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Effect of elastic target on Taylor–Hopkinson impact of low-density foam material

Hu Liu, Zhiqiang Zhang, Hua Liu *, Jialing Yang

Institute of Solid Mechanics, Beihang University, 100191 Beijing, China

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ABSTRACT

As a common approach to evaluate the dynamic strength of cellular materials, the Taylor–Hopkinson test is often carried out by utilizing cylindrical cellular samples striking on the Hopkinson bar axially and determining the dynamic stress through the final deformation of the projectiles. However, extensive related theoretical analyses regard the Hopkinson bar as a rigid wall and ignore the influence of the elastic target bar, which may lead to inaccurate estimation of the dynamic stress of foam materials. In this work, a theoretical model for a low-density foam projectile impinging against a semi-infinite elastic target bar is presented to investigate the effect of elastic target bar on the dynamic stress prediction of the Taylor–Hopkinson test. A shock wave model incorporating the elastic wave propagation in the target bar is developed to obtain the deformation history and kinematic process of the foam projectile. It is demonstrated that the elastic properties of the target bar have a significant effect on the duration and deformation of the impact process. It is also indicated that the material and geometric parameters of the foam projectile and the target bar, and the initial velocity of the foam projectile have great influence on the impact–contact duration and the final deformation of the foam projectile. The history and final deformation of the foam projectile predicted by the present model are compared well with experimental results and finite element simulations. The present analysis provides a more accurate way to take advantage of the Taylor–Hopkinson test to predict the dynamic behavior of low-density foam materials.

1. Introduction

Low-density cellular materials such as foams and honeycombs have aroused wide concern due to their excellent properties like high specific strength and stiffness, high buffering and energy absorption capability, and have been extensively used in the high-velocity protection fields such as aeronautics, astronautics, automobiles, and military ships [1]. Therefore, their dynamic properties have attracted numerous research interests. A considerable number of experimental, numerical and analytical studies on the dynamic properties of foam materials under impulsive loading have been reported in the past decades.

The split Hopkinson pressure bar (SHPB) and Taylor tests are two useful measures for dynamic tests of foam materials. Many studies according to these two methods have been widely revealed. For example, literatures [2,3] set up SHPB facilities to investigate the dynamic stress–strain relationships of foam materials at high strain rate. Lu et al. [4,5] applied the Taylor impact test to studying the dynamic stress of porous materials. In their study, the increment of the cross-sectional area is observed in the impact tests of medium and high relative density porous materials. While for low-density foam materials, numerous researchers [6–8] have studied the compressive behavior of these materials and pointed out that the plastic Poisson's ratio is close to zero and the cross-sectional area remains unchanged during compaction. Based on this assumption, the stress wave propagation theory is introduced to analyze the dynamic compression of low-density foam materials theoretically, i.e. the one-dimensional shock wave theory.

The one-dimensional shock wave model was firstly proposed by Reid and Peng [9] to discover the dynamic stress enhancement ahead of the shock front and energy absorption of wood specimens. In their research, a rigid perfectly-plastic locking (RPPL) idealization was developed and compared well with experimental results. Later, this model was extended to analyze the dynamic response of foam rods subjected to shock loading or impacted by mass striker [7,10–12], and the foam projectile striking on the rigid wall as well [13,14]. All the pioneering work indicated the existence of the discontinuous shock wave front during the dynamic compression of low-density foam specimens. There are many literatures focusing on the improvement of this classical shock wave model, especially on developing constitutive relations to replace the RPPL idealization. For instance, Lopatnikov et al. [15] presented an elastic-perfectly plastic-rigid (EPPR) idealization to determine the elastic effect on the

* Corresponding author. Institute of Solid Mechanics, Beihang University, 100191 Beijing, China.
E-mail address: liuhuarui@buaa.edu.cn (H. Liu).

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dynamic stress estimation. Karagiozova et al. [13] established a strain hardening analytical model to reveal the velocity decreasing in the impact process. Zheng et al. [14] proposed a rigid-power-law hardening (R-PLH) model to predict the strength enhancement and deformation localization of the closed-cell foam materials subjected to dynamic loading. Unfortunately, most existing literatures focused on the constitutive relations of foam material specimens with very few seeking for the influence of elastic properties of the target bar. Sometimes, assuming the target as a rigid wall may lead to an inaccurate dynamic stress estimation of foam materials, especially during the implementation of the increasingly popular Taylor–Hopkinson test.

The Taylor–Hopkinson test can overcome the disadvantages of SHPB and Taylor tests. It is well known that the SHPB test can determine the dynamic stress–strain relationship through capturing the strain signals in the input and output bars, but this test is generally limited to the medium strain rate range. The Taylor test can provide higher strain rate and predict the dynamic strength by measuring the residual deformation, but the results are not accurate enough. The Taylor–Hopkinson test can be carried out conveniently by employing a foam projectile striking onto an output bar directly. During this test, not only the residual deformation, but also the strain signal in the output bar can be obtained to make the analysis much more accurate. This measurement is extensively used in dynamic strength tests by many authors. For example, Lopatnikov et al. [15] set up this device to predict the dynamic properties of aluminum foam materials and proposed a simplified theory model regarding the Hopkinson bar as a rigid bar. Wang et al. [16] also carried out the Taylor–Hopkinson experiment to determine the dynamic constitutive relationships of foam samples and gave a theoretical analysis by considering the target bar as a rigid bar similarly. As noted above, many efforts have been made to analyze the dynamic stress of foam materials by Taylor–Hopkinson experiment. However, most theoretical studies ignore the elastic effect of the target bar. Obviously, this idealization may cause inaccurate estimation of the dynamic stress. Besides, PMMA and polymer bars are often employed for impedance matching in the Taylor–Hopkinson test of low-density foam materials. In this case, the elastic modulus of the target bar is not high enough and the target bar may undergo obvious elastic deformation. In fact, Liu et al. [17] have discussed the influence of elastic bar on the dynamic response in the Taylor–Hopkinson impact test, and pointed out that the neglect of elastic properties in the target bar may incur substantial mistakes. However, their model is only applicable for medium and high density porous materials.

In this paper, an improved one-dimensional shock wave model associated with elastic wave propagation in the target bar is proposed to study the influence of elastic bar on the dynamic response of low-density foam projectiles. The output bar is simplified as a semi-infinite elastic bar to determine the elastic effect of the target bar. The deformation history, kinematic process and final deformation of the foam projectile are investigated to clarify the elastic effect of the target bar. The comparison between the rigid bar and elastic bar shows the importance of considering the elastic property of the target bar. The current theoretical model can be degenerated into the classic shock wave model and is validated by comparing with experimental data and finite element (FE) simulations.

2. Analytical model and governing equations

2.1. Governing equations

As depicted in Fig. 1(a), a cylindrical low-density foam projectile rod of initial length L_0 striking normally on a semi-infinite elastic target bar with an initial velocity V_0 is considered. The geometric diameter of the foam projectile is much larger than the dimension of pores in the foam to make sure that the projectile can be treated as a continuum. A_0 is the cross-sectional area of the foam projectile and remains unchanged during impact. The densification strain ε_d satisfies

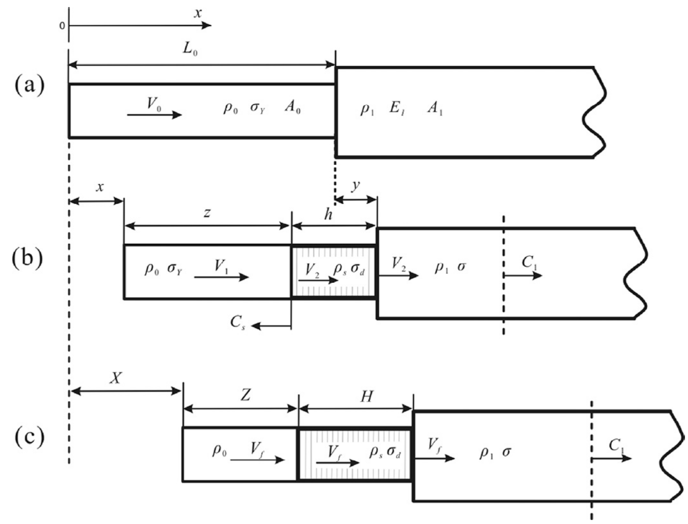

Fig. 1. Schematics of the Taylor–Hopkinson impact process of the low-density foam projectile: (a) initial stage, (b) intermediate stage, (c) final stage.

$$\varepsilon_d = 1 - \frac{\rho_0}{\rho_s} \tag{1}$$

where ρ_0 and ρ_s are densities of the foam projectile before and after compaction, respectively.

The behavior of the foam projectile is modeled as RPPL material with a plateau-stress level of σ_Y. Denote σ_d, the dynamic compressive stress, according to the densification strain ε_d. When the foam projectile strikes on an elastic bar, a shock front forms immediately in the layer of the impacted surface and propagates from the impacted end to the foam projectile with a Lagrangian wave speed $-C_s$, which can be written as

$$C_s = -\frac{dz}{dt} \tag{2}$$

where z is the un-collapsed length of the foam projectile rod ahead of the shock front.

Let x and y represent the displacements of the projectile and the elastic bar in the Lagrangian coordinate system, respectively. From the kinematics consideration, the following relationship can be obtained

$$\frac{dx}{dt} = V_1 \tag{3}$$

$$\frac{dy}{dt} = V_2 \tag{4}$$

where V_1 and V_2 are the particle velocities of the un-collapsed and densified regions of the foam projectile, respectively, as shown in Fig. 1(b). In the Lagrangian coordinate, the displacement continuity, and the momentum conservation conditions across the shock front of the foam projectile bar can be separately expressed as [16]

$$[V] = -C_s[\varepsilon] \tag{5}$$

$$[\sigma] = -\rho_0 C_s[V] \tag{6}$$