SAND98-2871C

RECEIVED
JUN 30 1999
OSTI

POLYURETHANE FOAM IMPACT EXPERIMENTS AND SIMULATIONS

Marlin E. Kipp, Lalit C. Chhabildas, William D. Reinhart, and Michael K. Wong

*Sandia National Laboratories, Albuquerque, NM, USA, 87185-0820**

Abstract. Uniaxial strain impact experiments have been performed to obtain shock compression and release response of a 0.22 g/cm^3 polyurethane foam in a configuration where the foam impacts a thin target witness plate. Wave profiles from a suite of ten experiments have been obtained, where shock amplitudes range from 40 to 500 MPa. A traditional P-α porous material model generally captures the material response. A fully three-dimensional explicit representation of the heterogeneous foam structure modeled with numerical simulations recovers some of the high frequency aspects of the particle velocity records.

INTRODUCTION

Shock propagation in distended materials continues to be of interest for isolation/protection applications. Polyurethane foam is one such material for which multiple applications in shock environments require operational models. From a modeling standpoint, the P-α model for distended materials was formulated by Herrmann (1) primarily to provide a mechanism to describe the behavior of slightly distended metals. Since then, the model has been extended to include materials with much larger distensions. Here we report a set of uniaxial strain experiments on a polyurethane foam that provides a basis for applying the model to these large distensions. In this study of polyurethane foam, gas gun impact experiments are used to obtain the foam material response at impact pressures of 40 to 500 MPa. These data represent part of an expanding database for this foam that includes multidimensional experiments as well, where divergent waves in the foam are created with sphere impacts and transmitted wave profiles are acquired (2).

Numerical simulations of the impact experiments are reported in which the foam is modeled both as a homogeneous material, using the P-α model, and with a three-dimensional explicit representation of the foam that captures the heterogeneous structure of the material with a random array of hollow spheres.

FOAM DESCRIPTION

The rigid polyurethane foam considered in the present study has a nominal density of 0.22 g/cm^3. Ultrasonic velocities of 1160 m/s (longitudinal) and 650 m/s (shear) have been measured on the sample (providing a Poisson ratio of 0.27). However, quasi static compression and tension tests on this foam indicated moduli ranging from 46 to 73 MPa, suggesting that a longitudinal velocity of about 500 m/s more appropriately characterizes this material (3). In addition, a crush strength of about 2.1 MPa was determined. The approximate pore dimension is 10's of μm.

EXPERIMENTAL CONFIGURATION

The present plate impact configuration consisted of a projectile launched with a gun of 2.5 inch bore. The projectile was faced with a 2 inch diameter aluminum substrate and a polyurethane foam disk of the

* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

DISCLAIMER

same diameter about 6 mm thick, which impacted a thin target plate of 6061-T6 aluminum or OFHC copper. The rear free surface of this witness plate was monitored with velocity interferometric techniques, VISAR, from which the velocity history of the rear surface was obtained (4). After impact, the wave transits the foam towards the projectile aluminum substrate, reflects, and returns through the compressed foam to the foam/witness plate interface. The wave transit time through the witness plate is much shorter, however, and makes up most of the reflections that lead to the series of reverberations that are monitored from the rear surface of the witness plate. In this arrangement, then, the first transit of the wave through the foam is not monitored, but the initial impedance of the foam is inferred from the amplitude of the first shock at the free surface. Subsequent wave transit behavior through the witness plate involves reflections at the compressed foam / witness plate interface.

DATA SUMMARY

The impact velocities of the foam in this series were in the range of 330 to 1540 m/s (Table 1). The wave profiles for all ten experiments are shown in Fig. 1a (lower velocity impacts onto aluminum) and Fig. 1b (higher velocity impacts onto aluminum and copper). The resulting initial compressive stresses at the foam / witness plate interface range from approximately 40 to 500 MPa. These impact stresses are determined from the witness plate impedance and the initial jump-off velocity, assuming that the particle velocity in the plate is one-half the jump-off velocity.

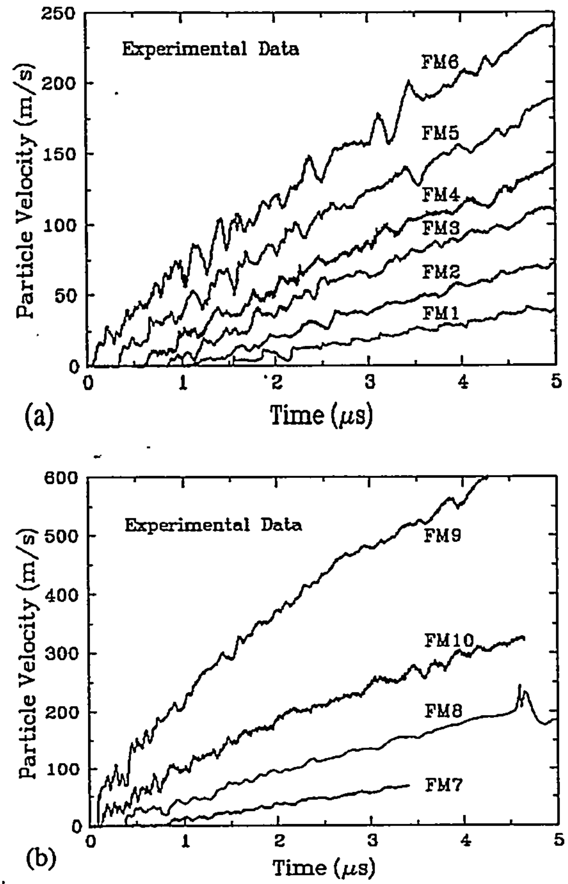

FIGURE 1. Particle velocity histories for lower velocity impacts on aluminum witness plates (a) and higher velocity impacts on aluminum and copper witness plates (b). (Arrival times have been arbitrarily time-shifted for clarity.)

TABLE 1. Summary and Results of Impact Conditions.

Shot	Impact Velocity (m/s)	Foam Thickness (mm)	Foam Density (g/cm^3)	Target Material	Target Thickness (mm)	Foam Pressure (MPa)
FMREVRB-1	328	6.322	0.2203	Aluminum	0.912	35
FMREVRB-2	459	6.342	0.2206	Aluminum	0.968	45
FMREVRB-3	565	6.314	0.2209	Aluminum	1.019	60
FMREVRB-4	648	6.317	0.2216	Aluminum	0.991	85
FMREVRB-5	746	6.218	0.2214	Aluminum	0.977	140
FMREVRB-6	843	6.294	0.2231	Aluminum	0.975	175
FMREVRB-7	938	6.317	0.2206	Copper	1.016	255
FMREVRB-8	1356	6.210	0.2249	Copper	1.026	510
FMREVRB-9	1540	6.248	0.2211	Aluminum	0.998	520
FMREVRB-10	1080	6.220	0.2213	Aluminum	0.996	240

The initial free surface motion is related to the initial stiffness of the foam. The aluminum substrate and witness plate (aluminum or copper) have higher impedances than the polyurethane. The reverberations within this arrangement lead to a generally increasing velocity of the witness plate and a gradual decrease of stress within the witness plate (ring-down). The stresses in the aluminum witness plates remain below its Hugoniot elastic limit (570 MPa) at all these impact velocities, and the stresses in the two experiments with copper witness plates exceed the copper Hugoniot elastic limit (250 MPa).

NUMERICAL ANALYSIS

The Eulerian shock-wave propagation code, CTH (5), was used for these simulations. The Mie-Gruneisen equation of state was the primary material model used, based on data from (6). The polyurethane utilized a tabular representation which includes the additional softening of the material at low particle velocities. Deviatoric property data is from Steinberg, (7). The parameters are summarized in Table 2.

TABLE 2. Material Parameters for CTH Simulations.

Property / Material	PU	Al	Cu
Density (kg/m^3)	1265	2703	8930
Bulk Sound Speed (m/s)	2486	5240	3940
Slope of U_s - U_p Hugoniot	1.577	1.40	1.489
Gruneisen Coefficient	1.55	1.97	1.99
Specific Heat (J/kg-K)	86	922	393
Yield Stress (MPa)	2.1	290	120
Poisson Ratio	0.18	0.33	0.346
Fracture Stress (GPa)	0.1	1.5	2.3

The basis for the P-α model is that the distended material assumes the properties of the solid material upon compression (1). Collapse commences beyond an elastic threshold, following a path to a pressure at full compression where all void has been removed. This collapse onto the Hugoniot is accompanied by large irreversible thermal increases. Deviatoric stresses in the elastic regime have been included. For this rigid polyurethane foam, the uncompressed elastic velocity is 500 m/s, the onset of crush beyond the elastic response begins at 2.1 MPa, and full crush to the solid material is estimated to occur at 10 MPa.

Simulations of these one-dimensional experiments are shown in Fig. 2 for a selection of experimental conditions over a range of impact velocities. Overall, the calculations match the data quite well, although some of the timing of major transitions in the record tend to drift out of phase. It is unclear whether wave propagation through compressed polyurethane is not being accurately modeled over these long recording periods, or if some minor variations in aluminum elastic wave speeds accumulate over the multiple transits through the witness plate:

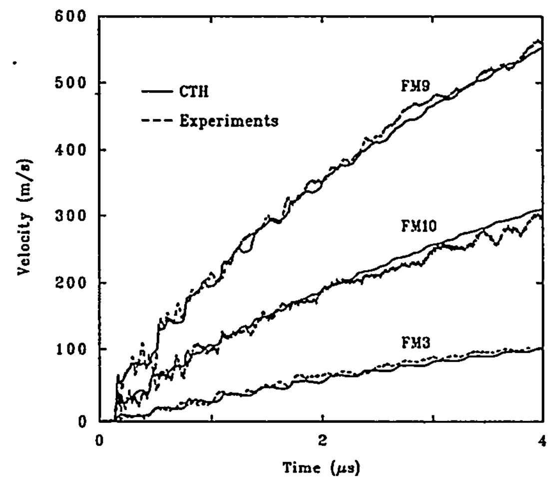

FIGURE 2. Comparison of calculated and experimental data over a range of impact conditions.

Within each velocity history record, the superposed noise of the velocity history reflects the heterogeneity of the foam. The witness plate is sufficiently thin that the effects of the structure are transmitted through the plate and appear on the velocity record. An attempt to address this aspect of the foam is made by explicitly representing the foam with hollow polyurethane spheres of uniform dimension. These spheres (of full density polyurethane) are randomly distributed spatially within a volume to obtain sufficient mass to create an average density of 0.23 g/cm^3. The spheres have an external diameter of 120 μm and an internal diameter of 100 μm, which is at the upper size range of the distended material pore dimension. About 25,000 spheres are required to fill a 5 mm x 5 mm x 2 mm volume to the proper density (Fig. 3). No interpenetration of the spheres was permitted in this construction. This volume and the accompanying 1 mm-aluminum witness plate were discretized with

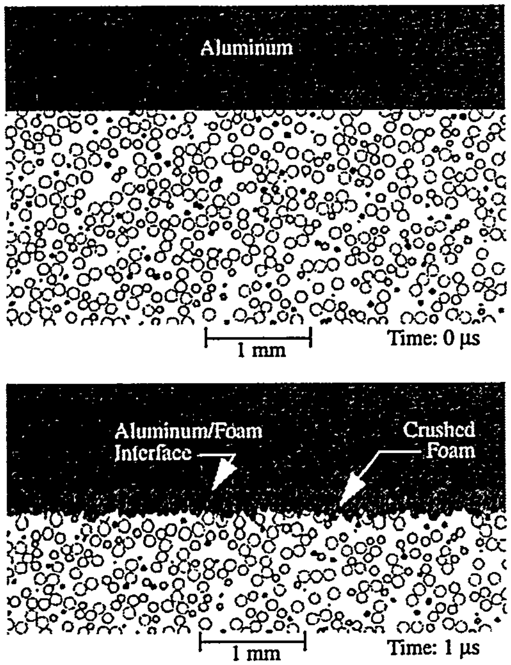

FIGURE 3. Cross-section view of a three dimensional representation of the polyurethane foam and aluminum witness plate for FM5: initial conditions (upper), and 1 µs after impact (lower).

approximately 85 million cells of uniform 10 µm resolution (one cell through the wall thickness).

The velocity history over the first 2 µs of Experiment FM5 was simulated in this manner. Particle velocity histories were monitored on the rear free surface of the aluminum witness plate at nine points located on a square matrix with 1 mm spacing. These records are superposed with the experimental velocity record in Fig. 4. The envelope of the response captures the behavior very well. In this 2 µs time interval, the wave has transited the aluminum witness plate several times, but propagated less than 2 mm into the foam (Fig. 3 shows shock at 1 µs). The amplitude of the noise generated by the heterogeneous material structure and translated through the plate appears to be larger in amplitude than the experimental data.

CONCLUSIONS

The data reported here provide basic support for utilizing the P-α model to describe behavior of materials with large distensions. Additional data at larger pressures is desirable, as is divergent data, both of which are being planned (2).

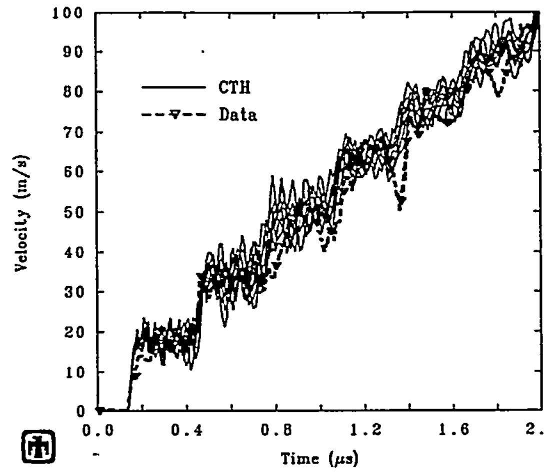

FIGURE 4. Numerical simulations of free surface particle velocity histories compared with experimental data (FM5).

The effect of pore size on the transmitted noise observed in the three-dimensional analyses (Fig. 4) can be addressed by reducing the hollow sphere diameter. The use of hollow spheres is a rudimentary technique to build a foam structure, however, with its most serious deficiency being that the wall structure is not very well represented. Alternate, and more realistic, foam structures have been studied and constructed by Kraynik, et al. (8) for quasi static loadings. These same structures are planned for utilization under the present impact conditions to determine their influence on the wave profiles.

REFERENCES

[1] Herrmann, W., *J. Appl. Phys.*, 40, 2490-2499 (1969).

[2] Chhabildas, L. C., Personal Comm., December 1998.

[3] Neet, T. E., "Development of Non-TDI Polyurethane Encapsulation Foams", PDO 705898 Final Report, September 1994.

[4] Barker, L. M. and Hollenbach, R. E., *J. Appl. Phys.*, 41, 4208-4226 (1970).

[5] McGlaun, J. M., Thompson, S. L., and Elrick, M. G., *Int. J. Impact Engng.*, **10**, 351-360 (1990).

[6] Group GMX-6, "Selected Hugoniots", Los Alamos Scientific Laboratory Report LA-4167-MS.

[7] Steinberg, D. J., "Equation of State and Strength Properties of Selected Materials", Lawrence Livermore Report UCRL-MA-106439, February 1996.

[8] Kraynik, A. M., Neilsen, M. K., Reinelt, D. A., and Warren, W. E., "Foam Micromechanics", Foams and Emulsions, Eds. J. F. Sadoc and N. Rivier, Kluwer Academic Publishers, Netherlands (1999).