Shock Hugoniot measurements in foam

To cite this article: O E Petel et al 2014 J. Phys.: Conf. Ser. 500 112050

View the article online for updates and enhancements.
Shock Hugoniot measurements in foam

O E Petel¹, S Ouellet², D L Frost³ and A J Higgins³

¹ Carleton University, Mechanical and Aerospace Engineering, Ottawa, ON, K1S 5B6, Canada
² Defence Research and Development Canada Valcartier, Québec, QC, G3J 1X5, Canada
³ McGill University, Department of Mechanical Engineering, Montréal, QC, H3A 0C3, Canada

E-mail: oren.petel@carleton.ca

Abstract. The present study outlines a new approach to collecting shock Hugoniot data in foams using photonic Doppler velocimetry to perform mid-plane measurements of the foam deformation. Plate impact experiments were carried out to investigate wave propagation in a closed-cell polymeric foam and an open-cell aluminum foam. Dual-wave structures were observed in both materials with the leading precursor wave determined to be an elastic wave. The discussion of the results focuses on the nature of foam compression under high-rate loading, particularly the difference between the strain history in a foam undergoing uniform stress compaction and uniaxial strain compression. These results are discussed in reference to the current interpretations of Taylor-Hopkinson bar experiments on similar metallic foams. The importance of gas-filtration driven flows in the wave dynamics of open-cell foams is discussed in relation to the nature of the precursor waves.

1. Introduction

Foams, which are often used in protective applications to attenuate the effects of an impact or blast wave, have been characterized over a wide range of relevant dynamic loading conditions, including shock tube, blast wave, split-Hopkinson bar, and impact loading [1-5]. Although foams have been used effectively to reduce force transmission, there are certain loading conditions under which the foam may amplify the force transmitted to a body [1]. Explanations of this amplification phenomenon have ranged from wave-based impedance arguments [6] to gas-filtration driven kinetic energy arguments [7], although recent experimental investigations have shown that the response of polymeric foams to blast wave loading is dominated primarily by wave dynamics [5]. Under blast wave loading, both open-cell and closed-cell foams exhibited attenuation behaviour that was consistent with classical elastic-plastic materials, particularly a dual-wave structure with an elastic precursor wave. In the present study, we extend the investigation of open-cell and closed-cell foams to their response under impact loading.

Open-cell foams are often discussed in terms of the gas filtration flow within the interstitial spaces of their skeletal structure. The leading edge of the waves propagating in open-cell foams has often been attributed primarily to this type of filtration flow [8] and by extension to the stress amplification seen in foams [7], particularly when these foams are loaded by a wave generated from a gas-driven flow. Recently, it was shown that a thin plastic barrier placed at the mid-plane of an open-cell foam, restricting the flow of interstitial gases during blast wave loading, had no effect on the stress transfer through the foam [5]. In the present study, a metallic open-cell foam is impacted while under vacuum to provide further evidence relating to the nature of the leading
compressive wave (precursor wave) transmitted through the foam, particularly investigating the influence of the interstitial gas.

In the present study, laser-based velocimetry was used to measure the mid-plane deformation of the foam that resulted from a plate impact. The mid-plane deformation history of the foams can be used to analyze the nature of wave propagation in foams. Of particular interest is the constant stress plateau region that is often interpreted as the primary source of energy absorption in foams under quasi-static compression [9], an interpretation that requires closer attention at higher strain rates. Due to the considerable body of work that has been published on the quasi-static and low-rate compression of foams, some concepts of quasi-static compaction have permeated the discussion of foam compaction under dynamic conditions. The idea of constant strain rate loading under impact has been discussed in the analysis of recent investigations on impact loading of metallic foams [3, 10]. Mid-plane velocimetry measurements in the foams will allow the strain history of the foams to be directly examined and the relevance of a constant strain rate loading to be discussed in the context of an impact event.

2. Experimental Configuration

The dynamic behaviour of foam at high strain rates was investigated using a plate impact technique. This experimental approach involved using a symmetric impact, meaning that both the impactor and target material were the same. The foam impactor samples were supported by a polyvinyl chloride sabot as they were accelerated in a 64-mm internal bore single-stage gas gun. The velocities of the impactors ranged between 200 and 650 m/s. The experiments were conducted in a target chamber which was evacuated to an absolute pressure of approximately 5 kPa prior to each experiment. A schematic of the experimental configuration is shown in figure 1(a). Notice from the configuration schematic that the primary diagnostic for the experiments was a photonic Doppler velocimeter (PDV) or heterodyne velocimeter [11], which measured the time resolved velocity history of the projectile and mid-plane of the foam samples. The PDV probes that were used in this experiment were collimators with an average spot size of 220 µm.

Two different foams were investigated in the present study, a polymeric foam and a metallic foam. The polymeric foam was a low density polyethylene closed-cell foam (MTI Polyfab) with an average density of 45 kg/m³ that will be referred to as LD45, while the metallic foam was a Duocel aluminum open-cell foam (ERG Aerospace) with an average density of 297 kg/m³. The average pore sizes of LD45 and Duocel foams were approximately 300 µm and 800 µm, respectively. The diameter of both types of foam samples were 57 mm and the mid-plane velocimetry measurements in the target foams were made at depths of 25.4 mm and 12.7 mm for the LD45 and Duocel respectively. The thicknesses of the impactor foams were double this measurement depth of the target foams for a given experiment.

The target foams were composed of two separate pieces of foam of the same thickness to allow measurements to be made at the mid-plane of the sample. Two holes (ϕ = 2.4 mm) were milled in the foams at a radius of 6 mm from the center to allow the collimated laser beam to reach the measurement surface. One of the holes continued through the entire sample to enable the PDV probe to measure the down-bore velocity of the impactor as well as the deceleration of the impactor at the impactor-sample interface. The second hole was only present in one of the foam target samples to allow the PDV probe to measure the motion of the mid-plane of the target foam. The relative hole placement and depths are seen in figure 1(a), while a photograph of a milled front-layer Duocel aluminum foam sample is seen in figure 1(b). Aluminum foil (0.02 mm thick) was placed on the surface of the impactor as well as at the mid-plane of the foam test sample to provide a reflective surface for the velocimetry measurement.
3. Results

A sample spectrogram combining the signals from both PDV probes obtained from a single experiment with LD45 is shown in figure 2(a). The velocity history data can be extracted from the spectrogram for each probe and is represented in figure 2(b). Note that the projectile velocity is stable as it exits the muzzle of the gas gun until encountering the foam target, which results in a rapid deceleration at the impactor-target interface. At a later time ($\sim 46 \mu s$), the initial effects of the impact arrive at the mid-plane of the foam target, which will be termed a precursor wave. The resulting increase in velocity seen at the mid-plane can be divided into two distinct regions of behaviour, consistent with the dual-wave (elastic-plastic) structure seen in this foam under blast wave loading [5]. The precursor disturbance, which can be shown to be an elastic wave, results in a low amplitude motion of the foam. The velocity of the foam following the elastic precursor wave is an order of magnitude lower than the expected equilibrium velocity following the impact (half the impactor velocity for a symmetric impact). The second, larger amplitude disturbance brings the motion of the foam to the appropriate equilibrium velocity from the impact (i.e., half the flyer plate initial velocity). The relative arrival of the two disturbances ($\sim 75 \mu s$ apart) at the mid-plane measurement is an indication of the velocity difference between the precursor wave and this compaction wave.

3.1. Polymeric Foam

The data collected for LD45 can also be represented in the standard wave velocity-material velocity ($U_s-u_p$) plane, as shown in figure 2(c), based on the relative arrival of the waves following the impact seen in probe 1. The propagation and material velocities associated with the elastic precursor wave as well as the compaction/plastic wave are considered separately in these graphs. The elastic precursor velocities measured in the LD45 foam (see Table 1) compare well with the estimated longitudinal sound speed in this foam (533 m/s) calculated previously in [12] with the
Figure 2. (a) Plot combining the spectrogram from both PDV probes for an impact experiment involving the LD45 foam. (b) A velocity history obtained from the spectrogram in (a). (c) The shock Hugoniot of the polymeric LD45 foam. (d) The velocity history from an experiment with the Duocel aluminum foam.

equation,

\[ C_L = \sqrt{\frac{\rho_0 (1 + \nu) E}{\rho_0 (1 + \nu) (1 - 2\nu)}} \] (1)

where \( E \) is the elastic Young’s modulus (6 MPa), \( \rho_0 \) is the initial density of the foam (45 kg/m\(^3\)), and \( \nu \) is the Poisson’s ratio of the foam (0.4). This estimate of the longitudinal sound speed is in agreement with the experimentally determined elastic precursor velocities measured in LD45 in the present study shown in figure 2(c).

The wave velocity measurements show that this precursor is an elastic wave as it matches the theoretical longitudinal wave speed in the foam. The average material velocity associated with the elastic wave in LD45 was found to be 10.8 ± 3 m/s. The compaction material velocities presented in Table 1 match the expected final material velocities resulting from a symmetric impact, within experimental error. These results provide a validation of the experimental technique.
Table 1. Experimental results for the polymeric foam, LD45.

| Experiment | Impact Velocity (m/s) | Elastic Wave Speed (m/s) | Elastic Material Velocity (m/s) | Compaction Wave Speed (m/s) | Compaction Material Velocity (m/s) |
|------------|------------------------|--------------------------|--------------------------------|-----------------------------|-----------------------------------|
| 1          | 179                    | 552                      | 8.5                            | 137                         | 70                                |
| 2          | 214                    | 531                      | 10.0                           | 117                         | 102                               |
| 3          | 339                    | 549                      | 12.5                           | 210                         | 167                               |
| 4          | 587                    | 480                      | 12.0                           | 372                         | 297                               |

3.2. Aluminum Foam

The velocity history in Duocel aluminum foam measured by the two probes is shown figure 2(d) for a single impact experiment. A comparison of the material velocity histories in both types of foam (figures 2(b) and 2(d)) shows that both foams exhibit a similar dual-wave response to impact loading. The velocity history of this compaction wave within the aluminum foam is noticeably more dispersive than those measured in the polymeric foam. The dispersive velocity profile means that the error bar related to the wave velocity measurements in the aluminum foam will have larger uncertainty, a feature that is likely due to the larger pores within this foam. The pore size, combined with a small spot size laser probe, means that the perceived dispersion could simply be a measurement technique artifact, rather than a material property of the foam itself.

In the aluminum foam, the average material velocity associated with the precursor wave was found to be $26 \pm 5$ m/s, while the average precursor wave propagation velocity was approximately 1500 m/s. This velocity of propagation disqualifies the possibility that the precursor is driven by gas-filtration since the impactor velocities was only 200 m/s and the interstitial air had an extremely low initial pressure. This result adds further experimental evidence suggesting that the role of gas-filtration driven flows are secondary to the elastic foam response in open-cell foams [5].

4. Discussion

The results of the present study illustrate that the compression of these foams under impact loading is not a constant strain rate process, as evidenced by the two main distinct increases in motion associated with the elastic and compaction waves within the materials (figures 2(b) and 2(d)). Across a steady wave, the local compressive strain can be determined by conserving mass across the wave and is expressed as

$$\epsilon = \frac{u_p}{U_s}$$

where $\epsilon$ is the local compressive strain, $U_s$ is the wave velocity, and $u_p$ is the material velocity behind the wave. Therefore, the strain history is directly related to the material velocity history for an impact of this nature. The plateau in material velocity is indicative of a constant strain state within the foam, precisely the opposite behaviour of the constant strain rate often encountered in lower-rate experiments. By extension, these results illustrate that the plateau in stress measured in Taylor-Hopkinson bar experiments on foams is not consistent with the dynamics of a constant strain rate compaction event. As a result, any direct comparison between a dynamic stress plateau and the quasi-static crush strength of a foam should be approached with care.

The prevailing shock model theory for metal foam compaction [3, 10, 13, 14] relates the dynamic stress in the foam to the impact velocity of the foam sample and the quasi-static crush
strength. The derivation of this dynamic stress term involves assumptions that the elastic wave in the foam and motion of the impacted Hopkinson bar can be neglected. Thus, the dynamic stress in the foam is defined as

\[ \sigma^d = \sigma^{qs} + \frac{\rho_0 V_i^2}{\epsilon_D} \]  

(3)

where \(\rho_0\) is the density of the foam, \(V_i\) is the impact velocity of the foam, \(\epsilon_D\) is the densification strain, and \(\sigma^d\) and \(\sigma^{qs}\) are the dynamic stress and quasi-static crush stress of the foam respectively. Recent experimental results have shown that this expression overpredicts the dynamic stress measured in the foam, prompting the authors to attribute this discrepancy to the fact that the experimental densification strain was larger than predicted for Duocel aluminum foams [10], based on the use of equation 3. While this interpretation could be valid, the assumption that the elastic wave and resulting motion of the Hopkinson bar can be neglected has never been thoroughly validated. Since the impactor velocity value is squared in the model, any error produced by neglecting these motions in the derivation can result in an overprediction of the model.

The mid-plane velocimetry technique allows us to consider the validity of the assumption concerning the elastic wave made in the derivation of (3). The material velocity associated with the elastic wave in the Duocel aluminum foam was found to be approximately 26 m/s. Considering that the impact velocities in the experimental work of Tan et al. [3, 10] ranged between 10-200 m/s, neglecting the material response relating to the elastic precursor wave is not a valid assumption. From the comparison of this theory to experimental data, it is probable that the overpredictions given by the theory is at least partially related to this oversight. This shock model of impact loading in aluminum foams must be reconsidered to account for the dual-wave behaviour in the foams, particularly at low impact velocities.

References
[1] Seitz M W and Skews B W 2006 Shock Waves 15 177
[2] Ouellet S, Cronin D S and Worswick M 2006 Polym. Test. 25, 731
[3] Tan P J, Reid S R, Harrigan J J, Zou Z and Li S 2005 J. Mech. Phys. Solids 53 2174
[4] Zaretsky E, Asaf Z, Ran E and Aizik F 2013 Int. J. Impact Eng. 39 1
[5] Petel O E, Ouellet S, Higgins A J and Frost D L 2013 Shock Waves 23 55
[6] Mazor G, Ben-Dor G, Igra O and Sorek S 1994 Shock Waves 3 159
[7] Zhu F, Chou C C and Yang K H 2011 Compos. Part B 42 1202
[8] Skews B W 1991 Shock Waves 1 205
[9] Gibson L J and Ashby M F 1997 Cellular Solids: Structure and Properties (Cambridge University Press)
[10] Tan, P J, Reid S R and Harrigan J J 2013 Int. J. Solids Struct. 49 2744
[11] Strand O T, Goosman D R, Martinez C, Whitworth T L and Kuhlow W W 2006 Rev. Sci. Instrum. 77 083108
[12] Petel O E, Jetté F X, Goroshin S, Frost D L and Ouellet S 2011 Shock Waves 21 215
[13] Reid S R and Peng C 1997 Int. J. Impact Eng. 19 531
[14] Harrigan J J, Reid S R and Yaghoubi S A 2010 Int. J. Impact Eng. 37 918