Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Air-blast response of cellular material with a face plate: An analytical–numerical approach

M. Aleyaasin*, J.J. Harrigan, S.R. Reid

Fraser Noble Building, School of Engineering, University of Aberdeen, King's College, Aberdeen AB24 3UE, UK

ARTICLE INFO

Article history:
Received 28 February 2013
Received in revised form
20 December 2013
Accepted 27 March 2014

Keywords:
Cellular material
Blast response
Fluid structure interaction (FSI)

ABSTRACT

The air-blast response of a sacrificial cladding consisting of a cellular material with a front face-plate is investigated. The cellular material is sandwiched between a rigid face-plate and a rigid support. The support represents the structure that is to be protected. The air blast is assumed to be an exponentially decaying pulse. The cellular material is idealised as rigid, perfectly-plastic, locking and the deformation is governed by the propagation of a compaction (shock) wave travelling through the material. A second order nonlinear ordinary differential equation is derived to predict the displacement of the face-plate and the compression of the cellular layer by coupling the reflected over-pressure with the stresses at the interface between the face-plate and the cellular material.

The cellular material may attenuate or enhance the shock transmitted to the structure. Extensive simulations are carried out to define the attenuation/enhancement boundary for a range of initial peak pressures and cladding parameters. Herein, enhancement is considered to occur if the shock front reaches the support. A new method of accounting for fluid–structure interaction (FSI) is derived. The predictions are compared to those with no FSI as well as an existing model that accounts for the FSI effect, but for a free-standing plate.

1. Introduction

The air-blast response of a sacrificial cladding is analysed. The cladding consists of a front face-plate and a layer of crushable, cellular material. This cellular material is sandwiched between the face-plate and the structure that is to be protected. Both the face-plate and the protected structure are considered to be rigid and the structure is fixed. The problem is illustrated in Fig. 1. The use of cellular material as a protective layer for blast loading has been much debated. The material is included to attenuate the load on the structure. However, experimental evidence has highlighted the fact that the presence of this “protective” layer can result in an enhanced loading of the structure, see e.g. [1,2]. This evidence is summarised by Li and Meng [3] and is not repeated here. Under an impulsive load caused by a blast wave, a cellular material deforms in a progressive manner with the cells adjacent to the loaded surface compacting first and the deformation then passing through the material in a wave-like manner. In Fig. 1, the cells adjacent to the face-plate will deform first and the compaction wave will travel through the cellular material. If the compaction wave comes to rest before it reaches the structure, the structure is protected. The maximum pressure acting on the structure is then associated with the crushing stress of the cellular material and the high pressures associated with the blast loading are attenuated. If the compaction wave reaches the structure it will be reflected and amplified. The stresses on the structure may be far greater than those associated with the blast load.

The attenuation/enhancement boundary for the set-up illustrated in Fig. 1 has been investigated previously, see Refs. [1–5]. However, previous studies have tended to apply an idealised prescribed load to represent the effect of a blast. The actual loading on the face-plate due to an air blast is the reflected over-pressure. The fluid–structure interaction (FSI) that occurs when the incident blast wave is reflected from the face-plate will affect this reflected over-pressure [6–9]. The actual loading pulse that is experienced by the face-plate is therefore affected by both the face-plate itself and the cellular material layer.

In order to provide a fuller understanding of the applicability of cellular material layers as blast attenuators, two topics that have received a great deal of attention in recent literature are combined. These topics are: (i) The dynamic compaction of cellular material; (ii) The effect of FSI on the reflected over-pressure.

Reid and Peng [10] provided the first compaction wave (or “shock wave”) predictions for cellular solids to explain certain experimental results, focusing on the enhancement of the crushing strength of wood specimens. For simplicity, the cellular solid was idealized as a rigid, perfectly-plastic, locking (*R-P-P-L*) material (see Fig. 2). Similar predictions have since been applied to a number of cellular materials. For example Tan et al. [11] used this approach for modelling metallic foams, the model being validated generally by their experiments [12].

---

* Corresponding author. Tel.: +44 1224 273497; fax: +44 1224 272497.
E-mail address: m.aleyaasin@abdn.ac.uk (M. Aleyaasin).

http://dx.doi.org/10.1016/j.ijmecsci.2014.03.027
0020-7403/© 2014 Elsevier Ltd. All rights reserved.

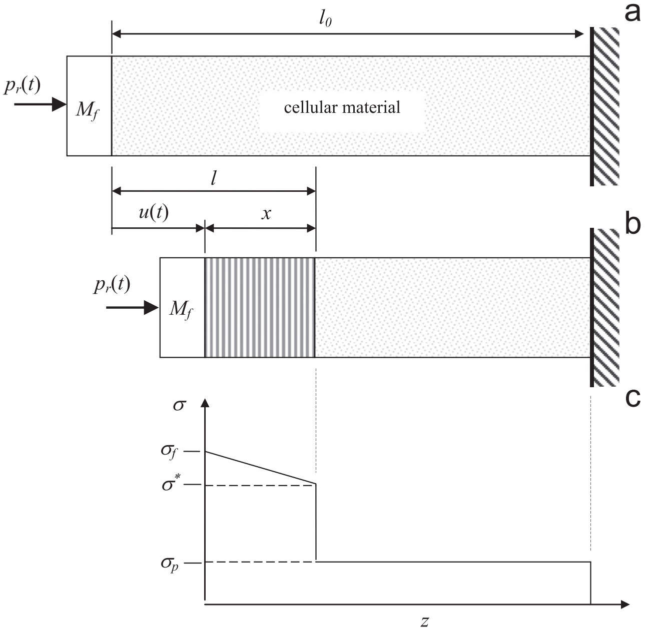

Fig. 1. Schematic of sacrificial cladding at times (a) $t=0$ and (b) $t>0$. For the compression stage illustrated in 1(b), the variation of stress with axial coordinate z is shown in 1 (c).

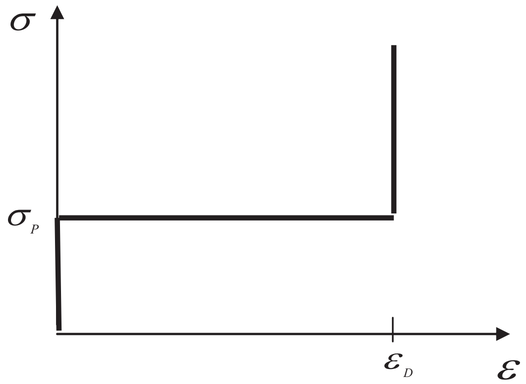

Fig. 2. *R-P-P-L* idealisation of the compressive behaviour of a cellular material.

Other recent papers (e.g. [4,13–15]) have applied the compaction wave theory, but extended the *R-P-P-L* material idealisation to include e.g. elasticity and hardening.

Many of the investigations on dynamic compaction of cellular materials have focused on the stresses just inside the compaction wave. In order to measure these stresses, foam samples with backing masses were fired directly at a load cell [10–12]. The attenuation-enhancement issue was not discussed directly, although it was noted that full compaction of a specimen led to a sharp rise in stress. Recently, Zhu et al. [16] published a review of experimental and analytical studies on the shock enhancement effect. Those papers that have considered the enhancement/attenuation boundary for cellular material layers under pressure pulses have tended to employ simplified, prescribed load pulses on the front face-plate. That is, the effect of FSI has been neglected. As examples, both Hanssen et al. [2] and Ma and Ye [5] employed a linearly decreasing pressure pulse and Harrigan et al. [4] employed a rectangular pressure pulse.

The *R-P-P-L* model for the response of the cellular material is employed here with a single value for the locking strain. Although experiments [14] and numerical simulations [17] suggest the locking strain is dependent on the jump in particle velocity across the compaction front, further investigations are required to give formulae that account for this dependency.

Kambouchev et al. [7] noted that FSI effects are rarely considered when determining air-blast loads on structures. Instead, the standard approach has been to assume that the structure is rigid and fixed. The blast loads are then determined from a purely hydrodynamic consideration of the propagation of the blast wave in air and its reflection at a fixed boundary. This approach tends to over-estimate the impulse applied to a structure. When a blast wave impinges on a plate, the motion of the plate relieves the pressure it is subjected to, leading to a decrease in the impulse transmitted to the plate. Recognising this, a model for FSI effects was developed using analytical and numerical methods by Kambouchev et al. [7] for an air blast impinging on a free plate. In this model, termed the KNR model, the nonlinear compressibility effects were considered and it was assumed that the back side of the plate that does not experience blast loading was at constant atmospheric pressure. The KNR model has been applied by Vaziri and Hutchinson [8] to determine the blast response of sandwich panels using the finite element (FE) method. In Ref. [8] the pressure applied to the sandwich panel in the FE simulations was determined using the KNR model for free plates. Further insights into the energy and momentum transferred to a freestanding plate under intense blast loads were provided by Hutchinson [9]. More recently, Peng et al. [18] have illustrated that the impulse delivered to the plate would be greater than that predicted by the KNR model if the shock wave formation in the air at the back face of the plate due to the motion of the plate is included in determining the reflected over-pressure at the front of the face-plate. This conclusion highlights that application of the KNR model for plates with a backing material is likely to be non-conservative. This could be important for cases where there is a compaction wave in the cellular material behind the face-plate (and a high stress at the interface between the face plate and the cellular material).

Herein, an exponentially decaying pulse is used to approximate the free-air, incident blast wave. This incident wave, $p_i(t)$, impinges on the face-plate resulting in a reflected over-pressure, $p_r(t)$, on this plate. This reflected over-pressure is estimated herein in three ways. First, the reflected over-pressure is assumed to be that for a fixed, rigid structure. This solution clearly neglects FSI and will over-estimate the impulse applied in a real blast and provide a conservative estimate for the attenuation/enhancement boundary. Second, the reflected over-pressure is assumed to be that predicted using the KNR model. This will under-estimate the impulse and provide a non-conservative prediction for the attenuation/enhancement boundary. Finally, a new analytical model is developed to incorporate both the effects of the FSI on the air/panel interface and the stress at the interface between face-plate and the cellular material. This new model, termed the Extended Taylor Theory (ETT), is shown to give predictions that lie between those of the KNR model and the predictions that neglect FSI.

Initially a dimensionless form of the governing equation for the motion of the face-plate is derived in order to determine the final percentage of the cellular layer that is crushed The pressure on the protected structure is restricted to the crushing stress of the cellular material if the final crushing is less that 100%, which is taken as a simple estimate for the attenuation/enhancement boundary.

A general expression that relates the displacement and velocity of the face-plate to both the reflected over-pressure and the properties of the cellular material is derived next. Following this, the over-pressure on the face-plate is defined using the three methods discussed above.

2. Compaction wave in cellular material

Using the simple *R-P-P-L* model for a cellular material, the material behaviour is determined by two basic parameters. They

Please cite this article as: Aleyaasin M, et al. Air-blast response of cellular material with a face plate: An analytical–numerical approach. Int. J. Mech. Sci. (2014), http://dx.doi.org/10.1016/j.ijmecsci.2014.03.027