Dynamic Detonation Failure in Charges of High Explosive

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1 Introduction

Failure diameter is a well-known property of solid plastic-bonded explosives (PBXs); it is the critical diameter below which a steady detonation wave in a cylindrical charge is unable to sustain itself. Established detonations in supercritical charges can fail dynamically as well, for example when negotiating a divergent geometry. Examples include corner-turning, where a steady wave in a donor cylinder develops a region of zero or partial reaction (a dead zone) as it turns around a sharp corner leading into an acceptor cylinder of larger radius [1], and hockey-puck experiments, in which a spherical detonation expanding around a corner displays a similar behavior [2]. Dynamic failure has also been observed in converging conical or pencil-shaped charges, where a detonation initiated in the cylindrical section of the charge with a supercritical diameter may fail as it traverses the tapered section [3, 4].

Prediction of failure and dead zones is a challenge for reactive-flow models of heterogeneous explosives [4]. In a recent computational study [5] of detonation diffraction with the Lee-Tarver ignition-and-growth (I&G) model [2], a model that has otherwise been successful in predicting a variety of detonation behavior, sustained dead zones subsequent to corner turning did not materialize. A temporary failure, manifested by a local separation of the lead shock from the reaction zone, did occur, but the unreacted or partially reacted region underwent a delayed reaction, either by self-strengthening or by being swept by a strong lateral detonation that developed elsewhere in the flow. In a later study [6] it was demonstrated that dead zones in the hockey-puck configuration could be recovered if the standard ignition-and-growth model were modified to explicitly include desensitization by weak shocks, a known phenomenon of PBX. This desensitization is caused by a physical consolidation of the explosive when it is subjected to a compressive stimulus too weak to initiate a detonation. The resulting decrease in porosity lowers the fractional volume available for hot-spot development and requires a much stronger subsequent compression to initiate.

The computational study in [6] considered only rigidly confined explosives. The thrust of the present work is to couple the desensitization model with a multi-material capability, and compute accurate solutions of diffracting detonations in compliant confinements. Corner turning at a sudden expansion in a cylindrically symmetric charge, and detonation propagation in a pencil-shaped configuration, are examined. For the former, it is found that the compliant confinement alone does not lead to dead zone formation; explicit inclusion of desensitization is essential. For the latter, compliant confinement proves sufficient in inducing failure, and the inclusion of desensitization has a relatively minor influence.

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2 Governing Equations

The governing equations for the two dimensional I&G model with both multi-material capability and shock desensitization are

$$\mathbf{u}_t + \mathbf{f}_x(\mathbf{u}) + \mathbf{g}_y(\mathbf{u}) = \mathbf{h}(\mathbf{u})$$

where

$$\mathbf{u} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \\ \rho\mu \\ \rho\lambda \\ \rho\phi \end{bmatrix}, \quad \mathbf{f}(\mathbf{u}) = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ u(\rho E + p) \\ \rho u\mu \\ \rho u\lambda \\ \rho u\phi \end{bmatrix}, \quad \mathbf{g}(\mathbf{u}) = \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ v(E + p) \\ \rho v\mu \\ \rho v\lambda \\ \rho v\phi \end{bmatrix}, \quad \mathbf{h}(\mathbf{u}) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \rho\mathcal{R} \\ \rho\mathcal{S} \end{bmatrix}.$$

Here the variables have the usual meaning of density ρ, velocity (u, v), pressure p, total energy E and reaction progress λ. The remaining variables are associated with the two-material and desensitization model. For the two-material capability μ is an indicator of reactive ($\mu = 1$) or inert ($\mu = 0$) material. The value of ϕ indicates fresh explosive ($\phi = 0$) or fully desensitized material ($\phi = 1$). The total energy of the system is given by $E = e + (u^2 + v^2)/2$, where the internal energy $e = e(\rho, p, \mu, \lambda)$ is given by an equation of state for the mixture consisting of JWL equations of state for the inert, solid, and gaseous constituents. The two rates $\mathcal{R}$ and $\mathcal{S}$ appearing in the right hand side $\mathbf{h}(\mathbf{u})$ correspond, respectively, to the reaction turning solid reactants into gaseous product and the consolidation turning fresh into fully desensitized material. The reaction rate $\mathcal{R}$ is a slightly modified version of the standard I&G reaction rate, $\mathcal{R} = \mathcal{R}_I + \mathcal{R}_{G_1} + \mathcal{R}_{G_2}$, where

$$\mathcal{R}_I = \begin{cases} 0 & \text{if } \rho/\rho_0 < 1 + a(\phi) \\ I(1-\lambda)^b(\rho/\rho_0 - 1 - a(\phi))^x & \text{if } \rho/\rho_0 \geq 1 + a(\phi) \text{ and } \lambda \leq \lambda_{I,\max} \end{cases}$$

$$\mathcal{R}_{G_1} = \begin{cases} G_1(1-\lambda)^c\lambda^d p^y & \text{if } \lambda_{G_1,\min}(\phi) < \lambda \leq \lambda_{G_1,\max} \\ 0 & \text{if } \lambda > \lambda_{G_1,\max} \end{cases}$$

$$\mathcal{R}_{G_2} = \begin{cases} 0 & \text{if } \lambda < \lambda_{G_2,\min} \\ G_2(1-\lambda)^e\lambda^g p^z & \text{if } \lambda \geq \lambda_{G_2,\min}. \end{cases}$$

The standard I&G rate law is modified in two ways to account for desensitization. First, the threshold density for ignition, a, is deemed to be a function of ϕ, i.e., $a(\phi) = a_0(1 - \phi) + a_1\phi$. Then, as the material becomes desensitized (ϕ departs from 0 and moves toward 1), the minimum compression required to switch on the ignition term increases from a_0 to a limiting value a_1 appropriate for fully consolidated material. Second, a ϕ-dependent switch $\lambda_{G_1,\min}(\phi)$ is introduced for the first growth term. The desensitization rate is postulated to have the simple pressure-dependence $\mathcal{S} = A_r p(1 - \phi)(\phi + e_r)$. The entire model has many parameters which must be chosen and the bulk of these are found through experimentation. The parameters associated with the desensitization model are chosen to match with experiment. This is guided by an understanding that desensitization must take place slower than initiation of reaction through the ignition term $\mathcal{R}_I$ but quickly enough for significant desensitization to take place and turn off ignition behind weak shocks. Additional details can be found in [6].

3 Computational Results

Numerical solutions to the modified I&G model are obtained using a high-resolution, Strang-type fractional step scheme. The convective portion of the equations are handled using a slope-limited Godunov step, which is extended to accurately capture material interfaces without unphysical artifacts, as well

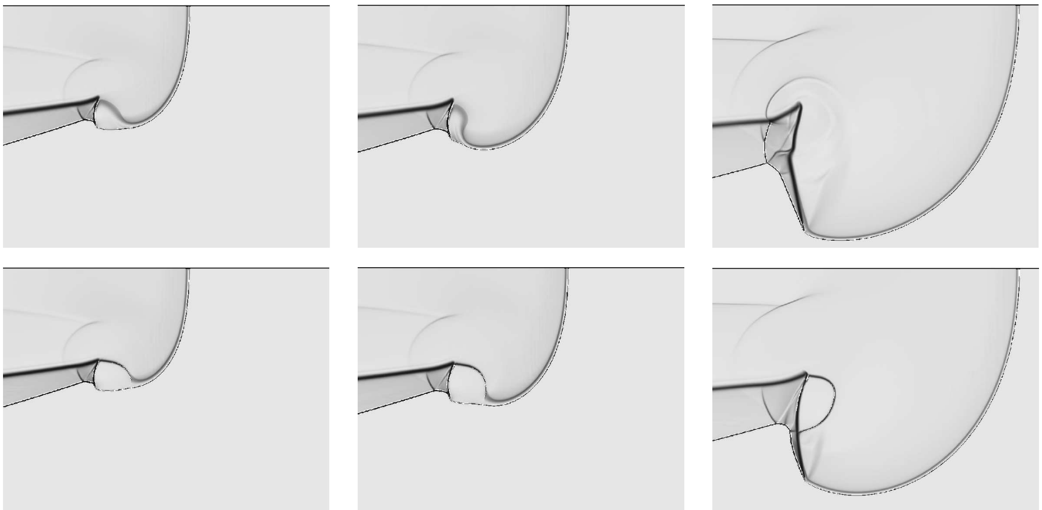

Figure 1: Sequential numerically-generated schlieren images of detonation propagation from a small-diameter donor cylinder into a larger diameter acceptor cylinder. Time increases from left to right. Standard I&G model (top), desensitized I&G model (bottom).

as to operate with the mixture JWL equation of state. The rate terms in the equations are handled using a Runge-Kutta error-control scheme which incorporates a sub-CFL time step where the time scale for the chemical reaction or desensitization dictates it. In order to achieve fully resolved computations, adaptive mesh refinement (AMR) is used extensively. The overall computational framework discretizes the governing equations on composite overlapping grids which can account for general, possibly moving, geometries in an efficient manner.

The fidelity of the numerical procedure was tested against known exact solutions in both 1D and 2D geometries. Diffraction and corner-turning behavior of detonations was examined in a variety of experimentally relevant configurations. Space constraints compel a very brief description of only some of the findings in this abstract. Figure 1 shows a detonation propagating from a small-diameter donor charge into a larger diameter acceptor charge, both encased in a weak confinement. The upper sequence of panels in the figure corresponds to the standard I&G model and the lower sequence to the augmented I&G model that accounts for desensitization. The standard model shows a separation between the lead shock and the reaction zone as the detonation turns the corner. However, the failure is only temporary and the explosive in the corner is fully consumed as the detonation advances further. On the other hand, a similar separation in the desensitized model gives rise to a sustained absence of reaction in a well-defined region near the corner. Thus it would appear that explicit consideration of desensitization is crucial for the appearance of experimentally-observed dead zones in this configuration. Similar results were obtained in the so-called hockey-puck geometry [2, 6].

Figure 2 displays propagation of a detonation from a cylindrical charge into a converging, conical segment. The top pair of panels correspond to a 20° cone angle and the lower pair to a 60° cone angle. For each case the upper set of images shows a sequence of pressure plots, and the lower set the corresponding sequence of numerically-generated schlieren plots. The standard I&G model was used in both cases. For the narrow cone the last panel in the sequence shows a distinct failure of the detonation, as evidenced by a precipitous drop in the pressure at the lead shock, and the distinct separation of the shock and the reaction zone. For the wider cone the failure does not occur until the detonation is essentially at the tip of the cone. This is a situation in which failure is dictated by the converging geometry and the compliant confinement; results for the desensitized model (not shown) exhibit a similar behavior.

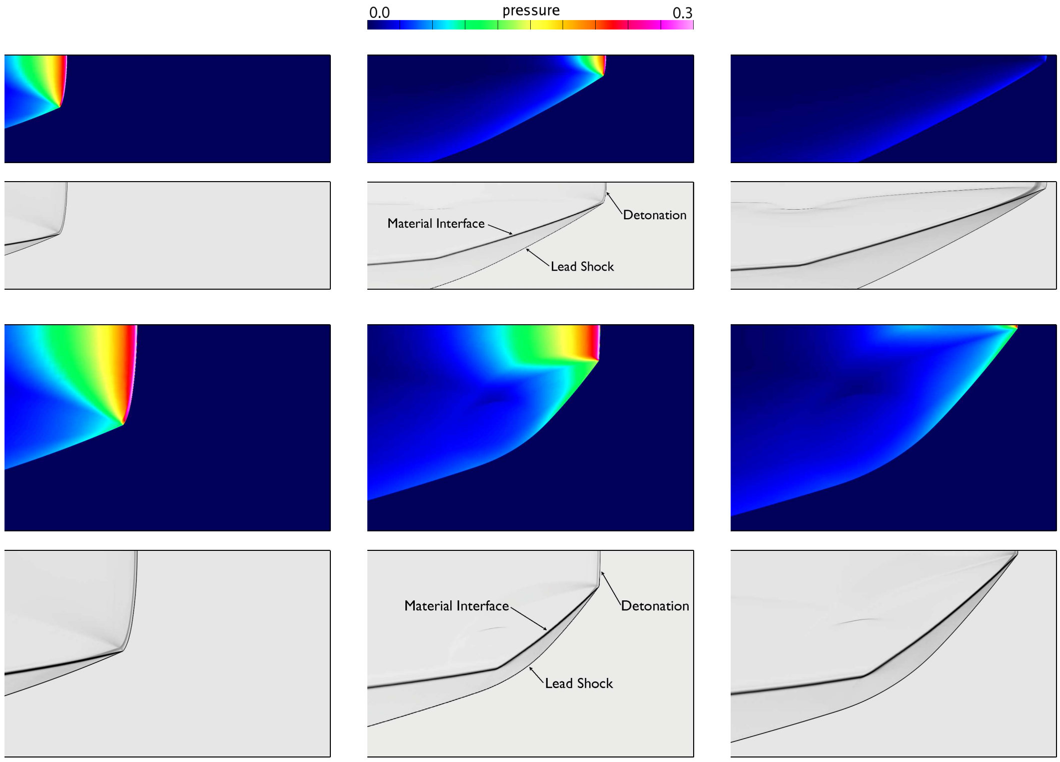

Figure 2: Pressure plots and numerically-generated schlieren images of detonation propagation in a converging conical charge. Time increases from left to right. The upper pair of panels correspond to a 20° cone angle, and the lower to a 60° cone angle.

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