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A numerical study of shock wave reflections on low density foam

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Abstract. A continuum mixture theory is used to describe shock wave reflections on low density open-cell polyurethane foam. Numerical simulations are compared to the shock tube experiments of Skews (1991) and detailed wave fields are shown of a shock wave interacting with a layer of foam adjacent to a rigid wall boundary. These comparisons demonstrate that a continuum mixture theory describes well the shock interactions with low density foam.

Key words: Porous material, Shock reflection, CFD

1. Introduction

In contrast to single phase materials, porous materials contain internal boundaries or interfaces which greatly influence their thermal and mechanical response to shock loading. For example, the combustion of granular energetic materials is enhanced by connected porosity, and accelerated reactive waves are known to produce compaction and compressive waves which ultimately focus to produce a detonation wave (Baer and Nunziato 1989).

In spite of the wealth of study of multiphase flow, much remains to be understood regarding the complex nature of shock induced flow in distended materials. Continuum mechanics has provided a firm foundation for theoretical study and mixture theory has successfully described various multiphase waves (Baer and Nunziato 1986). These studies have been previously applied to model strong shock wave response, but relatively little work has explored the behavior of weak shocks.

Recently, Skews (1991) reported a series of shock tube studies which resolved reflected waves from weak shock interactions with low density foams. Detailed pressure measurements identified multiple wave fields, and sufficient data were provided to test theoretical modeling. The following study applies continuum mixture theory to replicate these experimental observations. It is shown that the multiphase model describes well the complex structure of weak reflected shock waves.

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2. Theoretical description

The continuum mixture model in this study is taken, in its entirety, from the work of Baer and Nunziato (1986); only the final forms of this model are given here. For simplicity, the balance equations are given for one-dimensional two-phase flow. Thus, the effects of material strength and wall boundary friction are not studied. Each phase is denoted with a subscript a to identify a solid ($a = s$) and a gas ($a = g$). Associated with each phase are the material densities, ρ_a, temperatures T_a, and internal energies e_a. The Eulerian form of the balance laws, excluding the effects of mass exchange are given as:

mass

$$\frac{\partial}{\partial t}(\phi_a \rho_a) + \frac{\partial}{\partial x}(\phi_a \rho_a v_a) = 0 \tag{1}$$

momentum

$$\frac{\partial}{\partial t}(\phi_a \rho_a v_a) + \frac{\partial}{\partial x}(\phi_a p_a + \phi_a \rho_a v_a^2) = m_a^{\ddagger} \tag{2}$$

energy

$$\frac{\partial}{\partial t}(\phi_a \rho_a E_a) + \frac{\partial}{\partial x}\left((\phi_a \rho_a E_a + \phi_a p_a) v_a\right) = e_a^{\ddagger} \tag{3}$$

where $E_a = e_a + v_a^2/2$ and the $\ddagger$ superscript denotes a phase exchange quantity.

To describe the rate of change of solid volume fraction, a compaction model is derived from the entropy inequality given as

$$\frac{\partial \phi_a}{\partial t} + v_s \frac{\partial \phi_s}{\partial x} = \frac{\phi_s \phi_g}{\mu_c}(p_s - p_g - \beta_s) \tag{4}$$

and $\phi_s + \phi_g = 1$ is the saturation constraint. The intragranular stress β_s is the stress associated with the contact forces of the solid phase pore structure and is separate to the bulk stress

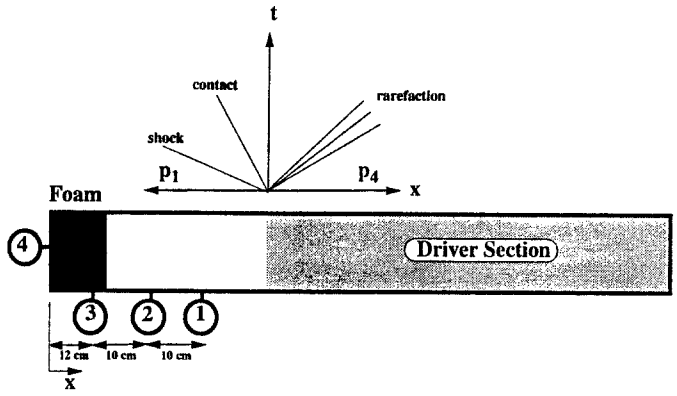

Fig. 1. Schematic of the shock tube geometry and pressure gauge locations

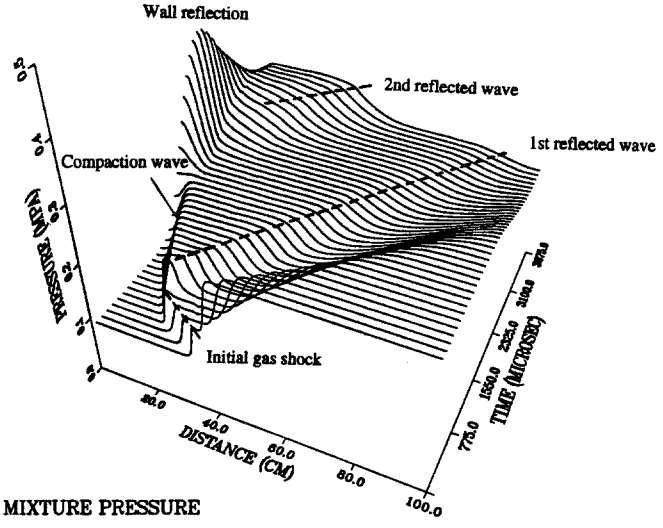

Fig. 2. Pressure wave profiles for a M = 1.25 incident shock interacting with 19 cm of foam

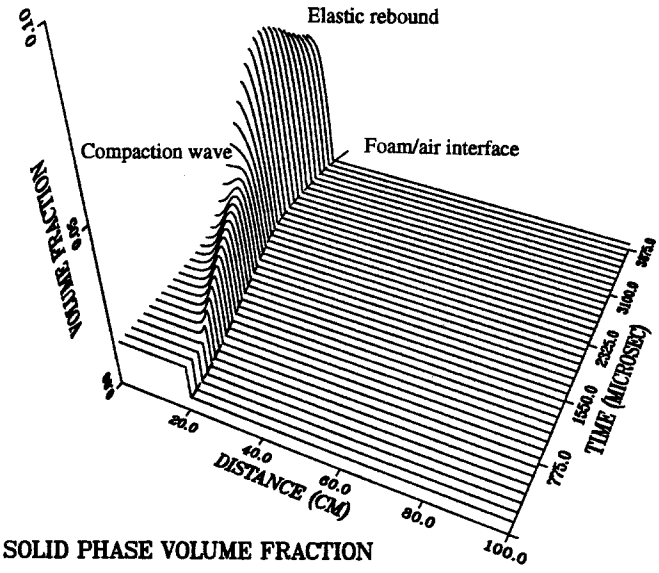

Fig. 3. Solid volume fraction profiles for a M = 1.25 incident shock interacting with 19 cm of foam

associated with the material compressibility. The intragranular stress is modeled using an effective bulk modulus defined by Warren and Kraynik (1991). At large strain, the material is assumed to undergo elastic buckling at a constant yield stress as described by Gibson and Ashby (1988). The compaction viscosity μ_c, dictates the rate at which the volume fraction adjusts to an equilibrium stress state: $p_s = p_g + \beta_s$, and its value is estimated to be $O(10^3 - 10^4)$ (poise) as used in prior dynamic compaction studies (Baer 1988).

Consistent with the formulation of mixture theory, the interaction of momentum and energy are given as

$$m_s^{\ddagger} = -m_g^{\ddagger} = p_g \frac{\partial \phi_s}{\partial x} - C_d(v_s - v_g) \tag{5}$$

$$\begin{aligned} e_s^{\ddagger} &= -e_g^{\ddagger} \\ &= m_s^{\ddagger} v_s - h(T_s - T_g) \\ &\quad - (p_s - \beta_s)\frac{\phi_s \phi_g}{\mu_c}(p_s - p_g - \beta_s) \end{aligned} \tag{6}$$

The drag coefficient C_d, and the interphase heat transfer exchange coefficient h, are retained in the forms determined in prior work (Baer and Nunziato 1986). Model closure is obtained using a solid phase thermoelastic equation of state which is fit to shock Hugoniot data. Additionally, the ideal gas law is used for the gas phase equation of state and the isentropic index of the gas γ is assumed constant.

3. Numerical solution

Appropriate numerical methods to resolve these highly stiff multiphase equations have been previously studied as reviewed by Baer et al. (1986). This study uses the method of lines numerical technique. In this Eulerian approach, spatial derivatives are discretizes using central differences and the resulting set of ordinary differential equations is solved using a stiff ODE solver. To stabilize the hydrodynamic calculation, a minimal amount of numerical viscosity is used to prevent numerical dispersion. An adaptive noding method is used to accurately follow contact surfaces and shock fronts. This also greatly reduces the effects of numerical diffusion. Typically 50 adaptive nodes are required in these numerical calculations.

4. Numerical calculation and comparison to experiment

Using the aforementioned model, one-dimensional numerical solutions were obtained in simulation of the shock tube experiments of Skews (1991). The computational domain was taken to be 1.0 m long and the high pressure air driver section was assumed to occupy 65% of the tube length

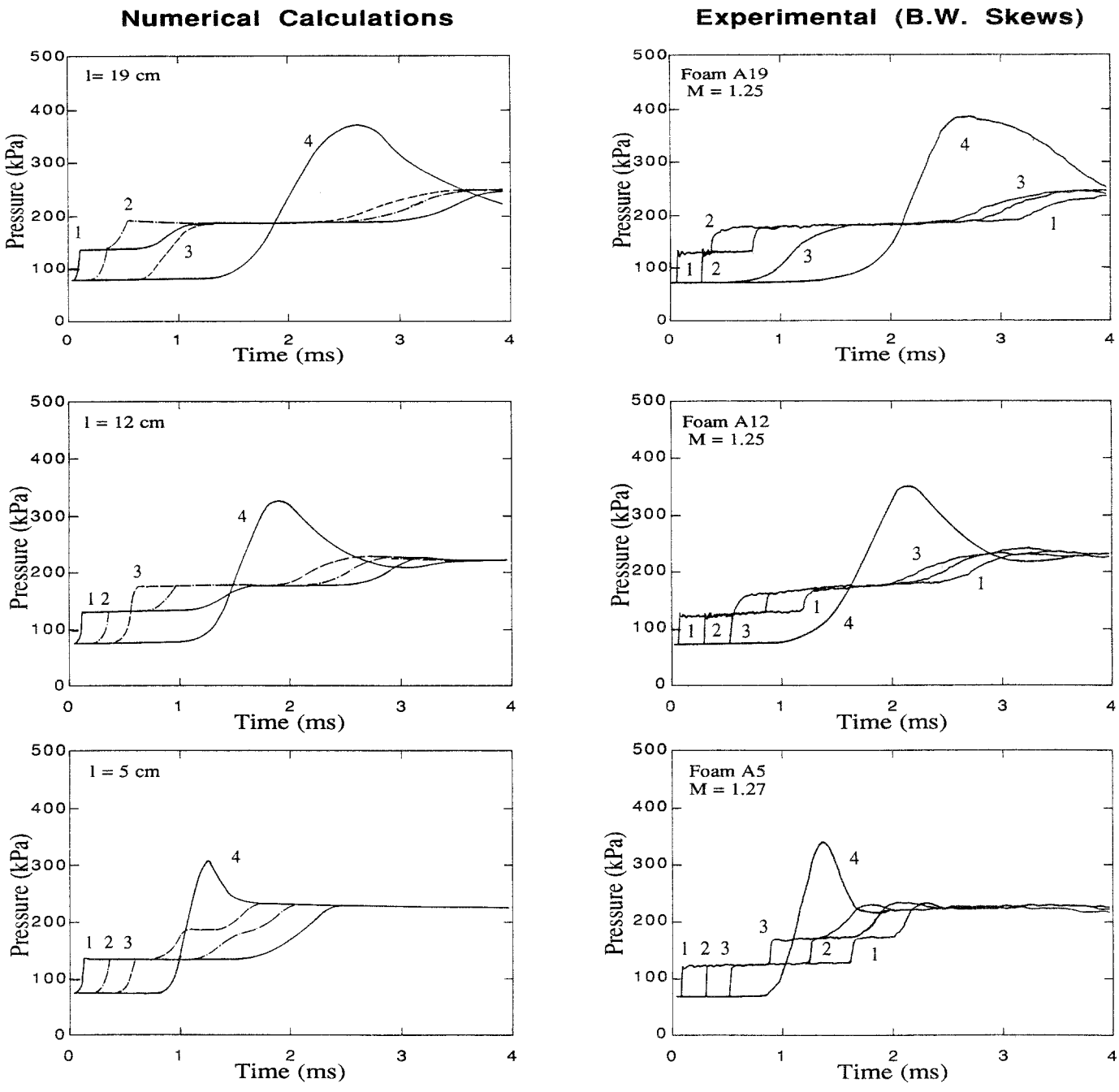

Fig. 4. Pressure histories at gauge locations for shock interactions on foams of varied length. Numerical calculations on the left side are shown in comparison to experimental pressure records (Skews 1991)

as shown in Fig. 1. As derived from one-dimensional gas dynamic theory, the initial high pressure is taken as

$$\frac{p_4}{p_1} = (1+z) \Big/ \left(1 - \frac{(\gamma-1)}{2\gamma}\left[\frac{2\gamma z^2}{2\gamma+(1+\gamma)z}\right]^{\frac{1}{2}}\right)^{\frac{2\gamma}{\gamma-1}} \qquad (7)$$

where

$$z = \frac{2\gamma(M^2-1)}{(1+\gamma)}$$

assuring consistency of the initial shock conditions to the experiments at specified Mach number M. The initial gas temperature was assumed to be 300 K.

In the numerical shock tube experiments, a region of low density, uniform porosity polyurethane is placed adjacent to a rigid boundary. Thus, a discontinuous solid volume fraction separates the gas and the gas-permeable porous regions. All of the physical properties were estimated using existing data as given in Gibson and Ashby (1988).

Numerical calculations for a $M = 1.25$ shock interacting with a low density (0.0148 g/cc) foam of length 19 cm are shown in Figs. 2 and 3 displaying the temporal and spatial variations of pressure and solid volume fraction.

Figure 2 shows an overlay of pressure wave fields projected in distance-time space. The initial shock wave structure is consistent with Riemann shock tube theory prior to impact on the foam. After the shock hits the foam, a reflected wave passes back into the driver gas and a compaction wave occurs in the foam as gas permeates into the porous material imparting momentum to the solid phase. A two phase shock hits the rigid boundary of the shock tube, and stagnation of material produces a large pressure rise. Reflection of this pressure pulse causes the second reflected wave. This wave has a dispersive front and an amplitude greater than that of the first reflection off the foam/air interface.

Figure 3 displays the variations of the solid volume fraction. The compaction wave produced after the gas shock hits the foam face is clearly evident and the compaction wave grows in amplitude until material hits the wall. The elastic rebound of the foam is seen at later times.

The shock interaction with foams of varied length have been simulated and compared with existing experimental observations. Figure 4 shows numerical calculations of the pressure histories commensurate with experimental pressure gauge locations. The experimental records (Skews 1991) have been reproduced for comparison to numerical calculations. Clearly, the mixture model replicates many aspects of the experimental observations. Multiple wave reflections are well resolved, and large pressures are observed for reflection off the rigid wall boundary. Reflected waves were calculated to be slightly dispersive due to the recession of the foam/air interface. In spite of the uncertainty in foam permeability and material properties at the low densities, it has been demonstrated that continuum mixture theory describes well the reflected wave behavior.

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