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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: Fragmentation; Explosive loading; Pipe Bomb; Euler-Lagrange Coupling; CTH; Sierra; Zapotec; Validation

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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

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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 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 deletion 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