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# Coupled Euler-Lagrange simulations of metal fragmentation in pipe bomb configurations

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**Abstract**

This paper details modeling of metal fragmentation of pipe-bomb configurations using the Euler-Lagrange code Zapotec. Zapotec couples the hydrocode CTH with the transient-dynamics finite element code Sierra/SM (also known as Presto) through a step-wise interchange of geometry, state data, and pressure. In this work, three experimental studies of pipe-bomb configurations were simulated using Zapotec, where the metal case was modeled using finite elements and the explosive was modeled with CTH. In the three examples, experimental and simulated debris distributions and early-time debris velocities generally showed excellent agreement. These studies both help build confidence in the use of Zapotec for simulating structural response under shock loadings.


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*Keywords:* Type your keywords here, separated by semicolons ;

## 1. Introduction

The fragmentation of materials during and after hypervelocity impact is a key factor in the resulting debris characteristics, and of great interest to the modeler of such impacts. To ensure that modeling techniques can properly capture the essential characteristics of material fragmentation, comparison of model to experiment is vital. While capturing data from experimental hypervelocity impacts is ideal for this, a close surrogate is the fragmentation of a metal case surrounding a cylindrical explosive charge, often referred to as a pipe bomb. Proper modeling of these configurations requires capturing shock processes within explosive detonation, the transfer of the shock into the surrounding metal, and the subsequent material response that leads to fragmentation. An array of existing experimental


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data is available for such comparisons, which often include fragment distributions ordered by mass and fragment velocities.

This work focuses on using the Euler-Lagrange code Zapotec to model pipe bomb experiments. Zapotec is a coupling between the Eulerian code CTH and the Lagrangian code Sierra/SM. The use of an Euler-Lagrange coupling for hypervelocity impact is of great use in bridging the inherent separate time-scales of material response: early-time shock events and damage, and late-time structural breakup. In this work, the pipe bombs are modeled with the explosive within CTH and the metal casing within Sierra/SM. Material failure in Sierra/SM is modeled using element death through the Johnson-Cook failure model.

The pipe bomb experiments modeled come from several sources. The first set of experimental data are from tests conducted by the Naval Surface Warfare Center at Dahlgren, Virginia, USA [1]. These experiments have been modeled before using CTH only [2]. The second set of data is from a set of experiments conducted at Eglin Air Force Base [3][4] using a slightly different configuration. These experiments have been modeled in an earlier version of Zapotec [5]; this work reinvestigates this case with the latest version. The final set of pipe bomb experiments were conducted at Lawrence Livermore National Laboratory by Goto et al. [6].

In this paper, section 2 covers the computational algorithm implemented within Zapotec. Section 3 discusses each of the experimental studies in more detail. Section 4 details the simulations conducted, and compares the simulation results with the experimental results. Section 5 concludes the paper with conclusions with the comparisons, and identifies future work to be completed.

## 2. Computational Techniques

The solution approach taken by Zapotec can be described as a loose coupling between two preexisting codes, CTH and Sierra/SM. CTH performs the Eulerian portion of the analysis, while Sierra/SM performs the Lagrangian calculations.

CTH is an Eulerian shock physics code that utilizes a two-step approach for the solution of the conservation equations [7]. The two-step solution approach first involves a Lagrangian step, where the Eulerian mesh is allowed to deform. The Lagrangian step is followed by a remap step. The remap algorithm advects material quantities (i.e., the volume flux, mass, momentum, and energy) from the deformed Lagrangian configuration back into the fixed Eulerian configuration.

Sierra/SM is an explicit Lagrangian, finite element code developed for modeling transient solid mechanics problems involving large deformations and contact [8]. The numerical formulation utilizes an updated Lagrangian approach whereby the reference state at each time step is updated to coincide with the current configuration. Although the Sierra/SM formulation accommodates a range of element types, Zapotec supports only a limited set. The supported element types are 8-node hexahedral element and 4-node quadrilateral shell elements.

In Eulerian methods, the mesh is fixed in space with material allowed to move through the mesh. This is advantageous for modeling problems involving large material deformations and/or diffusion and mixing of gaseous materials. However, the solution scheme presents some difficulties for material interface tracking and modeling complex material response, particularly that involving history-dependent materials. With a Lagrangian approach, the mesh deforms with the material. As a result, boundary and contact conditions are well defined, and history-dependent materials are more easily modeled. The major weakness of a Lagrangian method lies with mesh deformation, where severe element distortion degrades accuracy and can potentially lead to a failure of the calculation due to mesh entanglement. A coupled approach can overcome the weaknesses associated with the two methods, allowing for solution of a class of problems not readily solved by either method alone.

Zapotec is a coupled Euler-Lagrange computer code that links the CTH and Sierra/SM codes [9], enabling the use of the best computational approach for multi-domain problems. Example applications include earth penetration, blast loading on structures, and anti-armor applications. In a Zapotec analysis, both CTH and Sierra/SM are run concurrently. For a given time step, Zapotec maps the current configuration of a Lagrangian body and its state onto the fixed Eulerian mesh. Any overlapping Lagrangian material is inserted into the Eulerian mesh with the updated mesh data passed back to CTH. Once the material insertion is complete, the external loading on the Lagrangian material surfaces is then determined from the stress state in the Eulerian mesh. These loads are passed back to Sierra/SM as a set of external nodal forces. Once the coupled treatment is complete, both CTH and Sierra/SM are run independently over the next time step. In years past, the finite element code used in Zapotec was Pronto3d [10], however, in recent years, work has progressed in replacing this with Sierra/SM and in correcting a number of long-standing computational issues within Zapotec. This has greatly extended its robustness and accuracy, and has increased interest in comparing simulations with experiments.

## 3. Experimental Studies

Three experimental studies were considered for this paper. The first study utilizes data from a series of tests conducted at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) [1]. In this study, a heat-treated AerMet 100 steel cylinder, 20.3 cm in length with a 20.3 cm inner diameter and 0.82 cm thickness was filled with PBXN-110 and center detonated with a CH-6 booster. See Figure 1a for the test geometry. High speed cameras and flash radiography were used to record the fragmentation of the cylinder, and a soft fragment recovery system was deployed to collect fragments from a 25° segment of the cylinder.

The second experimental study was conducted at Eglin Air Force Base, which used a cylinder of Eglin Steel-1 (ES-1), 20.20 cm tall with a 5.08 cm internal diameter and a 0.40 cm wall thickness, explosively loaded by an aluminized PBX explosive [3]. See Figure 1b for the experimental setup. This test was run in two configurations; an open air case, where photonic Doppler velocimeters measured the velocity of the case during the detonation, and a case where an identical article was surrounded by a water-filled tank to provide soft-capture of the fragments. Zapotec modelling of this configuration have been conducted in the past [5]; this work serves to duplicate this work with the latest version.

The final experimental study was conducted at Lawrence Livermore National Labs (LLNL), with an Aermet100 cylinder, 20.32 cm high with a 5.08 centimeter outer diameter and 0.3 cm wall thickness, explosively loaded by an LX17 main charge detonated by an LX10 booster [6]. See figure 1c for the test configuration. The study also included tests with copper sleeves and metal rings to explore different loading conditions; these cases are not considered in this work. Like the Eglin experiments, the test setup was run in two configurations – an open air case where high-speed cameras and flash radiography captured the deformation of the cylinder, while a second case surrounded the cylinder with foam surrounded by a water tank.

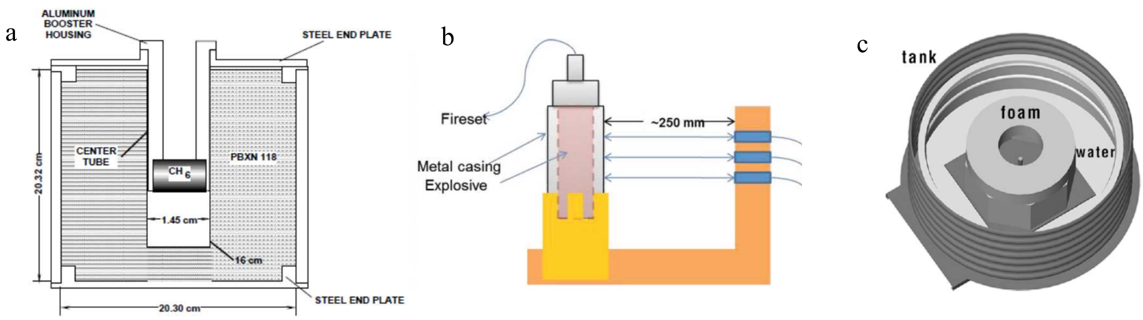


Fig. 1. Test configurations: (a) NSWC cylinder congifuration, from [1];
(b) Eglin cylinder configuration, from [4]; (c) LLNL cylinder capture tank configuration, from [6].

## 4. Simulation Details and Results

In each of these simulation configurations, the explosive was modelled in CTH, while the metal cylinder was modeled within Sierra/SM. In CTH, explosive properties were obtained either from standard databases or from communications with prior analysts. The detonator for the explosive was either modeled by a Jones-Wilkins-Lee model with programmed burn, or by providing a hot-spot to a History Variable Reactive Burn model. In all cases, the primary explosive was modelled using a History Variable Reactive Burn model, which was initiated by the detonator. The Zapotec simulations were run to several hundred microseconds. The simulations were fully coupled during the simulation time.

In Sierra/SM, the cylinder meshes used between 8 and 9 elements through the thickness. The elements were made to be close to cubic in aspect ratio. A Johnson-Cook strength and failure model [11] was used to model the cylinder material for all cases. In these analyses, no variation of the fracture parameters is included in the simulation; other researchers have indicated that this can lead to significantly improved comparison to fragmentation data [5][12].

Figure 2 compares the experimental results from the NSWCDD pipe bomb test to the simulation results. In Figure 2a, simulation results are shown next to the corresponding experimental images at several key points during the detonation of the pipe bomb. A number of key features appear to be matched; the deformation of the cylinder, initiation of fragmentation, and the leaking of explosive gasses through the fragmenting cylinder. In Figure 2b, the mass-ordered fragment distribution is shown with the corresponding experimentally recovered fragments. Since the fragments recovered were only within a 25° arc around the cylinder, the experimental masses were duplicated to produce an approximate full distribution. As is shown in the diagram, the distributions match reasonably well, with similar numbers of large fragments, and a similar tailing off to smaller fragment sizes. The simulation does have a longer tail of smaller fragments; this is attributable to the difficulty in capturing and measuring tiny fragments experimentally. Finally, the experimentally measured fragment velocity (taken from radiograph images) was 1822 m/s, and the simulation mass-weighted average fragment velocity was 1828 m/s, showing excellent agreement.

a b

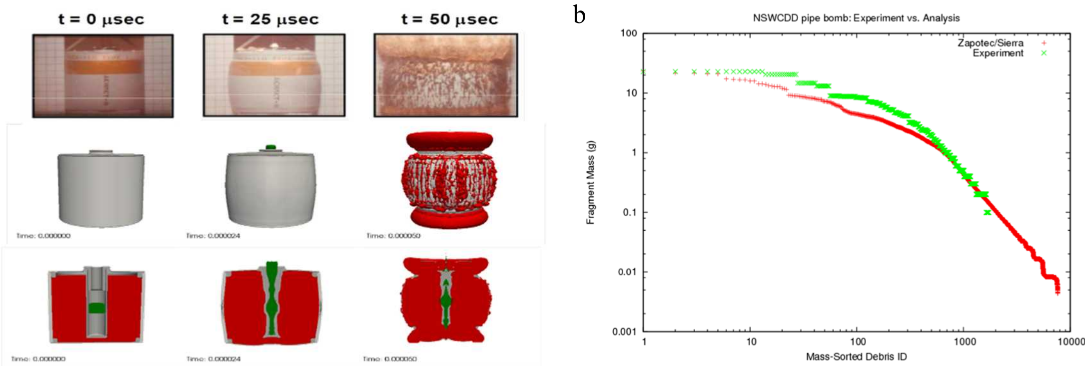


Fig. 2. Comparison of NSWCDD cylinder experiments and simulations:
(a) images from test compared to images from simulation at similar times; (b) comparison of fragment distributions.

For the Eglin pipe bomb, the major quantity of interest in this work was the early-time velocimeter data of the cylinder expansion. Figure 3a shows the experimental velocimeter data and the velocities at the same locations on the finite element mesh. The simulation results match well to the arrival time of deformation, the rate of increase of velocity, and the final velocity of the case. This follows in line with the work of Hopson et al.[5], which used an earlier version of Zapotec (with Pronto3D as the Lagrangian solver) for the same configuration, and which also compared predicted fragment sizes to experimental results while using statistically varying failure properties. Hopson's replication of his previous study using the latest (Sierra/SM-based) version of Zapotec is shown in Figure 3b. This confirms that the latest Zapotec updates, in particular the shift to using Sierra/SM, is still producing an excellent match to experiment for this case.

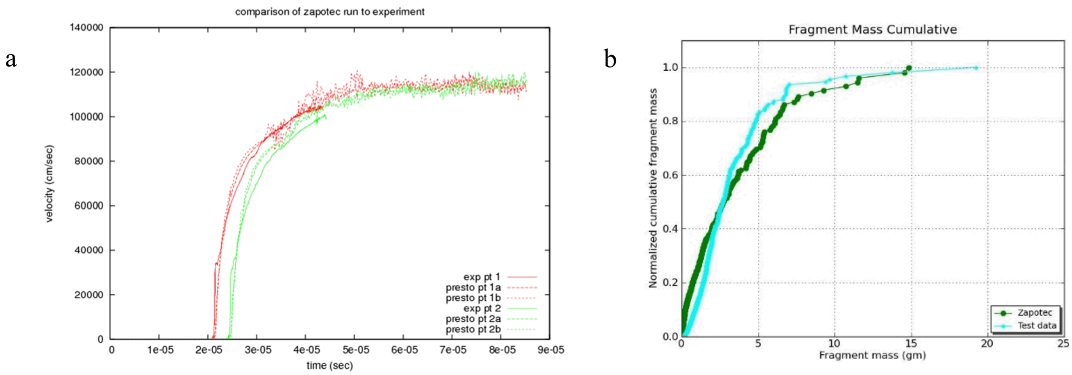


Fig. 3. Comparison of Eglin cylinder data to simulation: (a) velocimeter data; (b) fragment comparison (courtesy of Hopson)

The final study considers the LLNL pipe bomb. Figure 4 shows sample velocimeter data from the test and from the simulation. Zapotec shows strong agreement with the test data, both in arrival time and in final velocity. The fragment distribution (unable to be shown here) did not agree quite as well as in the previous cases, but showed overall similar fragment sizes.

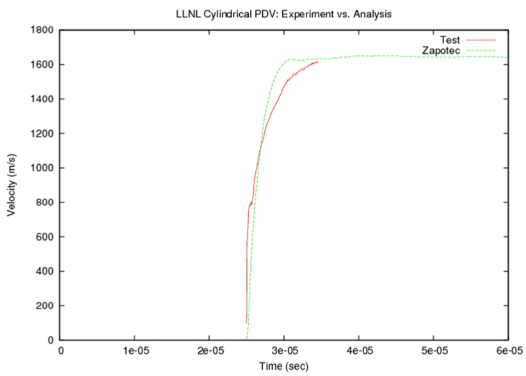


Fig. 4. Comparison of experimental and simulation velocimeter data from LLNL pipe bomb experiment

## 5. Conclusions

This work has explored the use of Zapotec in modeling material fragmentation in pipe bomb configurations. Zapotec is an Euler-Lagrange coupling of the hydrocode CTH and the explicit transient dynamics finite element code Sierra/SM. Three different experimental studies were modelled and compared to the experimental data. For the NSWCDD and Eglin pipe bomb configurations, Zapotec shows excellent matching to experimental data, both in terms of case/fragment velocities and in fragment distributions. For the LLNL case, Zapotec is less successful at matching experimentally gathered fragment data, but still matches key features well. These tests both show that Zapotec has significant promise in successfully modeling high-energy loading of structures.

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