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Air blast response of compaction foam having a deformable front face panel incorporating fluid structure interactions

Mustafa Turkyilmazoglu*

Department of Mathematics, Hacettepe University, 06532-Beytepe, Ankara, Turkey

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ABSTRACT

The present work is devoted to derive an analytical solution to the air blast response of dynamic compaction process of a sandwich composite containing a deformable front face and a cellular core. Shock wave model in association with the mass conservation and Newton's second law are employed to solve the problem. Both the weak fluid-structure interactions (FSI) such as those that are thought to occur due to air blast loading and the non-FSI cases are discussed and the results are compared with those available in the literature. The main contribution of this paper is that without having to numerically solve the governing equations, the form of the analytical solutions is capable of explaining the behaviour of enhancement zone for different choices of models including non-FSI, KNR (Kambouchev Noels Radovitzky) and FSI, which has potential advantages in practical applications. For instance, according to the results, the initial velocity of the face plate against the blast load will deter the cellular core compaction, which is basically the idea behind the "active armor". Therefore, the model developed in this paper may provide useful information for the design of such armor structures.

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1. Introduction

Since cellular material layers, due to their preferred mechanical characteristics, such as high deformation absorption, high crushing strength, high toughness and stiffness (despite the fact that the commonly used metallic foam usually has a plateau stress less than 10 MPa), high plastic energy absorbing, high vibration and sound isolation, ultra-light, non-flammable and, low cost and flexibility in design and manufacture [1], play a significant role as blast attenuators while protecting structures in industrial, military and civil engineering applications [2], the problem of determining response of sandwiched and crushable cellular materials when exposed to an air blast pressure has been at the heart of the recent studies in this direction. The present research also deals with such a problem when an explosive incident blast wave impinges on a deformable front face plate possessing different mass from the mass of the compacting core between the plate and the fixed rigid structure to be protected, refer to Fig. 1. Taking into account the fluid structure interaction effects, a mathematical analysis is implemented in this study for a realistic incident pressure wave.

Generally speaking, the impulsive loads induced by impact or blast are mitigated by cellular materials due to their feature of restricted stress transmitting in the compaction stage. However, the experimental set up by Song et al. [3] and one-dimensional model by Hanssen et al. [2] proved that if the whole energy due to the blast impact loading is not effectively absorbed by the used cellular material, it results in an enhanced transmitted force on the protective structure that is an unwanted situation in practical applications, refer to Section 2 for more description of the origin and type of physical phenomena. This fact accelerated the investigations towards correctly identifying the boundaries of attenuation/enhancement layer of the sandwiched foam corresponding to different blast loadings, blast end and distal end conditions, foam properties, see for instance Lopatnikov et al. [4], Fleck and Deshpande [5], Radford et al. [6], Harrigan et al. [7] and Aleyaasin et al. [8], and also the references therein.

The pioneering study of Reid and Peng [9]on the shock wave analysis of response of cellular solids consisting of wood pieces based on the idealized rigid, perfectly plastic, locking (R-P-P-L) material was extensively used for other cellular materials, such as metallic foams by Tan et al. [10], honeycombs by Hutchinson and Xue [11] and by Chi et al. [12], sandwich-type panels with steel plates by Karagiozova et al. [13] and hierarchical structures by Yi and Chen [14]. Since metal foams have the ability to dissipate a large amount of energy in the form of plastic energy, they are widely used for impact protection, for instance, the cushion pads used on the soft landing devices of lunar rovers and the bounding box of the automobiles as mentioned by Yi and Chen [14], and also advanced vehicle armor for improving the survivability of crew exposed to landmines or improvized explosive devices as

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* Tel.: +90 03122977850; fax: +90 03122972026.
E-mail address: turkyilm@hacettepe.edu.tr

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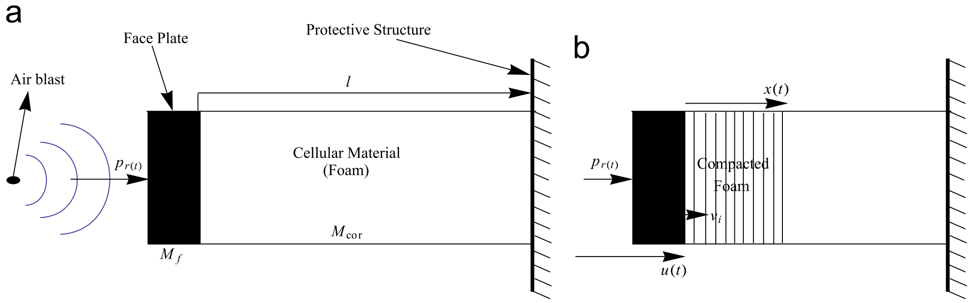

Fig. 1. The philosophy of the physical model. When the sacrificial cladding is at equilibrium in (a) and at motion in (b).

exemplified by Qi et al. [15]. Indeed, the experimental conduction by Liu et al. [16] approved that the peak load was reduced from 61.54 to 64.69% in sandwich panels with foam core compared to the mild steel plates without foam core. Additionally, the same observation was witnessed in the recent study of Qi et al. [15] in which a group of aluminum foam-cored sandwich panels with different combinations of face sheet materials was numerically investigated using the finite element method to measure blast-resistant behaviours.

For simplicity reasons, the aforementioned papers and most of the uncited here (see the review by Zhu et al. [17]) considered simplified loads due to pressure pulse at the ahead of contraction zone in the shape of either triangular (linearly decaying) pressure pulse [2] or of rectangular (plane) pressure pulse [7] and [18]. Moreover, the fluid-structure interaction (FSI) influences in general were disregarded, and during the blast loading, only the incident pressure wave was involved affecting the enhancement or attenuation of the blast waves through cellular material. However, as also clearly emphasized in the very recent article by Aleyaasin et al. [8], the form of actual loading pulse experienced by the front plate should arise from a reflected over-pressure and also should contain the effect of movement of the compacted foam. In the non-FSI approaches, the eventual impulse applied to a structure is over-estimated owing to the fact that the initial pressure pulse due to the air blast is evaluated from a purely hydrodynamic consideration. This deficiency was supposed to be overwhelmed in the partially FSI model, hereafter so-called as KNR (Kambouchev Noels Radovitzky) model, introduced by Kambouchev et al. [19] via considering a reduced impulsive load to the face plate as a consequence of incorporating the speed of sound to the compression duration. This model was later applied to estimate response of a free standing plate by Hutchinson [20] generating an under-estimated impulse on the reaction structure. It was also used to investigate the influence of mass distribution on the uni-axial crushing of cellular sandwich plates under air blast loading by Main and Gazonas [21]. It was however argued by Peng et al. [22] that the Kambouchev Noels Radovitzky model is not suited to fixed rigid plates yielding a reflected under-pressure, refer also to the comments of Aleyaasin et al. [8].

Taking into account the above critical cases of both non-FSI and KNR models, a very recent model was proposed by Aleyaasin et al. [8]. It is named extended Taylor theory (ETT) since it is based on extension of the theoretical work of Taylor [23] on the reflection of blasts in water. Employing an exponentially decaying pulse to approximate the free-air, incident blast wave, it was later shown in [8] that the estimates from this new method are between the above mentioned methods, more close to the non-FSI case clearly implying that the fluid-structure interaction influences are weak. This result was also indicated in the computational analysis of dynamic compaction of foam under blast loading by Nian et al. [24] that the fluid-structure interaction effects are significant only in the early part of the blast pressure history.

The prime objectives of the present research are twofold. From the physical point of view, the deformation phenomenon of compaction foam due to a deformable front face plate is accounted for loaded by an air blast of any rationally decaying type incident pressure. To be in line with the recent literature [8] for the comparison purposes, the reflected over-pressure is assumed to be as a result of impingement of an exponentially decaying pressure pulse on the deformable face plate. Initial speed of the plate is argued to be either prescribed or by some striking pieces of fragments and debris scattered from explosion. In terms of the representation of shock wave propagation and associated energy dissipation in the cellular core, the present model is compatible with those of Li and Meng [25] (except the lack of face plate in [25]) and of Tan et al. [10] (except the lack of loaded blast pressure in [10]), besides it is also equivalent to other models in the absence of initial speed/face plate. From the mathematical point of view, the fundamental aim is to obtain exact analytic solutions representing the displacement of the compacting cellular core as opposed to the existing numerical investigations in the literature. The obtained analytical solutions are surprisingly valid for all the cases considered in the literature, particularly the three scenarios outlined in Aleyaasin et al. [8] are fully covered, whose solutions were given only by numerical simulations.

The analytical results, on the other hand, enable us to examine the blast resistance performance of the compacting foam and to determine the boundaries of attenuation/enhancement of the cellular material driven by a deformable front face plate subjected to an air blast. Closed form expressions for the critical time and displacement yielding hundred percentage crushing of the sacrificial cladding are at the disposal of the practising engineers and scientists working on the subject matter. Moreover, the presented solutions are beneficial to understand the early stage of the dynamic compaction process and hence to control the response of the cellular material by shock waves, and also to get optimal designs for the survival of a structure against an impact/impulsive explosive loading. Finally, they constitute very useful data while resolving the physical phenomenon by other higher dimensional contemporary models simulated in general by finite element methods in the literature.

2. Physical model

A number of physical models were considered in the literature for the crushing resistance of cellular media adopting varying dynamic loadings. As illustrated in Fig. 1(a), we consider a cellular, crushable material consisting of sandwiched plates (foams or sacrificial claddings), acting like a protection zone/layer, attached at one end (proximal end) to a front face plate of mass M_f and at the other end (distal end) to a reaction structure to be protected, both of which are rigid and the structure is fixed. To control the force levels from blast loading to reaction structure by damping

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