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ALEGRA - Code Validation: Experiments and Simulations

L. C. Chhabildas, C. H. Konrad, D. A. Mosher, W. D. Reinhart, B. D. Duggins, R. Rodeman, T. G. Trucano, R. M. Summers, J. S. Peery
Shock Physics Applications Department
Sandia National Laboratories, Albuquerque, New Mexico 87185
Email: lcchhab@sandia.gov

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Abstract

In this study, we are providing an experimental test bed for validating features of the ALEGRA code over a broad range of strain rates with overlapping diagnostics that encompass the multiple responses. A unique feature of the Arbitrary Lagrangian Eulerian Grid for Research Applications (ALEGRA) code is that it allows simultaneous computational treatment, within one code, of a wide range of strain-rates varying from hydrodynamic to structural conditions. This range encompasses strain rates characteristic of shock-wave propagation (10^7/s) and those characteristic of structural response (10^2/s). Most previous code validation experimental studies, however, have been restricted to simulating or investigating a single strain-rate regime. What is new and different in this investigation is that we have performed well-instrumented experiments which capture features relevant to both hydrodynamic and structural response in a single experiment. Aluminum was chosen for use in this study because it is a well characterized material - its EOS and constitutive material properties are well defined over a wide range of loading rates. The current experiments span strain rate regimes of over 10^7/s to less than 10^2/s in a single experiment. The input conditions are extremely well defined. Velocity interferometers are used to record the high strain-rate response, while low strain rate data were collected using strain 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 varying from hydrodynamic to structural response[2]. This range encompasses strain rates characteristic of shock-wave propagation (10^7/s) and those characteristic of structural response (10^2/s). It combines the features of modern Eulerian codes such as CTH[3] with modern Lagrangian shock wave physics codes and transient structural analysis codes.

Validating a code requires both postdicting and predicting pertinent experimental data. The most useful validation experiments are reproducible and highly instrumented[4], with well-understood experimental errors. There are many parts of a calculation that we must validate: geometry, initial conditions, boundary conditions, material flow algorithms (remeshing and remapping algorithms), and material models, including EOS, constitutive relations and fracture models. There are also issues associated with meshing resolution and geometric fidelity. In many cases

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pertinent experimental data are available for a single strain rate regime and are used when appropriate to this regime. However, within certain applications that ALEGRA is addressing, there is a need to perform well-controlled experiments that capture material response at both high and intermediate strain rate regimes in a single experiment.

In this study, we provide an experimental test bed for validating features of the ALEGRA code[1], including material models, over a broad range of responses with overlapping diagnostics that encompass multiple strain rates. Aluminum is a well characterized material - its equation of state and constitutive properties are well established over a wide range of loading rates. Therefore, aluminum was used in this series of experiments. Pretest calculations were performed *to design and optimize* the experiment and to assist in instrumenting the experiment. 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 strain gauges. The test methodology is described in the next section. Results of these experiments are discussed and compared with ALEGRA simulations in subsequent sections.

Experimental Technique

A series of experiments were conducted on the Sandia terminal ballistics facility. This is a two-stage light-gas gun that can launch a sabot package carrying spherical projectiles to velocities over 6 km/s. In this study, a 9.5 mm, 6061-T6 aluminum sphere was launched to about 1.5 km/s. The impact velocity in each experiment is determined to an accuracy of 0.2% using a magnetic pick-up coil method[5]. The spherical projectile impacted one end of a hollow cylindrical can (also made of 6061-T6 aluminum) whose outer diameter is 63.5 mm, inner diameter 57.2 mm, axial length is approximately ~ 90 mm, with the front wall thickness of about 14 mm. The impact velocity and the front wall thickness is controlled to prevent rupture of the plate, while causing sufficient deformation/bulging as a result of impact.

The experimental configuration is indicated in Figure 1. A velocity interferometer, VISAR, is used to monitor the back surface motion of the free-surface both along the central axis and at off-axis locations. A total of twelve strain gauges, six to determine the axial strain (stress) and six to determine the hoop strain (stress), were used along the circumferential surface of the cylinder. The measurements were determined to an accuracy of better than 2% for velocity histories and 3% for strain gauge records.

Figure 1 illustrates the location of the velocity interferometer, VISAR, 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 directly diametrically opposite to strain gauges 1 to 3. The measured free-surface particle velocity history is shown in Figure 3 (along with the computed record), while the strain gauge records, which represent the axial strain measurements of strain gauges 1 to 3, are indicated in Figure 4. The first arrival time of all the strain gauge records is plotted versus its location in Figure 5. This yields the rate at which the stress front sweeps up in the cylindrical tube. Although not shown in this paper, multiple experiments were performed to determine the accuracy, and the repeatability of the experiments. The impact velocity was reproducible to within 1.3 % of the mean impact velocity of 1.5 km/s. 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. (Note the deviation is significantly small considering that the sphere is is launched over a distance of 6 meters from the muzzle of the gun to the impact location.)

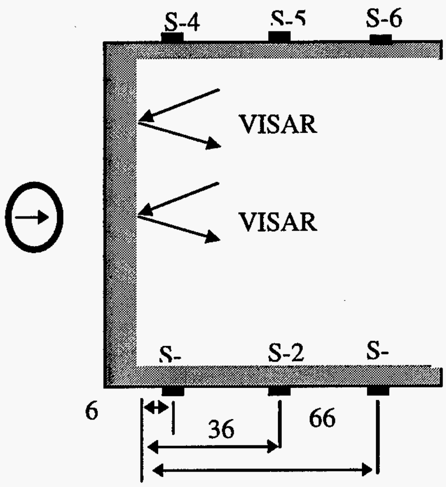

Figure 1. Experimental configuration used in this study.

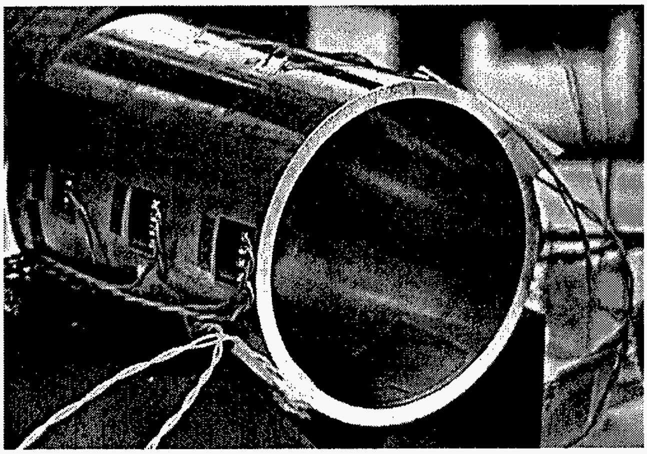

Figure 2. An instrumented can assembly.

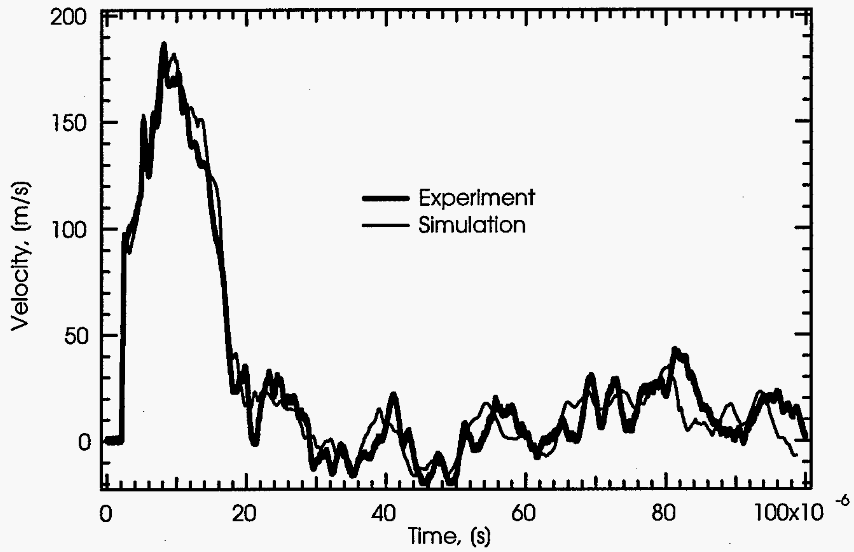

Figure 3. Experimental Velocity time history monitoring the back surface motion along the central axis of the can. However, Impact occurred 2.5 mm from center. The calculational simulation is also shown as a faint line in comparison to the experiments.

Results

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, significantly attenuates the resulting stress wave. The peak velocity measurement of about 0.2 km/s at the rear free surface indicates substantial wave attenuation. The leading edge of the wave is determined to travel at 6.4 km/s, which is representative of the elastic wave velocity in 6061-T6 aluminum. Although not shown in this report, the off-axis velocity interferometer measurements also suggest that the initial arrival time of the diverging stress wave is indicative of an elastic wave front. The leading precursor wave velocity is determined to an accuracy of 1%.

In these experiments, the relative time of arrival of all strain gauge records are known to within the sampling rate of the recording equipment, which is 20 ns for the current strain gauge records. The strain gauge records are indicated for strain gauges 1 to 3 in Figure 3. Gauge records indicate peak strain of ~2500 x 10^{-6} at a strain rate of 1.2 x 10^3/s at approximately 20 mm from the impact interface. This further reduces to a strain of 500 x 10^{-6} at a strain rate of 2 x 10^2/s at about 80 mm from the impact interface.

Figure 5 shows the first arrival time of the strain gauge record versus its location for all the strain gauges used in the experiment. Although the gauges 1 and 4, 2 and 5, and 3 & 6 are located at same location from the impact interface the arrival time of the leading edge of the wave is different. The time difference between the two gauges can be directly correlated to the non-centered nature of the impact. (In this experiment, the impact position of the spherical projectile is approximately 5.57 mm from the exact geometric center.) The data indicate that the stress front sweeps at a velocity of 5.6 km/s in the cylindrical tube.

Computational Simulations

The reasons for conducting the ALEGRA simulations are three-fold: i) to assist in the design of the validation experiments; ii) to produce results for comparison with the experimental data; and iii) to utilize the code and discover errors and inadequacies from a user's perspective. The combined goal is ultimately to contribute to the validation of the ALEGRA code for a certain class of problems or determine the net uncertainty from various possible sources of error. Since there is always the desire to improve the accuracy of a code, an additional goal is also to discriminate between the dominant individual sources of error.

Axisymmetric two dimensional simulations with Eulerian meshes were run in the baseline studies. A Mie-Gruneisen EOS and an elastic perfectly plastic constitutive relation were used for simplicity. In the experiments, velocities at the centerline were measured for the off center impacts, whereas in the two dimensional simulations this was approximated by off-center velocity measurements of centered impacts. This approximation will be most appropriate for early times (less than 20 μs) and for lower frequencies at the longer times.

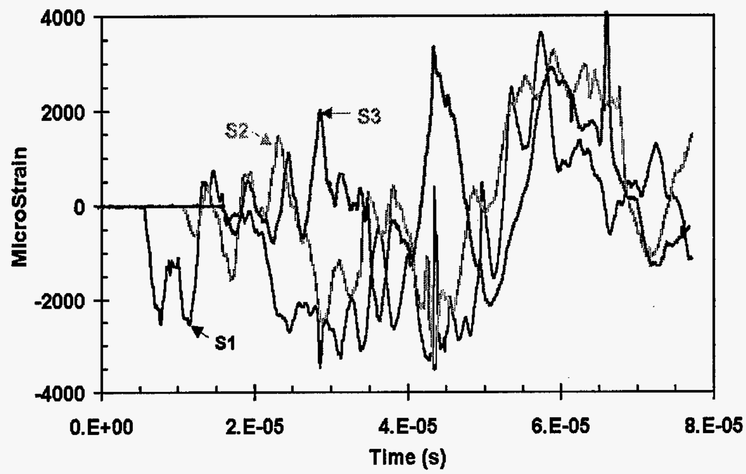

Figure 4. Axial strain gauge records of strain gauges 1,2,3. For the sake of clarity, not all gauge records are shown.

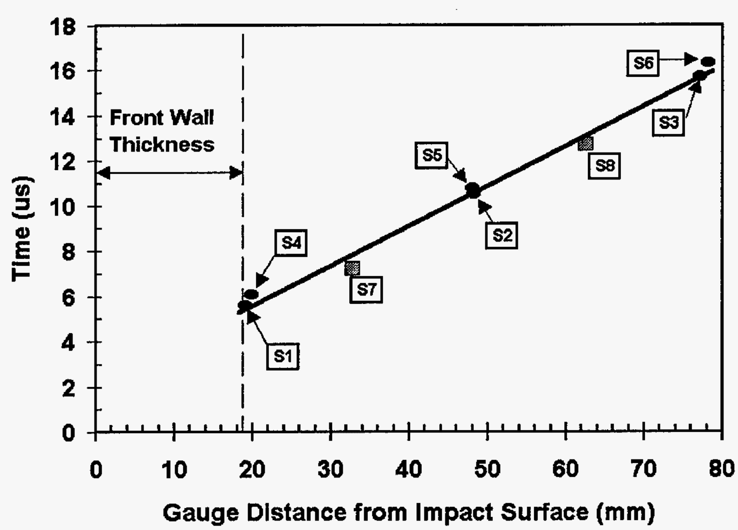

Figure 5. x, t diagram of all axial-gauge records indicates that the leading edge of the wave traverses at 5.6 km/s.

Both the VISAR and strain gauge measurements were made on the material surface. Time-resolved data for Eulerian calculations in ALEGRA are acquired by the use of massless Lagrangian tracers. These tracers move with the Lagrangian motion of the materials during the course of calculations. Because of tracking problems these tracers must be placed at least one zone away from material boundaries in order to move most accurately. Otherwise, numerical diffusion associated with multi-material Eulerian interface tracking will partially corrupt the data recorded by the tracers. In our simulations, results were recorded at locations which were 1.5 and 2.5 zones from the free surface to examine the effect of tracer location. Meshes with 0.5, 0.25 and 0.125 mm cell dimensions were used to examine mesh convergence effects. For the velocity type data as shown in Figure 3, a mesh size of 0.25 mm produced adequate convergence to approximately 2% error for the early time response. There was very little change in the calculated velocity history (see figure 6a) when the mesh size was further reduced to 0.125 mm, indicating mesh convergence for these mesh dimensions.

The consistency in Figure 3 between experiment and simulation is good, especially at early times and for lower frequencies at later times. The higher frequency details at longer times are not captured well due in part to the off center effects mentioned above. Three dimensional analyses are currently being set up to more accurately model the experiment. Based on a limited set of materials testing data, the yield strength of the aluminum was initially taken to be 300 MPa, and the early time velocity comparison had significant disagreement, as shown in Figure 6a. Subsequent examination of split Hopkinson bar results indicated that a choice of 400 MPa would be more appropriate. As indicated in Figure 3, the use of this value in the calculation resulted in much better agreement.

Total strain currently is not output from the code, but the stress components are. Since yielding was not observed at the strain gauge locations in the simulations, the elastic strains were calculated from the stresses and used in comparisons with experiment. Figure 6b shows the simulation and experiment for the strain gage location S2. The results agree reasonably well, but at later times disagreement becomes more significant. Possible causes are the accumulation of error from advection, three-dimensional effects, or the effect of artificial viscosity on elastic wave propagation. The mesh size convergence of the strain gauge records did not appear to be as good as for the velocity data because long time response is desired from the former, so that there is more time for errors to accumulate. Likewise, studies with ALE meshes, in which the strain gauged side wall was Lagrangian, did exhibit slightly better agreement with experiment than pure Eulerian ones, and it is anticipated that the improvement would be greater at longer times. Further study, including three dimensional simulations, and further study of ALE approaches, is required to draw firm conclusions about the uncertainty of the code for this type of problem.

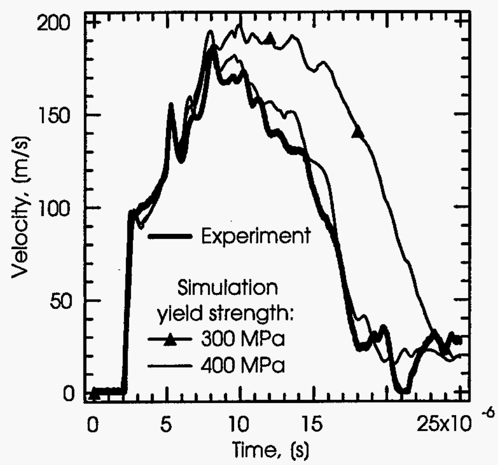

Figure 6 (a). Computational simulation of the history indicating the effect of yield strength on the simulations.

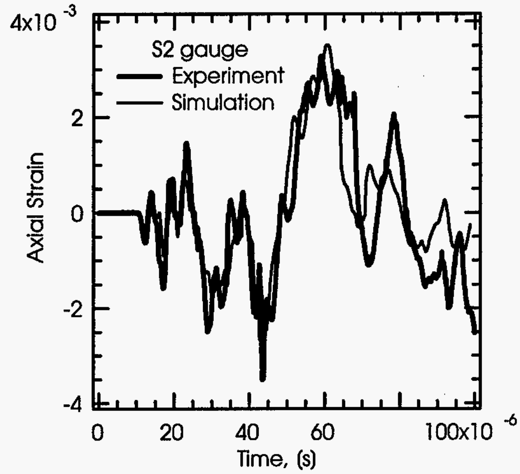

Figure 6 (b). Comparison of calculations velocity with experiments for strain gauge S2.

Conclusions

In this study, we provide an experimental test bed for validating features of the ALEGRA code over a broad range of responses with overlapping diagnostics that encompass the multiple strain rates. Aluminum was chosen in this study because it is a well characterized material - its EOS and constitutive material properties are well established over a wide range of loading rates. Specifically, the current experiments span the strain rate regimes of over 10^7/s to less than 10^2/s. Input conditions are well characterized; the input conditions are known to better than 0.2%, while the measurement precision is approximately 2% for the interferometer records and about 3% for the strain gauge records. The current experiments are extremely well-controlled two-dimensional loading experiments. Future experiments will consist of well-controlled three-dimensional loading conditions. Future experiments will also include a test bed at higher impact velocities, and an increased complexity of the test bed. The cylindrical can will be filled with structural materials of interest such as foam and steel to simulate many research and structural applications. This is ongoing work and it is anticipated that the current data set will be used to evaluate many aspects and issues related ALEGRA code validation.

Acknowledgments

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