EXPERIMENTAL BENCHMARK DATA FOR ALEGRA CODE VALIDATIONS

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Abstract. In this study experiments of increasing complexity have been conducted to provide a database for validating features of the Arbitrary Lagrangian Eulerian Grid for Research Applications (ALEGRA) code over a broad range of strain rates with overlapping diagnostics that encompass multiple responses. This range encompasses strain rates characteristic of shock-wave propagation ($10^7$/s) and those characteristics of structural response ($10^2$/s). The tests matrix consists of two experimental series; the first being a simple system test with diagnostics that capture features relevant to both the high strain-rate hydrodynamic response and the low strain-rate structural response of the target. The second series of experiments increased the complexity of tests with the addition of foam to the original simple series. The input conditions are extremely well defined. Velocity interferometers are used to record the high strain-rate response, while the low strain-rate data were collected using strain, carbon and PVDF gauges.

INTRODUCTION

Sandia National Laboratories is developing a code referred to as ALEGRA which is a multi-material arbitrary Lagrangian Eulerian code [1] for use in many programs related to research applications. A unique feature of ALEGRA is that it allows simultaneous computational treatment, within one code, of a wide range of strain-rates. In this study, we provide an experimental test bed and a methodology for validating features of the ALEGRA code, including material models, over a broad range of responses with overlapping diagnostics that encompass multiple strain-rates. Velocity interferometers were used to record the high strain-rate response and to determine the input conditions extremely accurately, while low strain-rate data were collected using either strain, carbon or PVDF gauges. In particular, the current experiments span strain rate regimes of over $10^7$/s to less than $10^2$/s in a single experiment. The experiments are well-instrumented to capture features relevant to both hydrodynamic and structural response in a single experiment.

EXPERIMENTAL TECHNIQUE

The experiments were conducted on the Sandia Terminal Ballistics Facility [2]. This is a two-stage light-gas gun that can launch a sabot package carrying spherical projectiles to velocities over 6 km/s. The projectile for all experiments consisted of a 9.52 mm, 6061-T6 aluminum sphere that was launched at ~1.5 km/s. Table 1 provides impact velocities and impact locations. The impact velocity in each experiment was determined to an accuracy of 0.2% using a magnetic pick-up coil.
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TABLE 1. Summary of Experimental Conditions

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Impact Velocity (km/s)</th>
<th>Front Plate Thickness (mm)</th>
<th>Wall Thickness (mm)</th>
<th>Impact Location (X,Y mm)</th>
<th>Radius (mm)</th>
<th>x-t Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>1.48</td>
<td>13.614</td>
<td>3.18</td>
<td>+0.12, +2.5</td>
<td>2.502</td>
<td>5.82</td>
</tr>
<tr>
<td>L5</td>
<td>1.52</td>
<td>13.665</td>
<td>3.19</td>
<td>-2.0, +5.2</td>
<td>5.571</td>
<td>5.66</td>
</tr>
<tr>
<td>F2</td>
<td>1.57</td>
<td>13.868</td>
<td>3.25</td>
<td>+0.8, -0.35</td>
<td>0.870</td>
<td>5.66</td>
</tr>
<tr>
<td>F5</td>
<td>1.69</td>
<td>14.018</td>
<td>3.18</td>
<td>0.0, 0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
</tbody>
</table>

method [3]. All impact locations are within 2.5 mm and 5.7 mm from the geometric center of the instrumented can, and are well within half the projectile sphere diameter. The spherical projectile impacted one end of a hollow cylindrical can, also made of 6061-T6 aluminum, with outer diameter ~63.5 mm, inner diameter ~57.2 mm, axial length ~90 mm, and a front plate thickness of ~14 mm. In this study, impact velocity and front plate thickness were controlled to prevent rupture of the plate, while causing sufficient deformation or bulging as a result of impact. The concept adopted in this study was to perform experiments of increased complexity in stages. At the first stage, a highly instrumented simple experimental configuration is used to provide baseline data for code validation [4]. The complexity of the experiment is increased by subsequently adding foam into the baseline system. The foam experimental configuration is indicated in Figure 1(a). A total of twelve strain gauges, six to determine the axial strain and six to determine the hoop strain were used. The measurements were determined to an accuracy of better than 2% for velocity histories and 3% for strain gauge records. Figure 1(a) illustrates the location of the velocity interferometer, VISAR [5] and the strain gauges used in this study. Strain gauges 1 to 3 are positioned on one side of the can while gauges 4 to 6 are installed diametrically opposite them. The strain gauges are positioned nominally at 19 mm (gauges 1 & 4), 48 mm (gauges 2 & 5) and 78 mm (gauges 3 & 6) from the impact plane, and along the circumferential surface of the cylinder.

Foam Series - A slightly undersized disk of foam ~4 mm thick is used in this study. The foam has a density of 0.223 ± 0.008 gm/cm³ and a pore size of ~10’s of microns. An assembly of three carbon gauges lying in the same plane is “glued/attached” to each parallel face of the foam. The gauges defined as the A-plane determine the stress state at the interface between the back wall of the can and the foam. The gauges named as the B-plane measure the stress state at the interface between the foam and a 1 mm thick aluminum disk that is used for VISAR measurements. This is shown in Figure 1a. Figure 1b shows the carbon gauges and VISAR locations. The use of multiple gauges allows measurement of arrival times, stress amplitude and stress attenuation in foam as a function of propagation distance. This configuration of strain gauges and VISAR locations were utilized in all experimental series.

![Figure 1](image-url)
EXPERIMENTAL RESULTS

VISAR Records

Baseline Series: Figure 2 shows the velocity profile for the baseline series experiment L1. Impact locations are within half the projectile sphere diameter of the geometric center of the can. Upon impact, peak stresses approaching 13 GPa are generated at the contact point. The loading strain rates at that point are in excess of $10^7$/s. A spherical diverging wave, in combination with edge relief, attenuates the resulting stress wave.

![Figure 2](image1)

**FIGURE 2.** Velocity time history for the baseline experiment (L1) and the foam experiment (F5).

The velocity interferometer was set up to monitor the particle-velocity at the exact geometric center of the can. The peak velocity of $-0.2$ km/s at the rear free surface was measured in the baseline series and indicates substantial wave attenuation. The leading edge of the wave in the front aluminum plate is determined to travel at 6.4 km/s, which is representative of the elastic wave velocity in 6061-T6 aluminum. The leading precursor wave velocity is determined to an accuracy of 1%.

Foam Series: Figure 2 shows experiment F5 velocity history of the diverging stress-wave as it propagates through the 4 mm foam as witnessed by the aluminum plate. The same input conditions were used in both the baseline and foam experiments. The addition of the foam disk further attenuates the stress wave resulting in a substantial decrease in peak velocity from $-0.2$ km/s to $-0.043$ km/s.

Carbon Gauge Records – Foam Series

X-t diagram: Figure 3a shows an X-t diagram of a least squares fit of data arrival times at the A and B planes versus their position within the can for experiment F5 of the foam series. The slope of the stress front going through the foam disk indicates a wave velocity of 1.22 km/s; this agrees well with the elastic longitudinal wave speed measurement of 1.16 km/s.

![Figure 3a](image2)

**FIGURE 3a.** X-t diagram for experiment F5, showing data arrival times at the A and B planes versus their position within the can.

Stress Record: Figure 4 is a record of the stress wave coupled from the aluminum can into the foam disk (CA1 and CA2) and the resulting stress wave exiting the foam disk (CB1 and CB2). The on-axis peak stress recorded in the A-plane is $-1$ Kbar; this wave attenuates through the 4 mm of foam to $-0.11$ Kbars at the on-axis B-plane location. The off-axis gauges show a peak measurement of $-0.2$ Kbars at the A-plane and attenuating to less than 0.04 Kbars at the B-plane.

Strain Gauge Records

Figure 3 shows an X-t diagram of strain gauge data for both the foam experiment F2, Figure 3a, and baseline series experiment L6, Figure 3b respectively. The lines are a least squares fit for
FIGURE 4. Carbon gauge outputs showing the attenuation through the 4 mm foam disk.

the arrival times of the leading edge of the strain wave data versus gauge location along the can. The strain gauge pairs (1,4), (2,5), and (3,6) for both series are located at the same location from the impact surface but diametrically opposite from each other on the circumference of the can. Any time shift between diametrically opposite gauge pairs is due to the non-centered nature of the impact. The data indicates that in both series the stress front sweeps by at an average velocity of 5.66 km/s in the cylindrical tube and the addition of foam to the can does not influence the velocity of the stress front as it sweeps down the can. Figure 5a and 5b display the axial strain data at the 20 mm and 80 mm locations for both series. The gauge records indicate peak strain of \(-2500 \times 10^6\) at a strain-rate of \(1.2 \times 10^3\) \(s^{-1}\) from the impact interface. This reduces to a strain of \(-500 \times 10^6\) at a strain-rate of \(2 \times 10^3\) \(s^{-1}\) from the impact interface. The peak strains and strain-rates agree between the baseline and foam series which indicate that the addition of the foam disk does not effect the amplitude of the stress wave as it travels down the skirt of the can.

CONCLUSIONS

In this study we have developed a methodology and provided an experimental test bed for validating features of the ALEGRA code over a broad range of responses with overlapping diagnostics that encompass multiple strain-rates. This provides a unique database for code validations. Specifically, the current experiments span the strain rate regimes of over \(10^3\) \(s^{-1}\) to less than \(10^2\) \(s^{-1}\). Input conditions are well characterized; and known to better than 0.2% while the measurement precision is \(-2\%\) for the interferometer records and \(-3\%\) for the strain gauge records. Future experiments will consist of well-controlled three-dimensional loading conditions.

REFERENCES