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Compaction of a double-layered metal foam block impacting a rigid wall

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ABSTRACT

The propagation of compaction waves in layered metal foam materials subjected to impact loading is analysed in order to examine the mechanism of compaction and reveal the phenomena that develop at the interface between the foam layers. The analysis is focused on double-layered configurations in which the individual materials exhibit strain hardening in the quasi-static regime of loading.

Complex patterns of compaction due to impact are revealed depending on the foam quasi-static stress–strain characteristics, sequence of layers and impact velocity. The compaction of the individual foam layers under an increasing and decreasing velocity is distinguished. It is established that either a strong discontinuity wave or a simple compression wave can start propagating from the layers interface inside the distal layer depending on the material properties. It is shown that a secondary compaction of the proximal foam layer is possible to occur due to the propagation of the reflected wave from the layers interface when a particular layer sequence is arranged. This can lead to a significant stress increase at the interface.

The present analysis is based on uniaxial models of compaction in which the compacted strains are not predefined but are obtained as a part of the solution being functions of the velocity variation. The proposed analytical models are verified by numerical simulations considering aluminium based foam Cymat with densities 253 and 570 kg/m^3 and Alporas with density 245 kg/m^3. The influence of the elastic material properties is briefly discussed.

1. Introduction

The response of foams with different characteristics to impact and blast has been studied extensively during the past decade. The continual interest in the behaviour of cellular materials under different loading conditions is mainly related to the ability of these materials to manifest a significant increase of strength and energy absorption when subjected to an intensive dynamic load in comparison with their quasi-static response.

The compaction mechanism is the major source of an enhancement of the energy absorption capacity of the foam and therefore different methods have been proposed in the literature to model foam compaction. A shock wave propagation model in cellular materials was proposed by Reid and Peng (1997) to explain the crush enhancement of wood specimens assuming a rigid perfectly-plastic locking (RPPL) mechanism. A thermo-mechanical approach is used in the formulation of the dynamic compaction process to provide a first-order understanding of two impact scenarios (Tan et al., 2005). Retaining the basic characteristics of the one dimensional shock wave models, more detailed material models were used to account for the elastic material properties. An elastic–plastic model with hardening was proposed by Harrigan et al. (2005) while an elastic perfectly-plastic-with rigid locking model was applied by Lopatnikov et al. (2004). Although different material models were assumed, a predefined strain value associated with the fully locked material was used. A summary of different boundary conditions for a uniaxial foam compaction was presented by Main and Gazonas (2008).

The widely used RPPL model is appropriate and easy to apply for the approximation of the stress–strain characteristic of a cellular material with negligible strain hardening. The densification strain is well defined and the model predicts the response of foam materials particularly well for high velocity impact. Many cellular materials, however, exhibit different degree of strain hardening depending on their topology and density. In order to apply the RPPL model to these materials different definitions of the densification strain have been proposed based on homogeneous material properties (Lopatnikov et al., 2004; Tan et al., 2005) and based on the cellular topology (Hu and Yu, 2010) all of them being used over

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the entire range of the velocities, which occur during the impact event.

However, a full compaction within the primary stress wave cannot always be achieved in foam materials exhibiting strain hardening as shown experimentally by Pattofatto et al. (2007). Recently Tan et al. (2012) reported experimental results on dynamic compaction of Duocell foam pointing out the dependence of the maximum compaction strains on the impact velocity. In order to analyse the foam compaction under moderate velocity impact, a uniaxial rigid-linear hardening-locking model was proposed by Zheng et al. (2012), which can predict compaction strains that are smaller than the locking strain.

Therefore, the concept of a predefined densification strain is not applicable to the analysis of foam materials with strain hardening and the application of the RPPL model to approximate the material properties leads to an overestimation of their energy absorption capacity. This is particularly true when the applied velocity is a decreasing function of time (Karagiozova et al., 2012).

Despite the different stress–strain curve approximations, the pre-defined locking strain is the common characteristic of the above studies. Differently, a model based on a power-law hardening stress–strain characteristic of the foam was used by Pattofatto et al. (2007) to estimate the level of compaction strains due to a constant velocity impact. A more realistic impact scenario when the velocity decreases with time was analysed by Karagiozova et al. (2012). The proposed approach allowed determining a non-uniform strain distribution behind the wave front with sufficient accuracy. A strong dependence of the strains on the impact velocity within the compacted regions was revealed. A uniaxial shock model also using a constitutive relation with plastic hardening for cellular materials was proposed by Zheng et al. (2013) to analyse the compaction under decreasing velocity. The numerical simulations using Voronoi open cell material model and closed-cell foam showed close agreement with the predictions of the analytical model.

Recently an extensive experimental study of the crushing behaviour of open-cell Al foam under impact were reported by Barnes et al. (2014) together with a numerical analysis based on the foam microstructural model (Gaitanaros and Kyriakides, 2014). It was revealed that the transition to shock is rather gradual and the foam responds in a quasi-static manner to impact velocities lower than 40 m/s. This findings support the conclusion made by the present authors that the shock wave theory can be applied only when specific conditions related to the impact velocity and material characteristics are met.

In order to broaden the understanding of the dynamic compaction of a particular class of cellular materials (those that can be considered as homogeneous material with a strictly concave stress–strain curve), an impact on a stationary foam block by a deformable low-density projectile was analysed by Karagiozova et al. (2013) with the emphasis on the history and final distribution of the strains within the compacted zones that develop in the projectile and stationary foam block.

While the idea of propagating of compaction waves in a single cellular layer has received considerable attention, the structures comprising layered cores have been less studied from the view point of propagation of compaction waves. Theoretical analyses of double-layer claddings were presented by Ma and Ye (2007) using the RPPL material approximation and by Karagiozova (2011) using the actual stress–strain curve for the foam material. Larger number of experimental tests and numerical simulations on layered cellular materials has been reported in the literature. Wang et al. (2009) and Gardner et al. (2012) studied experimentally the dynamic response of three-layer simply-supported sandwich beam to a blast loading in order to analyse the effect of the layer sequence on the midpoint deflections. Numerical analysis of piecewise graded foam block subjected to impact was carried out by several research groups to investigate the compaction of various cellular topologies (Cui et al., 2009; Rueda et al., 2009; Zhang and Zhang, 2013; Fan et al., 2013; Maheo and Viot, 2013). The penetration due to a low velocity impact on sandwich structures based on cores fabricated by bonding three foam layers with different density together was studied experimentally and numerically by Zhou et al. (2013).

The reported experimental and numerical studies are mainly focused on the final displacements of the layered structures while the stress–strain state trough the core and the stress level at the layers interface are usually outside the scope of these studies. Whereas the dynamic stress enhancement of various cellular materials is a positive feature from the view point of energy absorption, this phenomenon can have a negative effect in layered structures due to the possibility of significant stress enhancement at the layer interface. In this paper, an impact of a double-layer foam block on a rigid wall is analysed in order to reveal the phenomena that develop at the layers interface and to broaden the understanding of the dynamic compaction of foam materials under different loading conditions. The proposed analytical formulation gives a fundamental approach to the interpretation of the propagation of plastic waves in a given class of low density closed foam that is difficult to be directly interrogated from the experimental tests or from numerical analysis. The current analysis emphasises on the history and final distribution of the strains within the compacted zones, which develop in the foam layers. The compaction of the individual foam layers under an increasing and decreasing velocity is distinguished. Attention is paid on the stress variation at the interface between the two materials. Numerical simulations are carried out to verify the results from the analytical models' results.

2. Basic equations

No details of the cellular geometry are analysed in the present study and it is assumed that the class of foam materials can be modelled as a homogeneous material which exhibits strain hardening. The stress–strain dependencies for the examined foam materials are characterised by a strictly concave curve which has a general expression

$$\sigma = g(\varepsilon), \quad g''(\varepsilon) > 0, \quad \varepsilon > \varepsilon_Y \tag{1}$$

where ε_Y is the strain at yield. Curves in terms of nominal stress and strain with characteristics defined by Eq. (1) and used in the current study are presented in Fig. 1. The elastic portion of deformations is neglected and plastic stresses and strains are taken positive in compression.

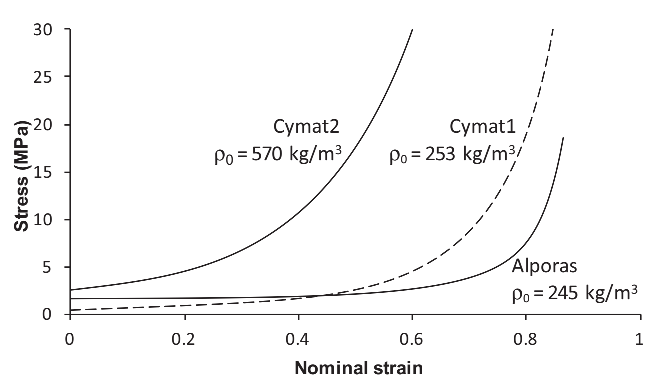

Fig. 1. Stress–strain curves of the examined materials, data for Cymat are taken from Langdon et al. (2010) and data for Alporas are taken from Pattofatto et al. (2007).