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Impact response of low-density foam impinging onto viscoelastic bar: A theoretical analysis

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ABSTRACT

The Taylor-Hopkinson test is widely used in predicting the dynamic strength of materials. For low-density foam materials, the output bar in the Taylor-Hopkinson test is often made from much weaker materials like polymethylmethacrylate (PMMA) to reduce the wave impedance mismatch between the foam sample and the output bar. These low impedance materials exhibit viscoelastic properties and may affect the dynamic stress prediction of foam samples. In this paper, the shock wave theory for the foam sample in conjunction with the viscoelastic wave propagation in the output bar is employed to illustrate the influence of the viscoelastic output bar on the dynamic response of foam samples in the Taylor-Hopkinson impact. The theoretical model presented in this paper can be degenerated into previous elastic target bar model and rigid target bar model. Finite element simulations are further performed to verify the proposed theory. The influence of material parameters on the final deformation of the foam sample, impact duration and residual velocity of the foam sample are investigated. The results in this paper not only help in understanding the effect of the viscoelastic bar on the dynamic response of foam samples, but also set up guidelines to perform the Taylor-Hopkinson test more precisely.

1. Introduction

Foam materials are well known for their outstanding mechanical characteristics, such as low weight, high specific strength and stiffness, excellent impact tolerance and energy absorption capability, which are increasingly used in automobile, aircraft and aerospace fields to protect persons and devices from suffering dynamic loadings [1–12]. In order to take full advantage of foam materials, it is quite essential to understand the dynamic behaviors of these materials. Experimental, numerical and theoretical analyses are common methods to investigate their mechanical features under dynamic loadings.

Experimentally, the dynamic stress of foam materials at high strain rates can be easily determined by using a rigid mass striking onto a foam sample or a foam specimen impinging onto a rigid wall directly. By using the former experimental method, Kader et al. [13,14] studied the shock wave propagation characteristics and pore collapse behaviors of closed-cell foam materials. Similar experiment was also carried out by Townsend et al. [15] to estimate the dynamic stress mechanisms of open- and closed-cell foams at high strain-rates. The latter method is also called Taylor impact test, and the dynamic stress can be predicted by measuring the residual deformation of foam samples. There are also many outstanding works on employing this experimental method to study the dynamic behaviors of foam materials. For example, Tan et al. [16] used a direct-impact technique to predict the dynamic compressive strength of metal foams. Lu et al. [17,18] set up the Taylor impact experiment to investigate the dynamic stress of porous materials. Ding et al. [19] adopted the virtual Taylor test to analyze the dynamic behavior of cellular materials. The related theories were proposed by many researchers, including the one-dimensional shock wave theory [16,20–24] and the mass-spring model [25]. Lately, the one-dimensional shock wave theory is proved to be much reasonable to simulate the dynamic crushing behavior of foam samples [26]. The shock wave theory was firstly proposed by Reid and Peng [27] to investigate the stress enhancement in wood samples under dynamic compressive loading. The rigid, perfectly plastic, locking (RPPL) assumption was widely adopted in the earlier studies. Subsequently, the constitutive models were extended. For instance, Lopatnikov et al. [28] presented an elastic perfectly plastic rigid (EPPR) model to replace the RPPL idealization. Wang et al. [29] developed a dynamic rigid-linear hardening plastic-rigid unloading model (D-RLHP-R) to investigate the dynamic constitutive behaviors of foam materials. Zheng et al. [30] analyzed the strength enhancement and deformation localization features of foam materials on the basis of the rigid-power-law hardening (R-PLH) idealization. Their studies all demonstrated that a discontinuous shock wave front could appear during the dynamic crushing process of foam materials. However, most of their studies treated the target bar as a rigid wall, and ignored the elastic or viscoelastic effect of the target bar. Under some specific conditions, this idealization may not hold and

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even leads to unacceptable accuracies.

For intermediate strain rate test, SHPB method is a widely used technique which can provide precise predictions of the dynamic crushing stress of foam materials via the accurate strain signals in the input and output bars. Employing this technique, Liu et al. [31] investigated the dynamic crushing behaviors of closed-cell aluminum foam samples. Yang et al. [32] built a SHPB testing system to detect the deformation localization characteristics of foam samples under middle speed impact. Wang et al. [33] studied the dynamic behavior of aluminum foams by using the SHPB test technique. It is worth noting that most of their experiment setups were made from low impedance materials (e.g., PMMA or polymer). This is due to the fact that the wave impedance of foam samples is much lower, and the traditional metallic SHPB setup may fail to provide a satisfying result because of wave impedance mismatch. Unfortunately, these test bars always exhibit viscoelastic behaviors, which may incur some unexpected deviations on the estimation of the dynamic stress.

The viscoelastic effect of Hopkinson bars on the dynamic stress evaluation has attracted a great deal of attention. Experimentally, Kolsky [34] investigated the pulse wave propagation along the viscoelastic polymer rods by recording the explosive wave traveling in the rod without considering the wave dispersion and geometrical effects. Zhao et al. [35] proposed a two-gage measurement method to separate the elementary waves caused by the viscoelastic effect which took the wave dispersion effect into account. Later, this method was adopted to the SHPB test of weak specimens [36]. Bacon [37] extended their study which considered not only the wave propagation dispersion but also geometrical effects on the wave attenuation in the PMMA bars. This method was also applied to the SHPB test of low-impedance specimens. Othman [38] estimated the errors caused by ignoring the viscoelastic behavior of Hopkinson bars in the SHPB test of aluminum honeycombs.

Apart from the above experimental investigations, theoretical analyses were also employed by many researchers to account for the wave attenuation and dispersion in viscoelastic Hopkinson bars. Wang et al. [39] provided a general model for determining the dynamic stress of foam samples by using viscoelastic SHPB devices. In their study, a theoretical method based on Zhu-Wang-Tang viscoelastic constitutive equation was used to characterize the viscoealstic wave propagation in Hopkinson bars. Butt et al. [40,41] proposed a parametric identification procedure based on the three-dimensional wave propagation analysis to rectify the uncertainties caused by noise signals. In their researches, the five-parameter model and the three-parameter model were selected to represent the viscoelastic behavior of the Hopkinson bar. Although different constitutive models were employed, their studies all indicated that the viscoelastic effect should be taken into consideration in the SHPB test for low impedance materials. The similar problem was also discussed by several different authors [42–49].

Recently, a new experimental technique named Taylor-Hopkinson test is employed by using foam samples impinging onto a semi-infinite cylindrical target output bar longitudinally to obtain the dynamic stress of foam materials [20,28,29]. This test system can provide higher strain rate than the traditional SHPB test, and the strain signals in the output bar can result in a more accurate prediction. Similar to the SHPB test, the target bar is often made from the low impedance material (i.e., PMMA and polymer) in the Taylor-Hopkinson test. Most related theoretical analyses still regard the target bar as a rigid wall for simplicity. In our previous analysis [50], we have studied the elastic effect of the target bar on the dynamic responses of foam samples, which has demonstrated that neglecting the elastic effect of the target bar may cause overestimating the dynamic stress of foam materials. Actually, the elastic assumption of the target bar is still not accurate enough and the viscoelastic effect should be incorporated. To the best of our knowledge, there is still a lack of the theoretical investigation of the viscoelastic effect of the output bar on the Taylor-Hopkinson impact for low impedance materials.

This paper aims at presenting a theoretical model to illustrate the viscoelastic effect of the target bar on the Taylor-Hopkinson impact of foam materials. The one-dimensional shock wave theory is extended to analyze the dynamic crushing behaviors of the foam rod under impact loadings, and the coupling effect of the viscoelastic wave propagating in the target bar is also taken into account. The comparisons among the viscoelastic bar, elastic bar and rigid target bar models are given to illustrate the viscosity and elastic effects of the target bar. Parametric analyses are carried out to shed light on the viscoelastic effect on the deformation history and final deformation of foam samples.

2. Basic equations

A cylindrical foam sample striking longitudinally onto a semi-infinite output bar with an initial velocity V_0 is established to simulate the Taylor-Hopkinson test. As depicted in Fig. 1, the semi-infinite output

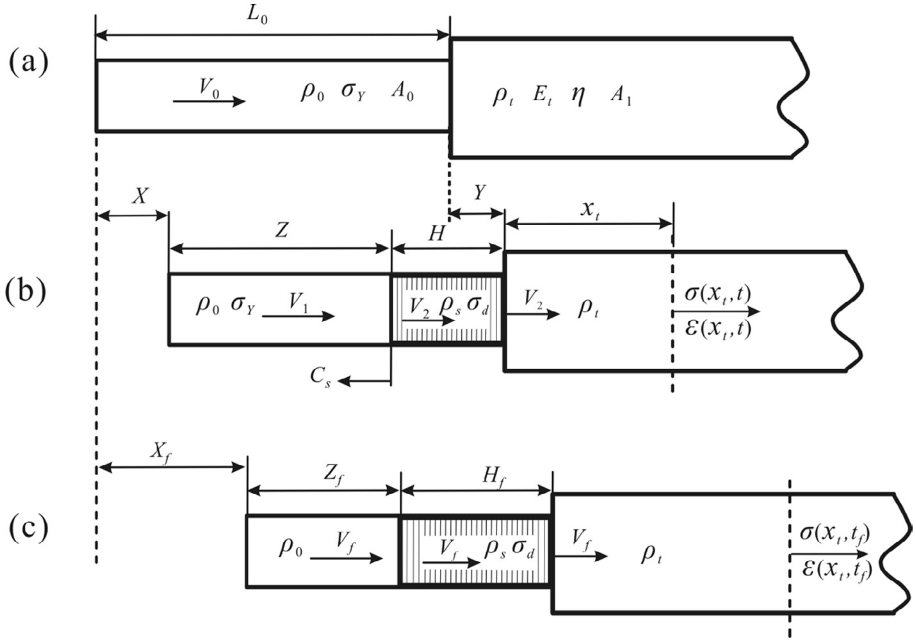

Fig. 1. Sketch of a low-density foam sample impinging onto a semi-infinite viscoelastic target bar: (a) initial instant, (b) intermediate instant, (c) final deformation.