relative density less than 0.3 are considered typical while cellular solids with relative density greater than 0.3 are generally treated as solids containing isolated pores or voids [Gibson and Ashby, 1997].

In fact, some structures including honeycombs and lattices, even the sandwich structures, can be considered as hybrid materials [Ashby, 2011]. These lightweight materials and structures have potential to perform stronger and more rigid than the naturally existing materials of the same weight and may broaden the occupied space of the "material selection and design map" [Ashby, 2011]. The properties and applications of cellular materials and structures are summarized in several valuable monographs and papers [Gibson and Ashby, 1997; Ashby, 2000; Lu and Yu, 2003; Evans *et al.*, 1999; Evans, 2001; Hanssen, 2002a].

2.1. Cellular solids in compression

2.1.1. Quasi-static and low-velocity compression

Among the behaviors of cellular solids under various mechanical loads such as bending, shear, tension and compression, the compression response is most important.

When a cellular solid is compressed, three clearly-defined stages are observed. Initially, when the nominal strain is small, the stress-strain curve is a straight line, where the cell walls undergo elastic bending of small deflection. Second, when the strain increases higher than a certain value, the stress remains almost constant with the increasing strain, forming a “plateau”, where the cell walls buckle elastically, collapse plastically or fracture brittly [Lu and Yu, 2003]. With further development of the strain, an increasing number of cell walls buckle. Finally, when the strain is sufficiently large, stress increases with strain dramatically, in which the collapsed cell walls are compressed together and compacted firmly.

It should be emphasized that in the second phase, the stress being almost constant for a nominal strain up to 0.8 or higher, makes it an efficient energy absorber.

The mechanical behaviors of cellular solids under low-velocity compression are similar to those under quasi-static load. For ideal honeycomb and foams, when they are initially crushed in a low velocity, localized band develops within them; with the advance of the loading, more and more localized bands occurs, until the honeycomb or foam is entirely crushed. For realistic foams with defects, Ruan *et al.*, [2003] experimentally studied the compressive behavior of close-cell metal foam under low and medium strain rates ranging from 10^{-3} to 10 s^{-1} . It is found that the deformation is not uniform over the whole specimen; instead, the weakest part is crushed first and the second weakest part crushed next. The next weakest part does not crushed until the weakest part is completely densified.

2.1.2. High-velocity compression

When the impact velocity is sufficiently high, for instance, 50–70 m/s, the deformation mechanism is totally different: the densification is highly localized in the impact part, where the honeycomb or foam is crushed to a densification strain. In the other part, no localized band, even no deformation occurs. This crushing or densification propagates progressively from the initially densified part to undisturbed parts, in a form of shock wave.

Subjected to a crushing speed between low and high velocities, the foam densification is in a transitional manner, which is a combination of the global deformation and progressive collapse. Localized bands occur within certain area from the impact end and other foam outside this region does not deform [Lu and Yu, 2003].

For typical honeycombs with hexagonal cells, similar densification mode dependency on the crushing velocity is revealed by numerical simulations [Ruan *et al.*, 2003]. For different cell wall thickness and impact velocities, a mode classification map is established. For a specific cell wall thickness, with the increasing crushing velocity, the densification displays X, V and I mode, respectively.

It is evident that the critical velocity does exist for a specific foam/cellular structure, above which the foam will undergo progressive collapse, otherwise the foam will deform globally. The critical velocity may depend on the cell wall thickness, cell wall length-to-thickness ratio, foam relative density, strain rate dependency of

the base material, etc. However, until now, this critical velocity is not successfully predicted yet in the sense of mechanism. Further work is required to fully understand the key parameters determining the critical velocity, where dimensional analysis and scaled test may help.

2.1.3. Plateau stress and densification strain

Since various cellular materials and structures undergo similar mechanical behavior when loaded compressively, metal foam is selected as an example to elucidate the characteristic parameters. Amongst, two parameters are of special significance: the plateau stress and densification strain. The plateau stress of cellular solids is determined by the following mechanism: elastic buckling, plastic collapse and brittle fracture [Lu and Yu, 2003]. For typical low density open-cell foam, the plateau stress can be empirically expressed as:

$$\sigma_{pl} = C_1 \left(\frac{\rho}{\rho_s} \right)^{\frac{3}{2}} \sigma_{ys} \quad (1)$$

where ρ is the foam density and ρ_s is the density of the base material from which the foam is made; C_1 is a constant obtained from experiment, 0.25 to 0.35 for aluminum foam [Ashby *et al.*, 2000]; σ_{ys} is the base material yield strength. If the foam is close-celled, the influence of trapped air cannot be neglected and more complicated empirical formulas are established [Lu and Yu, 2003].

The densification strain, defined as the strain at which the densification occurs (various criteria of the onset of the densification strain is discussed in [Li *et al.*, 2006]), is empirically expressed for both open-cell and close-cell foams as [Ashby *et al.*, 2000]:

$$\varepsilon_D = \alpha - \lambda \frac{\rho}{\rho_s} \quad (2)$$

Generally α can be taken as 1 or a value slightly smaller. Set α as 1 and the strain is:

$$\varepsilon_D = 1 - \lambda \frac{\rho}{\rho_s} \quad (3)$$

where λ is a constant determined by experiment, taken empirically as 1.4 or 1.5 [Ashby *et al.*, 2000] for open-cell metal foams. Hu and Yu, [2010] theoretically analyzed the out-of-plane crushing of a hexagonal honeycomb and found the theoretical value for λ is 4/3 for such cell array. In fact, the parameter λ has straightforward physical implication. By conserving the mass before and after the densification, the foam density after densification is:

$$\rho^* = \frac{\rho}{1 - \varepsilon_D} \quad (4)$$

Combination of Eq. (3) and Eq. (4) leads to:

$$\rho^* = \frac{\rho_s}{\lambda}, \quad \lambda = \frac{\rho_s}{\rho^*} \quad (5)$$

From Eq. (5), λ is the ratio of base material density to the crushed foam density after densification, which reflects how compact or firm the foam is crushed in a specific densification event. Therefore, λ should be a function of the compressive load intensity and velocity. In a limit condition, the value of λ should approaches 1 if the open-cell foam is compressed by a load with extremely high intensity. The most frequently encountered situation is when the crushing velocity is not high, the foam behind the shock front may not be compacted to the defined nominal locking strain, which is experimentally and numerically observed [Pattofatto *et al.*, 2007]. The densification strain dependence on the densification velocity and other parameters should be further investigated.

For typical close-cell metal foams, the plateau stress and densification strain are further complicated by the trapped air. When subjected to high velocity crushing, the air within the foam cell has a remarkable influence on the densification strain and makes it much smaller compared with that of the open-cell metal foams. Generally, the value λ for open-cell foam ranges from 3 to 5, depending on the foam relative density [Shen *et al.*, 2010a]. In a medium strain rate, i.e., 10^{-3} to 450 s^{-1} , the test results of close-cell metal foams, obtained by a high strain Instron Testing System, indicate that the plateau stress remarkably depends on the strain rate but the densification strain is relatively insensitive to the strain rate [Wang *et al.*, 2011].

2.2. Material models of foams under dynamic crushing with applications

2.2.1. Rigid-perfectly-plastic-locking model and improved models

Among all the models delineating the metal foams under high velocity crushing, the most important and effective one is the shock model based on the rigid-perfectly-plastic-locking (RPPL) idealization. Reid and Peng, [1997] experimentally studied the high velocity impact of wood and found that the crushing is localized and propagates like a shock wave front. Based on the observation, a RPPL model was proposed to theoretically describe the crushing process. It is found that the model is successful in predicting the wood response under high velocity impact, especially suitable for modeling the dynamic enhancement. Further, it was widely applied to delineate and predict the responses of various foam-like materials and structures, i.e. metal foam. Tan *et al.*, [2005a; 2005b] experimentally and theoretically investigated the dynamic compressive strength of homogeneous metal foam. Different from others, they used a direct-impact technique and found that the collapse strength is significantly dependent on the compression rate. Lopatnikov *et al.*, [2003] conducted a Taylor cylinder-Hopkinson bar test to investigate the dynamic behavior of

Fig. 1. Shock fronts under various impact velocities [Lopatnikov *et al.*, 2003].

foam under high velocity compression. During the test, the shock fronts were clearly captured, indicated in Fig. 1.

Deshpande and Fleck, [2005] theoretically investigated the dynamic response of sandwich plates under impulsive loading. The effect of strain hardening of the foam core is studied and it is found that for realistic mass ratio of core to face sheet, the strain hardening effect can be neglected. Further, responses of sandwich structures to underwater explosion were analyzed.

Lopatnikov *et al.*, [2004] theoretically examined the high velocity impact on metal foam. Four discrete impact velocity divisions were established. Two of these regimes are of special significance and discussed in detail: one is the impact velocity higher than the elastic wave speed of the foam, the other is the impact velocity smaller than the elastic precursor velocity but higher than the effective sound velocity corresponding to the plateau region. Different mechanism was discussed. Li and Reid, [2006] discussed some fundamental problems on dynamic foam crushing, including physical quantities jump at the shock front, effective sound velocity and impact velocity, as well as the ‘strain frozen’ assumption. They also analyzed the relevant part on the accident of space shuttle Colombia. Li *et al.*, [2006] also examined several commonly used definitions of the onset of the densification strain and clarified the ambiguity of them. It is found that the densification strain onset determined by the energy absorption efficiency is unique and consistent. Harrigan *et al.*, (2010) theoretically re-examined the shocks in cellular materials. They clarified some conflicting predictions for the response of cellular solids in various loading situations.

In addition, several other models, are further developed based on this RPPL model with similar nature. The RPPL model ignores the elastic response of the foam, by assuming it absorbs negligibly small energy in a small strain range and

locks the strain in an abrupt way, which results in crushing response too sensitive to densification strain. To accurately depict the dynamic behavior of cellular solids under impact, the sudden locking of the strain is modified to behave in a power law [Pattofatto *et al.*, 2007]. Similarly, Harrigan *et al.*, [2010] compared the difference between the RPPL model and the more refined elastic-perfectly-plastic-enhancement (EPPH) model, which considered the elastic wave propagation and more realistic enhancement.

2.2.2. *FEM model: Voronoi or honeycomb model/ Continuous model in hypercodes*

To validate the theoretical prediction of the foam behaviors, a Voronoi meso-scaled model [Ma *et al.*, 2009] was established and it is found that densification stress at the stationary end is insensitive to the strain rate while it is strongly rate-dependent at the impact end. Zou *et al.*, [2009] numerically simulated two-dimensional honeycomb under dynamic crushing with FEM. It is found that when the crushing velocity is higher than a critical value, a shock front forms with a thickness of a cell size. The densification strain increases with increasing crushing velocity and converges to a value once the critical velocity is achieved. The study numerically validated the RPPL model and pointed out the RPPL model slightly over-estimates the densification stress and energy absorption.

With the wide application of the metal foam in the fields of marine vessels, civil infrastructures and military vehicles, several leading commercial softwares such as ANSYS/LS-DYNA and ANSYS/AUTODYN also developed and implemented foam model into their hydrocodes. The detailed micro-structure is ignored and the foam is idealized as a continuous solid, whose model can be used in the same way as those of other solids.

2.2.3. *Spring model*

Besides continuous models, the behavior of cellular materials can also be described with a discrete model. This one-dimensional model discretizes each cell layer into a lumped mass and a massless spring then idealizes the cellular material into a series of such masses and springs. The governing equations for each layer/cell were established and solved numerically. However, Harrigan *et al.*, [2010] found that the mass-spring model has disadvantage in predicting the shock behavior of foams thus it should be examined carefully if used.

3. Blast Mitigation of Structures

With exceptional energy absorption capacity, cellular solids may find wide applications in structure protection against extreme loads, such as blasts. In the viewpoint of protection mode and desired performance, blast mitigation with cellular solids

and structures can be roughly categorized into two groups: one is using sandwich structures to replace some parts of lightweight structures, i.e., high speed trains, air and water vehicles; the other is attaching blast mitigation claddings to the exteriors of concrete buildings and structures, whose protection philosophies are examined respectively.

3.1. *Sandwich structures*

When certain structures have potential threats from blast loads, sandwich beams and plates/panels with foam or honeycomb cores can be designed and installed to replace some monolithic parts, i.e. the carriages of high speed trains. The requirement for such sandwich structures is under a specific load, it should have a smaller deflection (exactly, back sheet deflection) after absorbing all the imparted energy, compared to the monolithic counterparts of the same mass. It is worth noting that one drawback of the sandwich structures is they occupy relatively larger space than the solid structures.

Sandwich beams or plates with a honeycomb core or metal foam core are typical blast energy absorbers. It is widely accepted that they outperform their monolithic counterparts of the same weight [e.g. Xue and Hutchinson, 2003]. While typical metal foams are isotropic, for sandwich structures with honeycomb cores (2-dimensional), from the viewpoint of energy absorption efficiency, the honeycomb should undergo out-of-plane crushing, rather than in-plane crushing [Hu and Yu, 2010]. Zhu *et al.*, [2010] reviewed plastic deformation, failure and energy absorption of sandwich structures with various cellular solids and structures cores in detail. The mechanical behaviors of sandwich structures under quasi-static and low velocity loading were extensively studied and there is a huge collection available. For instance, the failure mode maps of sandwich panels under quasi-static load were established [Andrews and Moussa, 2009]. The sandwich behaviors under high velocity loadings, i.e., high velocity impacts and blast loads, are relatively less investigated.

3.1.1. *Far to mediate field blast*

If the explosion is relatively distant from the sandwich structure, the non-uniformity and arrival time difference of blast load applied on the structure is not significant thus can be neglected, simplified as a plane wave exerted on a beam or plate. When theoretically analyzing a typical sandwich beam with cellular material or structure core subjected to a uniform blast induced by airburst or underwater explosion, the dynamic response of the beam/plate is divided into three phases [Fleck and Deshpande, 2003; Qiu *et al.*, 2003; Zhu *et al.*, 2009a; Zhu *et al.*, 2010]. Phase I: one-dimensional fluid-structure interaction. In this phase, the blast load is considered as a simplified plane wave normally and uniformly applied on the face sheet. Phase II: one-dimensional core crushing. The impulse from the support reaction is neglected

and the core is crushing by the face sheet with uniform initial velocity until the core and both face sheets achieve the same velocity. Phase III: dynamic bending of the structure, where different deformation modes and travelling plastic hinges are considered. Although the real situation for a sandwich beam/plate subjected to a blast has a fully coupled nature both for the fluid-structure interaction and the interaction between the face sheets and core, the structural response prediction by the decoupled three-phase model is found rather accurate, when validated by a parallel study by finite element simulation [Xue and Hutchinson, 2004], implying the division of the phases is meaningful and reasonable. Further, the core compressive strength has limited influence on the sandwich beam response [Qiu *et al.*, 2003]. More recently, Qin and Wang, [2009a] investigated the dynamic response of a sandwich beam subjected to a uniform impulsive load with membrane factor method and established more accurate and narrower “bounds”.

3.1.2. Near field blast

When the standoff distance between the detonation and the structure is sufficiently small, the curvature of the blast load has to be considered to accurately depict the dynamic structural response. Nurick *et al.*, [2009] used a close explosive disc to generate localized blast load around the center region of a clamped circular sandwich plate with honeycomb core. Two phases are observed: first, both the front and the back face sheets deform and the crushing of the honeycomb core is focused on the plate center region until the crushing limit of the core is achieved in the center; then, the rate of the back face sheet displacement increment corresponding to the increasing impulse changes to another gradient and the core is crushed in a larger area. During the second phase, the destruction of the honeycomb core in the center region was observed. In parallel, finite element simulation was performed [Karagiozova *et al.*, 2009] to investigate the sandwich behavior under localized air blast and found that the load transfer to the back face sheet is determined by combined factors including load intensity on the front face sheet, core thickness and flexibility of the sandwich structure.

The blast load can not only be generated directly from a close explosion, but also can be produced by an impact by a metal foam cylinder [Radford *et al.*, 2006a]. It is observed that the pressure time histories applied on the structure mid-span is almost independent of the plate impedance. Therefore metal foam cylinder impact can be used to test the blast/shock resistance of both monolithic and sandwich structures. It is confirmed that sandwich structures with cellular cores outperform its monolithic counterpart of equal mass in the sense of permanent back face sheet deflection. In addition, for various sandwich plates with different metal foam cores but equal total mass, the thicker the foam core, the smaller the back face sheet deflection will be. Further, pyramid core is the weakest among various cores including corrugated plate, square honeycomb and pyramid cores [Radford *et al.*, 2006a; Radford *et al.*, 2006b]. When large deflection effect, i.e. the interaction between

plastic bending and stretching, is considered, Qin and Wang, [2009b] investigated the dynamic response of a sandwich beam subjected to a localized impulsive load on the central patch and updated the “bounds” tighter and more accurate.

3.2. Blast mitigation claddings for buildings

When it comes to the blast protection of buildings and structures, things are different. For a typical existing concrete building, it is not applicable to replace certain part with cellular-solid-cored sandwich structures. Instead, a blast alleviation cladding consisting typically of a face sheet and cellular solid core is attached to the exterior to the protected structure. The requirement for such claddings is that for a specific blast load, while the blast is retarded by the resistance from the face sheet stretching and core crushing, the thickness of the cladding should be as small as possible, at the same time, the protected structure should not be overloaded.

The nature of blast mitigation cladding is that it establishes a system with unequal force/stress input and output, where the input is the blast load applied on the cladding and the output is the transmitted load on the protected structures. When a cladding is subjected to a blast load, the cellular core undergoes progressive collapse, in which the core behind the shock front is almost fully densified and the core ahead of the shock front is nearly undeformed [Ashby *et al.*, 2000; Lu and Yu, 2003]. If the insignificant elastic stress wave propagation and reflection in the undeformed foam part is neglected, no matter how high the blast load is, the stress transmitted to the protected structure is the plateau stress of the cellular core, provided that the cellular solid is not fully crushed.

It is widely accepted that the cellular material and structures can absorb a large amount of energy in a relatively low stress level compared to its solid counterpart with the same mass and similar dimensions, due to the long stress plateau with nominal strain as high as more than 0.8 [Gibson and Ashby, 1997; Ashby *et al.*, 2000; Lu and Yu, 2003].

One straightforward idea is by attaching a metal foam cladding to the exterior of a building, a large portion of the energy from the blast is absorbed by the cladding crushing, leading to a small part of energy imparted to the protected structure. This seemingly sound analysis is rigorously applicable to structure protection against penetration. In fact, to mitigate a blast, the energy needed to be dissipated by the cladding is equal to the imparted energy from the blast. Further, the imparted energy to the cladding is equal to the energy extracted by the cladding from the blast, which depends on blast load and the properties of cladding. For instance [Ashby *et al.*, 2000], for a specific blast, if the load alleviation effect due to fluid-structure interaction is insignificant, considering the impulsive nature of the blast load, the heavier the face sheet, the less energy extracted by the cladding. Therefore the ability of absorbing large amount of energy does not necessarily imply effective protection against blast loads. Instead, analysis of load and impulse imparted to the

Fig. 2. Illustration of the blast loaded pendulum [Hanssen *et al.*, 2002b].

cladding and transmitted to the protected structure, rather than energy absorption, is more reasonable.

The effect of attaching cladding with a cellular solid (i.e., metal foam) core on structure protection is still not fully understood. In fact, during the past decade, whether blast protection by adding metal foam cladding is effective or not has been under debate. Hanssen *et al.*, [2002b] experimentally tested the blast mitigation effect of structures by attaching a foam layer to the bob of a pendulum, indicated in Fig. 2, and found that the energy and impulse transferred to the bob is even higher than that without the cladding. Through a theoretical analysis of a simplified one-dimensional metal foam cladding subjected to a blast load, it is concluded that the impulse imparted to the cladding and to the protected structure is the same. Further, some possible reasons are proposed to account for the discrepancy between the test results and the analytical prediction, such as the effect of face sheet shape change.

In addition to the protection of movable structures, i.e., the above mentioned pendulum, the protection of stationary buildings and structures are of greater significance. Such a situation was partially examined by analyzing a frame protected by a three-layered sacrificial cladding subjected to a blast [Guruprasad and Mukherjee, 2000a; Guruprasad and Mukherjee, 2000b]. As the load is induced by an airburst, the fluid-structure interaction is not remarkable and ignored. The configuration of the periodical cladding is judiciously selected to ensure sequential progressive collapse, shown in Fig. 3: first the outmost layer is crushed by the blast and deform and evolve into more stable configurations. The second layer will not undergo crushing until the first layer is in a “rigid” configuration compared to the undeformed layers. So does the third layer. The crushing mode of the proposed topology of the sacrificial layer core is validated by finite element simulation and field test, whose set-up is in Fig. 3. With this sacrificial cladding, the force transferred to the protected structure is successfully reduced to a lower level.

Fig. 3. Three-layered sacrificial cladding protecting a frame against blast load [Guruprasad and Mukherjee, 2000a; Guruprasad and Mukherjee, 2000b].

In fact, the mechanism of the progressive collapse mode of the multi-layered cladding is similar to that of a typical metal foam under a high velocity crushing, where the inertial effect plays a dominant role in the collapse sequence. The three-layer cladding may be considered as a metal foam cladding with “macro cells”. While the force transmitted to the protected frame is reduced, whether the total impulse transferred to the frame is also reduced or not is not discussed. The original blast load with a high intensity and a short duration is transformed into a nearly constant load with a much lower intensity and a lengthened duration.

The trade-off of the load transforming is the sacrificial layer should have sufficient thickness to avoid full crushing, in which the load transferred to the protected structure will be much higher, even greater than that without the cladding. Subsequently, the volume of the cladding will be bulky then most importantly, the stand-off distance between the protected structure and the potential threat is inevitably shortened. This consideration is also confirmed by a recent report in ASCE Civil Engineering Magazine [Brown, 2011] in that whether barrier of liquid, foam, or other energy-absorbing materials on their own can lessen the effect of an explosion. It is believed [Brown, 2011] that to deflect or absorb a blast by adding material to the exterior of a structure is extremely difficult; and instead, carbon fiber reinforced polymer may be effective if properly attached inside the structure.

It is worth noting that almost all the studies on blast mitigation of structures [Hanssen *et al.*, 2002b; Ma and Ye, 2007a; Ma and Ye, 2007b; Karagiozova *et al.*, 2010; Main and Gazonas, 2008] only focus on the cladding itself and ignore the possible contribution from the protected structure. Consider a limit situation, if the protected structure is rigid and stationary, the impulse gained by the cladding will be fully transferred to the protected structure. Further, the load transferred to the protected structure may be amplified in some situations [Zhu *et al.*, 2011]. If the

Fig. 4. Load-cladding-structure model for structure blast mitigation [Ye and Ma, 2007].

structure flexural rigidity is taken into consideration, the protection effect is more reasonably examined by Ye and Ma, [2007]. In the study, a Load-Cladding-Structure (LCS) system, shown in Fig. 4, is established in which the foam under blast load is assumed to behave according to the rigid-perfectly-plastic-locking model [Reid and Peng, 1997]. The protected structure, assumed elastic in a service condition, is delineated by a SDOF model with lumped-mass equivalent method [Biggs, 1964], where only the maximum flexural deflection is of major concern and the bending, shear and membrane force within the structure are neglected.

The initial peak pressure and the impulse are normalized to:

$$p = \frac{P_0 A}{k y_c / 2}, \quad i = \frac{I_0}{y_c \sqrt{k m_{se}}} \quad (6)$$

where the numerators are parameters of the blast load and the denominators are parameters of the simplified SDOF model of the protected structure. Then two important non-dimensional parameters are introduced:

$$\kappa = \frac{\sigma_0 A}{k y_c / 2}, \quad \tau = \frac{t_m}{T/2} \quad (7)$$

The former is defined as the ratio of the force applied to the protected structure (in fact the plateau stress times the loading area, provided that the foam is not fully densified) to the resistance of the protected structure; the latter is the ratio of foam crushing time to the natural period of the protected structure. Both the non-dimensional parameters are defined by combining the properties of the blast load, cladding and the protected structure. Then useful design maps for attaching metal foam cladding for blast mitigation is established, indicated in Fig. 5.

Based on the design map, in region I, if the foam plateau stress is greater than a certain value, the protection effect is unsatisfactory no matter the value of τ is. In region II, where τ is smaller than a certain value corresponding to a specific κ , the foam is fully densified, in which the transmitted load to the protected structure is

Fig. 5. A typical design map for blast mitigation with metal foam cladding [Ye and Ma, 2007].

even higher than that without the cladding thus this situation should be avoided. The desirable design of metal foam should fall in region III or IV. With this LCS model, the negative mitigation reported [Hanssen *et al.*, 2002b] can be reasonably explained: the scenario of the field test falls in region I.

Despite the very useful guidance for cladding design for a specific protected structure can be readily obtained through the design map [Ye and Ma, 2007], the map can be further improved and the understanding on blast mitigation with metal foam can be deepened if the following aspects can be addressed. According to the map, the mitigation effect is favorable if τ is large, which implies either the foam crushing time is long or the protected structure is very rigid. For the former situation, the foam plateau stress should be low, subsequently the foam thickness should be large; therefore, the difference of the standoff distances with and without the foam (the thickness of the cladding) should be considered since the decay of the free-field blast load is sensitive to the standoff distance, especially if the standoff distance is small [Smith and Hetherington, 1994]. For the latter situation, if the rigidity of the protected structure approaches infinity, the impulse imparted to the protected structure should be exactly the same no matter the cladding is attached or not, provided that the supports of the protected structure do not move. However, this situation is not supported by the design map.

Another issue worth consideration is, blast load mitigation of a typical-size structure may encounter difficulty since according to the study [Ye and Ma, 2007], if the value of τ is smaller than 0.5, the protection efficiency will be unsatisfactory. In fact, for a typical structural member of a building and a typical blast, it is very likely that τ is smaller than 0.5. This issue should be further examined and addressed.

4. Discussions and Future Research

Although intensive research has been conducted on the blast mitigation of structures with cellular materials and structures, the underlying mechanism determining the protection efficiency is not thoroughly understood and the key parameters governing and controlling the protection efficacy is not fully identified. Effort is still required to put forward the boundaries of understanding of the structure protection against blast load. The possible future research is presented with discussion.

4.1. *Fluid-structure interaction*

In a number of theoretical investigations of structure analysis subjected to blast, the load time history applied on the structures are prescribed as a known function of time and space, where the fluid-structure interaction (FSI) is ignored. It is reported that due to the interaction, the impulse imparted to the sandwich structure is substantially reduced to about one half of that imparted to a monolithic plate with the same mass for underwater explosion, while this effect for airburst induced blast load is not significant [Xue and Hutchinson, 2004]. However, due to recent nonlinear studies [Main and Gazonas, 2008; Kambouchev *et al.*, 2006; Hutchinson, 2009; Vaziri and Hutchison, 2007], the influence of FSI for air blast is more remarkable than the traditionally used linear FSI. The topology and shape of the air blast-loaded structure influences the load applied on itself. For instance, the direction of the load may be altered by the FSI, subsequently leading to the change of the blast load on the structure in a specific direction. This is confirmed by study on curved metal foam cladding subjected to blast load [Shen *et al.*, 2010b], the outward curve of the cladding has some merits compared to the normal flat ones. The underlying mechanism is that the initially curved surface makes the highly compressed shock front air layer to have a trend of leaving the nearest point on the structure from the detonation. On the contrary, in Hanssen's test [2002b], initially flat face sheet experiences cratering, leading to the concentration of the shock front air layer to the crater center to some extent.

In numerical simulations, i.e. the commercial software such as LS-DYNA, the FSI is automatically incorporated [Zhu *et al.*, 2009b], the load applied onto the structure is updated in each iteration to make sure the slightly changed direction and intensity can be described based on the structural response calculated in the previous step. Obviously, it is difficult even impossible to deal with the FSI in this way when the theoretical solution is being sought, especially when the geometry of the structural configuration is complex. Nevertheless, if the topologies of the studied structure and charge shape are relatively simple, i.e., a spherical detonation applied on a relatively rigid flat plate, the effect of FSI can be estimated with an adequate accuracy with the application of some analytical results [Kambouchev *et al.*, 2006; Hutchinson, 2009].

4.2. *Claddings with gradient foam core*

In most of the research, the material used as cladding cores are homogenous metal foams; otherwise, periodically repeated truss or lattice structures are employed. The material and structure properties of the core do not vary with the cladding thickness, indicating the core is homogenous and uniform. Recently, research on the non-homogeneous foam for impact and blast mitigation emerged. Roughly, there are two categories of non-homogeneous foams: one is several layers of homogeneous foams with different densities stacked together to form a step-wise gradient foam; the other is foam with continuous density variation.

The static compression behavior of gradient foam was experimentally investigated [Beals and Thompson, 1997] and it is found that the crushing is initiated from the weakest part- the layer with the lowest density, then the next weakest layer, until the whole foam specimen is completely densified. This progressive collapse from the weakest foam part is the same as the homogeneous foam with defects. For mechanical behavior of gradient foam, Kiernan *et al.*, [2009] numerically studied the gradient foam with FEM. After calibrating the FEM model with a SHPB test on homogeneous foam, the calibrated numerical SHPB test is employed to investigate the wave propagation properties of gradient foam. It is found that the energy dissipation is shaped by the gradient. Sun *et al.*, [2010] studied the gradient foam filled thin-wall structure under low velocity impact using FEM. It is found that the gradient foam filled structure is superior to its uniform counterpart in overall crash-worthiness. Cui *et al.*, [2009] conducted FEM simulation for gradient foam under impact and drew the similar conclusion: the energy absorption characteristics are improved by the gradient. The larger the density gradient, the more efficient is the energy absorption. The same conclusion is also achieved by Ajdari *et al.*, [2011] based on FEM simulation.

Zeng *et al.*, [2010] numerically investigated the foam system consisting of several homogenous foam layers with different relative density stacked together and found that placing the hardest layer near the distal end and weakest layer as the proximal end (to the protected structure) has some merits in energy absorption and reduction of the stress level transmitted to the protected structure, modeled as an unmovable rigid wall. Li *et al.*, [2011] used the commercial code ANSYS-LS/DYNA to simulate the multi-layered graded foam subjected to blast loads and found that the energy absorption capacity was improved while keeping a lower stress transmitted to the protected structure if the gradient of the foam density was properly arranged: the densest part placed nearest to the explosion. To understand the underlying mechanism of the merit of the gradient foam, Zhou and Ma analytically studied a continuous gradient foam subjected to a strong blast load and found the total energy needing dissipation is reduced by placing the relatively denser part closer to the blast.

Until now, the investigations on graded or gradient foam are still less reported. While this non-homogeneous foam have the potential exceptional qualities as blast mitigation cladding core, its mechanical behaviors under high velocity crushing or

Fig. 6. Some typical blast mitigation cladding cores [Wadley *et al.*, 2010].

compression should be thoroughly studied. Not only numerically, analytically, but also the experiments on gradient foam should be designed and conducted to directly examine whether the proposed gradient concept effectively mitigates blast load as expected. Zeng *et al.*, [2010] used split Hopkinson pressure bar to load the layered foam system in a mediate strain rate but found the stress alleviation is not as favorable as expected. However, in numerical simulation with higher impact velocities, the merits of energy absorption and transmitted stress reduction can be observed. It is believed that the reason accounting for the poor mitigation performance is the crushing velocity is not sufficiently high. Further development of theories and models on gradient and graded cellular materials and structures subjected to high velocity crushing should be based on direct observations from well-designed experiment. Therefore in the future experiment design, apparatus generating even higher loading rate, such as the Taylor test, may be employed.

4.3. Other forms of novel protective structures against blast load

Traditionally, metal foam and corrugated metal sheet, as well as the various types of truss and honeycomb structures [e.g. Dharmasena *et al.*, 2011] are used to mitigate the blast load. The major requirement of the cladding core are: the overall load-displacement relation of the core in compression should have a long plateau, with which a large amount of energy can be absorbed; further, take the cladding core as a black box, the blast load as input and the load transmitted to the protected structure as output. The force output should be much lower than the input so that the protected structure will not be over-loaded, which implies the plateau stress of the above-mentioned load-displacement curve should be lower than a specified level. With this requirement satisfied, various materials and structures can be used as cladding cores, shown in Fig. 6.

Actually, the core materials and structures are not limited to these forms. Palanivelu *et al.*, [2011] used empty beverage cans as sacrificial cladding core to form a “macro-foam structure”. In fact, for a typical structure or building, it is not economical to construct cladding with core of foam or lattice when the dimensions of the protected structure are large. Then some more economical and effective materials and structures should be selected, tested and applied.

Fig. 7. Metal foam application in structure protection: (a) External explosion; (b) Internal explosion; (c) Energy absorption at joint; (d) Energy absorption at ground.

4.4. Other applications of cellular solids in structure protection

As an exceptional candidate for energy absorption and blast mitigation of structures, cellular solids were mainly used as sandwich cores and penetration preventers attached to the structure exteriors. In fact, in the viewpoint of structure protection against blast load, the cellular solids should find wider applications. In addition to being used as an exterior blast alleviation cladding core as Fig. 7(a), the interior of a structure can also be protected by adding a metal foam cladding similarly (Fig. 7(b)). In the dynamic analysis of the cladding and structure, the only difference from that with an external blast load is besides the primary shock load, the reflection of the shock load and dynamic gas pressure, induced by the blast-induced airflow, are not negligibly small and should be incorporated [Smith and Hetherington, 1994]. Other forms of structure protection by cellular solids are also possible, for instance, to reduce the lateral force to be transferred to a beam, an energy absorption device can be attached to the beam-to-column joint (Fig. 7(c)); to avoid excessive vibration of a base, a simple isolation system can be designed as Fig. 7(d).

4.5. Active protection concept

In most of the existing literatures, the structure protection subjected to blast load is realized by adding a layer of relatively soft material which makes the stress transmitted to the protected structure at a low level. Since this kind of protective claddings can not perform any activity according to the incident blasts, the protection is categorized as ‘passive’. To achieve favorable protection efficiency, the imparted energy

Fig. 8. Active blast load mitigation cladding [Wadley *et al.*, 2010].

from the blast load should be dissipated before all the protection layer is fully densified, which may lead to an extremely high stress level transmitted to the protected structure. The requirement for the cladding cores is the density/stiffness of the core should be below a certain value, thus the core thickness must be adequate to avoid fully densification. Satisfaction of these requirements generally leads to an excessive core thickness. Nevertheless, a large core thickness reduces the standoff distance between the explosion and the cladding, inevitably resulting in a higher imparted impulse, making the protection a dilemma.

To overcome the difficulty and reduce the thickness of the cladding core, Wadley *et al.*, [2010] recently proposed an active concept for the blast mitigation with claddings, indicated in Fig. 8. Initially the cladding core, made of truss with rotational nodes, is folded and compacted. When there is a detonation nearby, the sensors installed in the cladding will respond immediately by monitoring the electromagnetic emission induced by the explosion and unfolds the core at a high rate by propellant detonation. Before the blast load can compress the cladding core and load the protected structure, it must neutralize the momentum in the opposite direction carried by the face sheet and core. The so-called momentum cancellation is numerically proved to be effective and the volume of the protection system is reduced by introducing the deployable pre-compressed cladding core. Since the shock wave propagates very quickly in air, the deployment of the folded cladding core is proposed to be released by a propellant. It is worth noting that the rapid release of the cladding also produces a load on the protected structures, which should be carefully calculated and selected to avoid overloading the structure.

However, prior to a real application of the active protection idea, some practical and challenging difficulties must be addressed. Amongst, the essential one is whether the detection-response-deployment process is sufficiently rapid to respond to the close range blast. In addition, if the deployable cladding core is mistakenly released too early, the standoff distance from the blast is significantly reduced. Therefore

the timing of the core release relative to the explosion occurring time becomes a critical issue.

In addition to the present active mitigation method, more feasible active devices and system should be incorporated into the blast protection of structures. Further, smart materials and structures, i.e., shape memory alloy, may also be introduced into this field. Besides, if the methodology of deployable structures is utilized, the thickness of the blast mitigation claddings can be significantly reduced so that the standoff distance between the possible threat and the structure is lengthened, which may improve the alleviation efficiency and avoid the negative mitigation effect. In addition, if the protective system is equipped with micro-processors and can perform different actions according to a specific blast events, that is, “intelligent” protection is achieved, then the blast mitigation will be revolutionized.

5. Conclusions

The blast mitigation of buildings and structures with cellular solids is briefly surveyed. The merits and drawbacks of various applications of such materials in structure protection are examined and discussed. Further, various fields relevant to structure protection against blast loads, including fluid-structure interaction, gradient cellular materials and structures, other novel protective structures, other application of cellular solids in various structures and active blast mitigation design, are discussed for possible future research.

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