

Characterization of viscoelastic materials for low-magnitude blast mitigation

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Abstract. Recent research indicates that exposure to low amplitude blast waves, such as IED detonation or multiple firings of a weapon, causes damage to brain tissue resulting in Traumatic Brain Injury (TBI) and Post Traumatic Stress Disorder (PTSD). Current combat helmets are not sufficiently protecting warfighters from this danger and the effects are debilitating, costly, and long-lasting. The objective of the present work is to evaluate the blast mitigating behavior of current helmet materials and new materials designed for blast mitigation using a test fixture recently developed at the Naval Surface Warfare Center Dahlgren Division for use with an existing gas gun. The 40-mm-bore gas gun was used as a shock tube to generate blast waves (ranging from 0.5 to 2 bar) in the test fixture mounted on the gun muzzle. A fast opening valve was used to release helium gas from the breech which formed into a blast wave and impacted instrumented targets in the test fixture. Blast attenuation of selected materials was determined through the measurement of stress data in front of and behind the target. Materials evaluated in this research include polyurethane foam from currently fielded US Army and Marine Corps helmets, polyurea 1000, and three hardnesses of Sorbothane (48, 58, and 70 durometer, Shore 00). Polyurea 1000 and 6061-T6 aluminum were used to calibrate the stress gauges.

1. Introduction

The dynamic response of viscoelastic materials to low-amplitude (<2 bar) blast waves is of interest for protection against blast-induced traumatic brain injury (TBI). Viscoelastic materials have a demonstrated ability to dissipate shock waves and absorb impact energy [1-3]. Many of these materials are soft, making them likely candidates for use in helmets to protect the head from low-amplitude blast waves. Sorbothane, for instance, is a soft viscoelastic polymer used in a number of shock and vibration isolation applications including insoles, recoil pads, and vibration dampers to protect delicate components subject to intense mechanical vibrations [3]. The goal of the present work is to evaluate the blast mitigating behaviour of current helmet materials and to determine if blast protection can be improved by incorporating viscoelastic materials, such as Sorbothane, into the helmet pad system.

To evaluate materials for blast mitigation, we employed a recently developed test fixture designed for use with an existing gas gun to generate planar blast waves in the range of 0.5 to 2 bar for 2 ms duration [4]. The human threshold for TBI blast injuries is not explicitly defined, but falls in the range of 0.2 to 5 bar for pressure pulses of several milliseconds duration [5]. The experiments performed in this present research represent the low to middle end of this pressure range.

The instrumented test fixture, designed for the Naval Surface Warfare Center Dahlgren Division's (NSWCDD) research gas gun [6], provided measurements of blast wave amplitude and velocity as



well as input and output stress in the material sample. From these measurements, techniques for determining longitudinal wave velocity and particle velocity were validated using materials for which wave speed and particle velocity parameters were readily available in the open literature. Blast attenuation was then calculated using the stress measurements and calculated particle velocities. Materials evaluated in this research include polyurethane foam from the pads used in the currently fielded Advanced Combat Helmet (ACH), three highly viscoelastic polymers from Sorbothane, Inc. (48, 58, and 70 durometer, Shore 00), and polyurea 1000 (a rigid viscoelastic polymer with shock properties characterized in [7]).

2. Experimental Approach

The blast wave experiments were conducted using the NSWCDD 40 mm diameter smooth bore, single-stage light gas gun. The expanding muzzle adapter was attached to the end of the barrel allowing blast waves to expand to 63.5 mm diameter and reform into planar waves through a straight section as shown in figure 1 [4]. (The larger diameter of the muzzle adapter allowed larger target diameters which, in turn, provided one dimensional strain conditions in the sample center for longer times before release waves from the target edge reached the center). Blast wave velocity and magnitude were measured by two pressure gauges, denoted PG1 and PG2, and blast wave planarity was measured by PG3 and PG4.

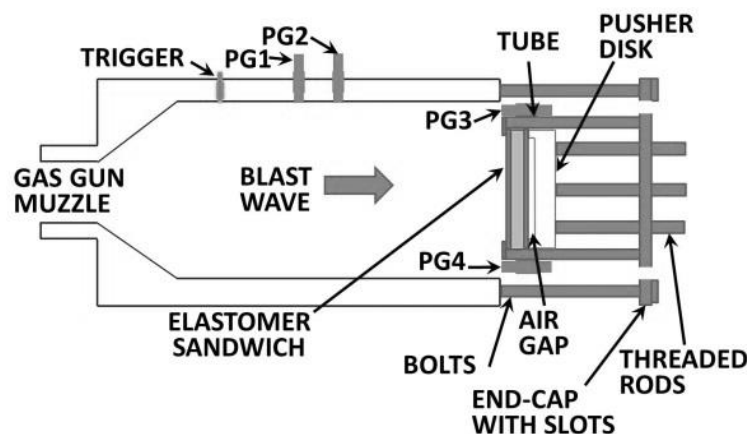


Figure 1. Schematic of gas gun muzzle region for investigating blast wave attenuation. PG1 and PG2 measured blast wave magnitude and velocity. PG3 and PG4 measured blast wave planarity.

Figure 2 is a schematic of the 38.1 mm diameter elastomer sandwich. Stress measurements were recorded using polyvinylidene difluoride (PVDF) thin-film stress gauges [8]. The PVDF gauges could not be epoxied directly to the Sorbothane and polyurethane samples because the large strains induced in these materials under loading exceeded the strain limits of the gauges. Therefore, the gauges were sandwiched between two 6061-T6 aluminum disks: 2.4 and 0.8 mm thick. The 2.4 mm thick piece was three times thicker than the 0.8 mm piece to allow sufficient time for the blast wave to reach the sample and stress gauges before release waves from the free surfaces arrived at the gauges. A low viscosity epoxy was used to bond the PVDF gauges to the aluminum [9]. The Sorbothane, polyurea, and polyurethane samples were tested in this configuration. For the aluminum calibration sample, the PVDF gauges were placed between a 3.2 mm thick interior disk and two 2.4 mm thick outer disks.

The pads in the ACH combine two open-cell polyurethane foams manufactured by Team Wendy: a 9.5 mm layer of Zorbium 110i and a 9.5 mm layer of Zorbium 83i [10]. The Zorbium 83i samples had

a measured density of 0.058 g/cm^3 and a measured hardness of 6 durometer (Shore 00). For viscoelastics, hardness is a measure of the materials resistance to indentation from an indenter foot; the lower the durometer, the softer the material [11]. The Zorbium 110i samples had a measured density of 0.066 g/cm^3 and measured hardness of 40 durometer (Shore 00). The three Sorbothane samples had a measured density of 1.3 g/cm^3 and were labeled by the company as 30, 50, and 70, but the measured hardnesses were 48, 58, and 70 durometer (Shore 00), respectively. The polyurea 1000 had a measured density of 1.1 g/cm^3 and a measured hardness of 92 durometer on the Shore A scale (the Shore A scale is used for harder materials than those tested on the Shore 00 scale) [7].

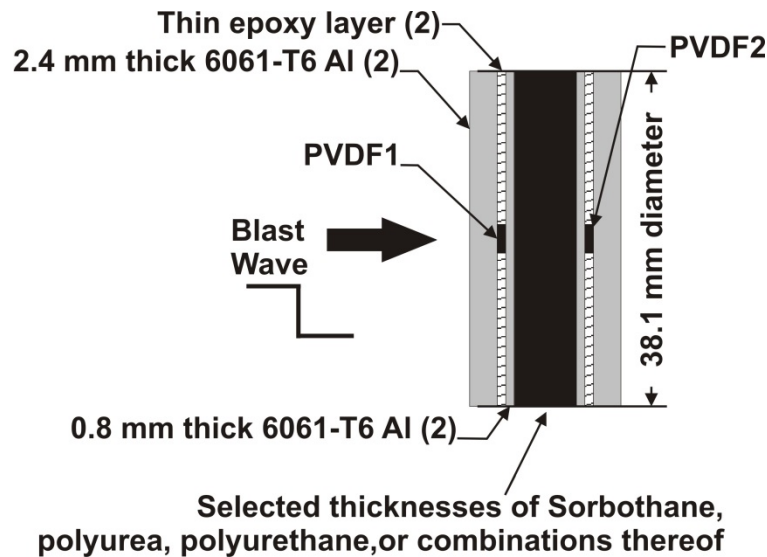


Figure 2. Schematic of elastomer sandwich. PVDF gauges were sandwiched between 2.4 and 0.8 mm thick 6061-T6 Al discs and placed on either side of the sample for measuring input and output stress. The 0.8 mm thick disks were omitted for the Al calibration sample.

The gas gun is equipped with a pneumatically actuated fast-opening ball valve [12]. The ball valve (versus a burst diaphragm) is well suited for performing blast wave experiments at low pressures because the blast pressure can be easily controlled in a continuous manner. Experiments were performed at three blast pressures for each sample: 0.5, 1.3, and 2.1 bar (± 0.1 bar). Single material samples were evaluated initially. Then the best performing materials were combined into a layered configuration to determine which combinations provided the largest attenuation. The thicknesses of the samples used in the layered material samples were reduced by approximately one-half to maintain a combined thickness comparable to the thickness of the single material samples.

3. Results

3.1. Wave and particle velocity calculations

3.1.1 Aluminum 6061-T6.

The longitudinal wave velocity, U_L , for the 6061-T6 aluminum sample was determined according to:

$$U_L = d / \Delta t_{PVDF1-2}$$

where d is sample thickness and $\Delta t_{PVDF1-2}$ is the blast wave transit time between PVDF1 and PVDF2.

Particle velocity, u_p , was calculated according to:

$$u_p = \sigma_1 / (\rho_0 U_L)$$

where σ_1 is the stress measured in PVDF1 and ρ_0 is the initial density of the sample.

3.1.2 Sorbothane, Polyurea, and Polyurethane.

For the Sorbothane, polyurea, and polyurethane samples, U_L was determined according to:

$$U_L = d / (\Delta t_{\text{PVDF1-2}} - \Delta t_{\text{Al}})$$

where Δt_{Al} is the transit time through the two 0.8 mm thick aluminum disks. To determine Δt_{Al} , the total thickness of the aluminum disks was divided by 6.37 mm/ μs , the longitudinal wave velocity of 6061-T6 aluminum [13].

The experimental longitudinal wave velocity and particle velocity measurements for 6061-T6 aluminum and polyurea 1000 are compared to previously published results in figure 3. The experimental values are in good agreement with the published data; within 2% for 6061-T6 and within 6% for polyurea 1000. It is important to note that the wave velocities are approximately constant at these pressures because the induced stresses are below the yield strength of the material.

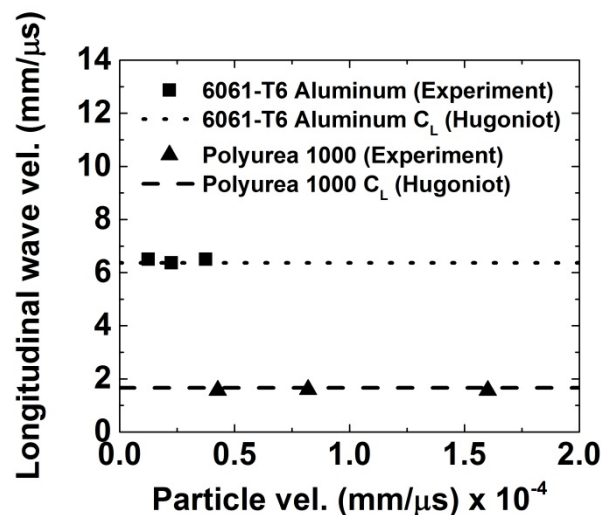


Figure 3. Longitudinal wave velocity versus particle velocity for 6061-T6 aluminum and polyurea 1000. C_L represents the longitudinal wave velocity published in the literature [13,14].

3.2. Blast attenuation calculations

The transit time for the blast wave to travel from PVDF1 to the sample interface and reflect back to PVDF1 was estimated to be less than the rise time of the gauge. Therefore, it was assumed that the stress measured by PVDF1 was equal to the stress at the interface between the first 0.8 mm thick aluminum disk and the front of the sample. Impedance matching was used to determine the rear interface stress from PVDF2 [15]. Blast attenuation was calculated as the average percent reduction in the front and back interface stresses for the three blast pressures. Results for the single materials, summarized in table 1, indicate that the softer materials (lower durometer) attenuated low-magnitude blast waves more than the harder materials. Sorbothane 48 provided 11-12% more attenuation than the 58 and 70 durometer materials even though it was approximately 10% thinner. Likewise, Zorbium 83i attenuated 7% more than the thicker 110i material. These results suggest that material hardness

(i.e. material resistance to deformation) is inversely proportional to energy absorption and blast attenuation at the blast pressures investigated in this study.

Table 1. Blast attenuation results for single material samples.

Sample	Hardness (durometer/ Shore scale)	Sample Thickness (mm)	Average Blast Attenuation (%)	Std Dev (%)
Polyurea 1000	92/A	6.4	66	13
Sorbothane 48	48/00	5.8	83	4
Sorbothane 58	58/00	6.4	71	7
Sorbothane 70	70/00	6.6	72	6
Zorbium 83i	6/00	8.6	83	7
Zorbium 110i	40/00	10.2	76	7

Since Sorbothane 48 was the best performing of the viscoelastic materials evaluated in the single material experiments, 4.6 mm thick disks of this material were combined with 3.0 mm thick disks of Zorbium 83i and 4.0 mm thick disks of Zorbium 110i to form two separate two-layer samples. The Sorbothane 48/Zorbium 83i samples were oriented with the Sorbothane on the front (blast side) because this would be the orientation in the helmet since Zorbium 83i is designed to make the helmet comfortable to wear. The Sorbothane 48/Zorbium 110i samples were evaluated in both configurations (Sorbothane on blast and non-blast sides). In addition, Zorbium 83i and 110i disks (4.8 and 4.1 mm thick, respectively) were combined and tested to simulate the current protection system and for comparison with the Sorbothane/Zorbium results.

The combined material results, shown in table 2, indicate that combining Sorbothane 48 with either Zorbium 110i or 83i attenuates more blast pressure than the current pad system (Zorbium 110i/83i) when the Sorbothane is on the blast side. An increased attenuation of approximately 10% was achieved by combining Sorbothane 48 with the Zorbium 83i foam. This improvement is likely due to the impedance mismatch caused by the density reduction in the elastomer sandwich at the Sorbothane/Zorbium interface. The impedance mismatch would cause the magnitude of the initial stress wave to decrease [14], thereby increasing attenuation of the blast wave. When the Zorbium 110i was on the blast side, the density increased at the interface, causing the stress to rise thereby reducing the attenuation.

Table 2. Blast attenuation results for combined material samples.

Sample Blast/Non-blast	Combined Thickness (mm)	Average Blast Attenuation (%)	Std Dev (%)
Sorbothane 48 / Zorbium 83i	7.6	91	5
Sorbothane 48 / Zorbium 110i	8.6	84	8
Zorbium 110i / Sorbothane 48	8.6	80	6
Zorbium 110i / 83i	8.9	81	9

The results of this research indicate that layers of soft viscoelastic materials with decreasing densities could improve blast attenuation of the current ACH pads. Future studies to evaluate blast attenuation at higher pressures [on the order of 15 bar (200 psig)], with a broader range of sample densities, and larger sample sizes to accommodate multiple layers are necessary to fully understand the benefits of incorporating viscoelastic materials into the helmet system.

4. Acknowledgements

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