Experiment on Effects of Porosity in the Interaction of Shock Wave and Foam*

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Head-on collision of a planar shock wave with open-cell materials was studied experimentally. Three kinds of polyurethane foam are treated: foam 350 × 70 × 70, which is of low porosity (\(\phi = 0.76\)) and high density (\(\rho_c = 290\text{ kg/m}^3\)); foam 50 × 50 × 50, which is of high porosity (\(\phi = 0.98\)) and low density (\(\rho_c = 26\text{ kg/m}^3\)); and foam 13 × 13 × 13, which has the same density and porosity as foam 50 × 50 × 50, but has a different internal structure of foam material. Stress-strain curves of foams show high non-linearity and hysteresis. The maximum stress value behind the foam just in front of the solid end wall, is larger than the reflected shock pressure at the normal solid wall. When a shock wave hits a foam surface, part of the shocked gas penetrates into the foam and interacts with the foam material. Measured stress histories at the foam base of the shock tube show stress which is significantly higher than that due to the pressure behind the reflected shock wave at the solid wall. In the high density foam 350 × 70 × 70, the peak stress is the highest, the mobility of gas in the foam is very low, and its dynamics can be approximated by a single-phase problem. In the foam 50 × 50 × 50 and low density foam 13 × 13 × 13, peak stresses are low and the peak value depends on the internal structure of the material. In these cases, the mobility of gas in the foam is high, and the dynamics must be treated as a two-phase problem.

Key Words: Porous material, Shock–Foam Interaction, Environmental Problem

1. Introduction

The interaction of shock waves with cellular material has recently received the attention of many investigators. Since the porous foam is composed of open-cell material, air can flow through the foam, and, after a collision at the foam surface, some portion of the incident shock wave can penetrate into the body. Study of the interaction of shock waves with porous compressible foams has revealed a number of interesting features; in particular, it is shown that if the rigid end wall of a shock tube is covered by foam, the stress behind the foam is significantly higher than the gas pressure of the reflected shock wave at the solid wall.

The porous compressible foams was investigated experimentally by Skews. Baer used a two-phase flow model to treat this interaction. His theory can explain the experimental results quite well. Mazor et al. and Ben-Dor et al. investigated the interaction of shock waves with rubber and/or specific cellular materials by considering the dependence of air-foam interaction on the stress-strain relations of materials. A study of Yasuhara et al., using high density, low-porosity open-cell foam indicated that the stress behind the foam reaches a very high peak stress \(\sigma_{\text{max}}\) followed by a damping-like vibration approaching the gas pressure \(P_g\), behind the reflected shock wave at the solid wall.

To investigate the effects of porosity and of the internal structure of foam on the dynamic interaction of the shock wave with foam, three different types of foam are investigated experimentally in the present work. After investigating the static stress strain relations of cellular materials, shock tube experiments are conducted, with special attention paid to the pressure field resulting from the gas body interaction, measured at the fixed end of the shock tube.

2. Elastic Nature of the Foam

Before treating one dimensional (1D) collision dynamics between a shock wave and a polyurethane foam, it is important to investigate the static stress strain relations. The interaction of a shock wave with

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foam depends on the internal structure of the foam which determines its physical properties.

A cellular material is defined by Gibson and Ashby(1). Properties of a foam depend on its structure and on the properties of its cell wall material. There are different compressibility properties for different types of cellular structures (open or closed cells). In general, the salient structural features of a foam can be divided into open or closed cell. Open-cell foam is that in which the cells are connected through open faces, and passage of gas is possible from one cell to the next. Closed-cell foam is that in which air in each cell is separated from neighboring ones. When loading is compressive, cell walls bend and collapse if the cells are open. The effects in the case of closed cell foams are more complicated when the membranes which form the cell walls do not rupture.

One of the most important properties of foam is its relative density \( \rho_c/\rho_s \), where \( \rho_c \) is the density of the cellular material and \( \rho_s \) is that of the solid polyurethane skeleton. In addition, the porosity (void fraction) of cellular material is defined as

\[
\phi = 1 - \frac{\rho_c}{\rho_s}.
\]

Characteristics of experimental foams are given in Table 1 and in Photos 1 (a), (b) and (c) showing skeleton structures. In the present paper, all foams are of open cell type. The skeleton density of polyurethane is \( \rho_s = 1200 \text{ kg/m}^3 \) as given by Gibson and Ashby(1). The three kinds of polyurethane foam are all composed of three-dimensional networks of thin wires: foam \( 350 \times 70 \times 70 \) is of low porosity (\( \phi \approx 0.76 \)) and high density (\( \rho_c \approx 290 \text{ kg/m}^3 \)); foam \( 50 \times 50 \times 50 \) is of high porosity (\( \phi \approx 0.97 \)) and low density (\( \rho_c \approx 26 \text{ kg/m}^3 \)); and foam \( 13 \times 13 \times 13 \) has essentially the same density and porosity as foam \( 50 \times 50 \times 50 \), but both the cell size and the wire diameter of the skeleton network are larger than those of foam \( 50 \times 50 \times 50 \).

The stress strain relation of the foam was measured using a Shimadzu material-testing machine (Auto-Graph AG 500 A). Uni-axial strain type compression loading is shown in Fig. 1. The foam can move along the loading \( x \) direction, but the lateral

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\text{Table 1 Characteristics of open cell type polyurethane foam}
\]

<table>
<thead>
<tr>
<th>Polyurethane foam</th>
<th>Density ( \rho_c [\text{kg/m}^3] )</th>
<th>Porosity ( \phi )</th>
<th>( x \times y \times z^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam350 ( \times 70 \times 70 )</td>
<td>290</td>
<td>0.76</td>
<td>350 ( \times 70 \times 70 )</td>
</tr>
<tr>
<td>Foam50 ( \times 50 \times 50 )</td>
<td>26.3</td>
<td>0.98</td>
<td>50 ( \times 50 \times 50 )</td>
</tr>
<tr>
<td>Foam13 ( \times 13 \times 13 )</td>
<td>27.5</td>
<td>0.98</td>
<td>13 ( \times 13 \times 13 )</td>
</tr>
</tbody>
</table>

* All materials are products of Bridgestone Co., Japan
* \( x \times y \times z \) denote nominal (statistical mean) numbers of open cells per 25mm of length in \( x \), \( y \) and \( z \) directions, given by Bridgestone Co., Japan
* Each cell of foam \( a \) composed of irregularly looped thin wires connected 3-dimensionally, as shown in a regularized form below

Fig. 1 Schematic illustration of uniaxial strain loading

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movement is bounded.

The nominal stress $\sigma$ is defined as the force $F$ divided by the initial cross-sectional area $A_0$ before deformation ($\sigma = F/A_0$). The suffix $x$ represents the axial direction of the external force. $\lambda$ is the extension ratio of the soft body based upon its initial length in the $x$-direction. For a body under compressive loads $\lambda < 1$, for extension $\lambda > 1$, and for the stressless condition $\lambda = 1$.

Figures 2(a), (b) and (c) show results obtained from machine tests for the three kinds of polyurethane foam. In the present tests, one test cycle includes loading and unloading. The maximum loading for foam $350 \times 70 \times 70$ amounts to about 6 MPa, while that for foam $50 \times 50 \times 50$ and foam $13 \times 13 \times 13$ amounts to about 0.14 MPa. The curves in Fig. 2 have good reproducibility under repeated test cycles. Figures 2(b) and (c) show that after a very short linear rise at low stress, a sudden buckling occurs and a long collapse plateau at nearly constant stress follows, and then the final region of densification is reached in which the stress rises steeply. The unloading curve does not coincide with the loading curve, and one test cycle shows a hysteresis.

In contrast, the curve for foam $350 \times 70 \times 70$ in Fig. 2(a) shows no region of linear elasticity, indicating that the buckling occurs almost from the beginning of the total loading of 6 MPa, about 40 times larger than the 0.14 MPa loading of Figs. 2(b) and (c).

As was mentioned above, the stress-strain relations for the present three kinds of polyurethane foam can be divided into two types: high density foam (foam $350 \times 70 \times 70$) and low density foam (foam $50 \times 50 \times 50$ and foam $13 \times 13 \times 13$).

3. Shock Tube Facility and Experimental Methods

The shock tube used in the present 1D interaction experiments is shown schematically in Fig. 3. The inner diameter of the driven section is 124 mm and the length is 10.2 m. The inner diameter of the driver section, which is fixed outside the driver tube coaxially as shown in Fig. 3, is 300 mm. The driver can be separated from the driven tube by the quick-acting magnetic valve. The foam is attached to the rear end wall of the driven section, as shown in Fig. 4. The diameter of foams used in the present experiment is restricted to 122 mm, while their initial lengths are 30, 60, and 90 mm. The initial clearance between the side face of the foam and the wall of the shock tube is about 2 mm, corresponding to about 1.6% of the tube diameter. Thus, the model fills 98.4% of the shock tube diameter, and we may assume the whole loading as uniaxial strain loading. Initial pressure $P_1$ in the driven tube is kept at atmospheric pressure ($P_1 = 0.1$ MPa).
MPa), and that in the driver tube $P_1$ is kept at $P_1$ = 1.47 MPa. The measured incident shock Mach number is $M_s \geq 1.7$.

Stresses in the foam are measured as shown in Fig. 5(a) by piezo resistance pressure transducers, which are in contact with the foam skeleton, and therefore their output includes both contact force of the foam skeleton and gas pressure inside the foam. Also, to measure the gas pressure separately from the contact force, a different arrangement is used. As shown in Fig. 5(b), the transducer is positioned about 7 mm away from the foam surface so that the surface of the transducer will not contact the foam skeleton. Pressure transducers were mounted on the side wall (A, B and C) and back wall (D) of the tube as shown in Fig. 3.

4. Experimental Results and Discussion

Figure 6(a), (b) and (c) show pressure and stress histories at the shock tube end D after the initial shock wave passed the point A. Thin lines indicated by the label $P$ show pressure histories at D when there is no foam, and thick lines $\sigma$ show stress histories when the foam of length $L_n = 30$ mm is attached to the end wall of the tube. The stress behind the foam $350 \times 70 \times 70$ (Fig. 6(a)) rises rather gradually compared with the stepwise pressure jump $P_1 \rightarrow P_5$ behind the reflected shock wave, and after reaching
the maximum stress $\sigma_{max}$, it eventually approaches the reflected shock pressure $P_r$ followed by a damping-like vibration. Also the start of the stress ($\sigma_t$) rise is delayed compared with that of the pressure ($P$) rise. This means that the arrival of the stress wave at the foam end is later than that of the pure gas shock wave. The delay time is 0.3 ms, and the effective mean velocity of the first stress wave through the foam $350 \times 70 \times 70$ is about 88 m/s which is far less than the incident shock wave speed of about 570 m/s. The wave transmitted through the foam is decelerated due to the large inertia of the foam. The ratio of the maximum dynamic stress $\sigma_{max}$ to the final step pressure $P_r$ ($\sigma_{max}/P_r$) at the end wall is defined as the dynamic load factor (DLF). For a material such as metal with a linear stress strain relation ship; the theoretical value of DLF is 2. The value of DLF in the present experiments for foam $350 \times 70 \times 70$ is about 3.3. In the case of foam $50 \times 50 \times 50$, for which results are shown in Fig. 6(b), the stress behind the foam indicates a lower DLF value, about 1.7, and the stress vibration is more damped compared to that of foam $350 \times 70 \times 70$. The delay time of the stress wave compared to the pure gas shock wave is much smaller than in the case of foam $350 \times 70 \times 70$. It can be considered that some part of the incident shock wave penetrates into the foam $50 \times 50 \times 50$ more easily than into the foam $350 \times 70 \times 70$. In the case of foam $13 \times 13 \times 13$, for which results are shown in Fig. 6(c), the experimentally obtained DLF value is 1.1~1.2, which is the smallest of the three types of foam. Also the curve shape of stress history $\sigma_t$ is very different from that for the case of foam $350 \times 70 \times 70$. It is considered that the incident shock wave can penetrate into the foam $13 \times 13 \times 13$ very freely.

In each plot of Fig. 7 two stress histories are shown, the total stress $\sigma_t$ (foam + gas), which is the sum of the contact stress of the foam skeleton and the gas pressure in the foam, and the gas pressure $P$ measured by the method shown in Fig. 5(b). The results in Fig. 7(a) for foam $350 \times 70 \times 70$ show that the gas pressure $P$ increases very slowly compared to the variation of the total stress $\sigma_t$. This is due to the dense skeleton structure of the high-density, low-porosity foam. In other words, the incident shock wave penetrates less into the high density foam, and the mobility of gas inside the foam is very low. Thus we assume that the foam $350 \times 70 \times 70$ behaves like a single phase medium. Figure 7(b) shows results for foam $50 \times 50 \times 50$ with $L_0=60$ mm. Unlike in Fig. 7(a), the gas pressure $P$ shows a good agreement with the variation of total stress $\sigma_t$ and the gas inside the foam has a high mobility. Figure 7(c) shows results for foam $13 \times 13 \times 13$ ($L_0=60$ mm). The gas pressure $P$ shows almost the same variation as the total stress history $\sigma_t$. The mobility of gas is very high, and most of the total stress $\sigma_t$ comes from the gas pressure. Thus it can be considered that flows corresponding to Figs. 7(b) and (c) can be treated as two-phase flow problems. In Figs. 7(b) and (c), there can be seen some time intervals where the gas pressure $P$ slightly exceeds the total stress $\sigma_t$, which is considered to be approximately the sum of $P$ and the contact stress. One reason may be the deviation of the phenomena from one dimensionality.

In Figs. 8, 9 and 10, stress histories at $D$ for
different initial foam lengths \( L_0 \) are compared. Figure 8 for the foam \( 350 \times 70 \times 70 \), shows that the peak stress \( \sigma_{\text{t max}} \) increases as \( L_0 \) increases, or as the total mass and momentum of the compressed material increases. Figures 9(a) and (b) show time variations of the total stress (foam + gas), and the gas pressure for the foam \( 50 \times 50 \times 50 \). Note that peak stress values \( \sigma_{\text{t max}} \) are low compared to the case of foam \( 350 \times 70 \times 70 \), and also that the value of peak pressure \( P_{\text{max}} \) does not change much with increasing \( L_0 \). Figures 10(a) and (b) show time variations of the total stress (foam + gas), and the gas pressure for the foam \( 13 \times 13 \times 13 \). The peak stress values \( \sigma_{\text{t max}} \) are the lowest among the three kinds of foam.

Figure 11 shows the dependence of the maximum dynamic stress \( \sigma_{\text{t max}} \) at \( D \) on the pressure \( P_1 \) behind the reflected shock wave, for the three types of foam. The solid line in Fig. 11 is the pressure behind the reflected shock wave at the rigid wall of the shock tube corresponding to \( DLF = 2 \). It is clear from Fig. 11 that \( \sigma_{\text{t max}} \) increases significantly as the pressure \( P_1 \) increases. The rate of increase for foam \( 350 \times 70 \times 70 \)
is the highest of the three foams. It is considered that if the internal structure of the foam material is the same, the higher density foam gives a higher peak stress value at the end wall D, and also that a different internal structure of foam will give a different stress variation and peak stress value, as shown by comparison of $\sigma_{\text{max}}$ for foam $50 \times 50 \times 50$ and foam $13 \times 13 \times 13$, both of which have the same density.

5. Conclusion

Experiments concerning shock wave interactions with porous bodies were conducted for three kinds of polyurethane foam fixed to the rear wall of a shock tube. The stress histories behind the foam end, D, were measured in two ways, the total stress (sum of the contact stress of the skeleton material and the gas pressure in the foam) and the gas pressure. The purpose was to investigate the dynamic behavior of gas in the foam space. Total stresses at the foam end, D, showed stress which is significantly higher than that due to the final gas pressure $P_{\text{g}}$ behind the reflected shock wave. For foam $350 \times 70 \times 70$, the peak stress value is the highest among the three foams investigated. After the peak stress, some damping vibrations follow, approaching the final pressure $P_{\text{g}}$. The peak stress value for foam $50 \times 50 \times 50$ is lower than that for foam $350 \times 70 \times 70$ has lower density. Although the density of foam $13 \times 13 \times 13$ is the same as that of foam $50 \times 50 \times 50$, the peak stress value of foam $13 \times 13 \times 13$ is lower. This is a result of the different internal structures of these two foams. From measurements of the total stress and the gas pressure at the tube end, D, the mobility of gas in low-porosity foam like foam $350 \times 70 \times 70$ is very low, and the motion of the foam can be approximated as that of a single-phase medium. On the other hand, the gas in foams like foam $50 \times 50 \times 50$ and foam $13 \times 13 \times 13$ can move with high mobility, and their motions should be treated as that of a two-phase medium.

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References


