

Modeling the Combustion of Pyrotechnic Materials inside Sealable Ammunition Containers Using Abaqus Explicit - CEL

J. Jablonski¹, P. Carlucci¹, and C. Ingerick¹

¹U.S. Army – ARDEC, Picatinny Arsenal, Picatinny, NJ 07806

Abstract: Sealable ammunition containers are widely used by the U.S. Army to ensure safe transport and storage of various types of munitions for the warfighter. In the case of accidental ignition, ammunition containers are designed to fail in a way that minimizes risk to nearby personnel and reduces the chances for a sympathetic detonation. In the constant effort to improve the performance and safety of such containers, extensive live testing is required to assess new or modified designs. This testing is time-consuming, costly, and often yields only pass/fail results with little or no data for failure analysis. Using the Coupled Eulerian-Lagrangian capability (CEL) in Abaqus Explicit, the structural failure of ammunition containers due to self-ignition was characterized by incorporating pressure dependent combustion models for arbitrary propellants and pyrotechnics. Several analyses were conducted simulating generalized design concepts as well as potential redesign concepts. The details of these analyses and comparison to theoretical models will be discussed along with their practical implications in military and commercial applications.

Keywords: fluid-structure interaction, compressible inviscid flow, Noble Abel gas, propellant combustion, closed bomb, safety

1. Background

1.1 Overview

Abaqus Explicit - CEL has the capability to define nodes which are able to generate mass at a defined temperature during a simulation. These particular nodes are referred to as inflator nodes and were initially intended to allow the automotive industry to simulate air bag deployment. Inflator nodes can be arbitrarily located in space, irrespective of the Eulerian mesh. Wherever an inflator node is located within an Eulerian element, an associated mass is introduced into the element as a point source. The authors refer to these elements (Eulerian elements with internal inflator nodes) as inflator elements, though the elements which contain inflator nodes can change arbitrarily during an analysis. The mass generation rate of an inflator node can be defined as a function of the pressure acting on its corresponding inflator element through the use of user subroutines.

1.2 Theory of Inflator Nodes

The governing Navier-Stokes equations for a compressible inviscid flow that account for the behavior of inflator nodes can be written in conservation form as follows:

Continuity Equation:

$$\left(\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial t} \Big|_{inf} \right) + \nabla \cdot (\rho \vec{v}) = 0 \quad EQ-1$$

Momentum Equation:

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = \rho \vec{f} - \nabla p \quad EQ-2$$

Energy Equation:

$$\frac{\partial}{\partial t} \left[\rho \left(e + \frac{v^2}{2} + e_{inf} \right) \right] + \nabla \cdot \left[\rho \left(e + \frac{v^2}{2} \right) \vec{v} \right] = \rho \dot{q} - \nabla \cdot (\rho \vec{v}) + \rho \vec{f} \cdot \vec{v} \quad EQ-3$$

As can be seen from (EQ-1), an inflator node adds a mass source term to the continuity equation. This generation term is lumped with unsteady density fluctuations within the control volume and is not correlated to the mass flux through the control surface. As a result of this modeling assumption, the momentum equation (EQ-2) remains unchanged. However, the generation of mass within the control volume also leads to an additional energy term coupled with the unsteady energy fluctuations within the control volume as seen in the energy equation (EQ-3). Present implementation of inflator nodes assumes that the mass generated within the control volume entered through some virtual boundary (i.e. boundary works was required) and thus its corresponding energy addition can be expressed in terms of enthalpy. Thus, the following relation (EQ-4) can be established.

$$e_{inf} = c_p T_{inf} \quad EQ-4$$

In essence, mass generation is treated as an external flow into the inflator element through the inflator node. In this respect, the inflator node is treated as a boundary of an open system. Schematically, the function of an inflator node within an Eulerian element is shown in FIG 1.

Previous efforts demonstrated that inflator elements were a viable candidate to couple propellant combustion models into Abaqus. Essentially, an inflator node can be used to abstractly represent solid propellant and simulate the introduction of gaseous propellant (as it burns from its solid state) into the Eulerian domain of the model. This allows the gas dynamics of propellant combustion to be incorporated into a structural code without directly modeling the grains of propellant (a task that is computationally infeasible for practical problems). Through the utilization of user subroutines, pressure dependent propellant models were integrated to govern the mass generation rate of inflator nodes. It is important to note that in this approach, the solid propellant is not modeled and, consequently, the interplay between the propellant gas dynamics and the structural response of the solid propellant is neglected. However, in many practical applications this effect is negligible.

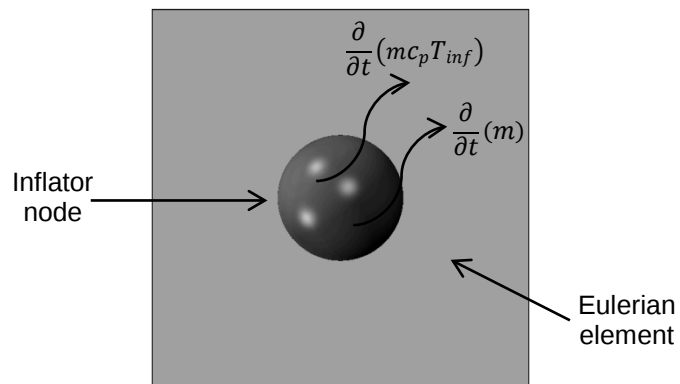


Figure 1. Schematic function of an inflator node.

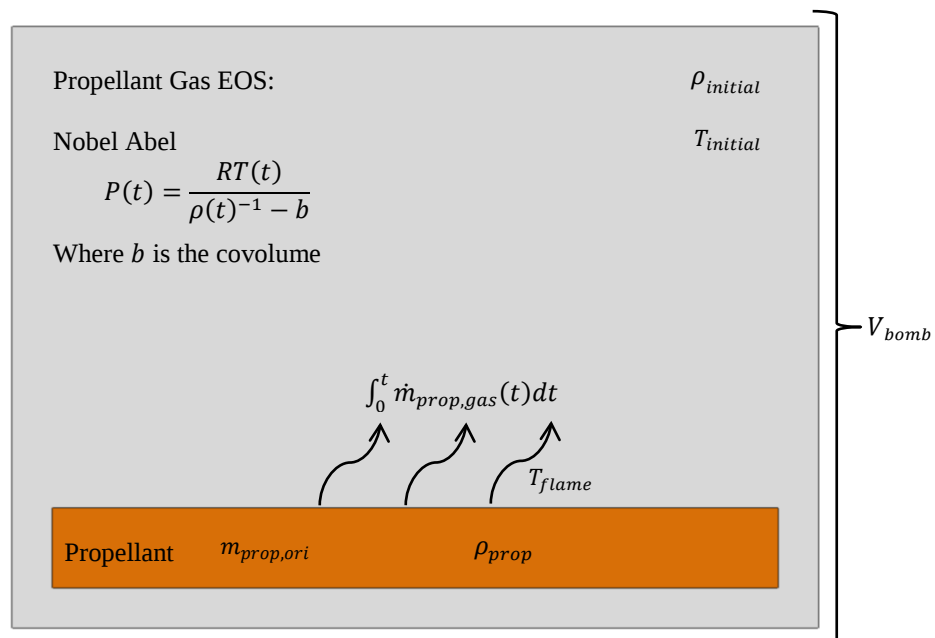


Figure 2. Conditions inside of a rigid closed bomb with burning propellant at $t = 0$

1.3 Theory of a Closed Bomb

To better understand the physics of an ammunition container failure, it is pertinent to simplify the problem to that of a closed rigid bomb, as detailed in FIG 2. In modeling the behavior of a closed bomb, it is assumed that the conditions of the gas initially present in the bomb (i.e. before the ignition of the propellant) are known. Additionally, it is assumed that the specific heat of the initial gas is comparable to the specific heat of the propellant gas. This is a reasonable assumption as a primer will usually burn prior to propellant ignition in practical environments. The gas generated as a result of propellant combustion is assumed to obey the Noble Abel equation of state and be at the adiabatic flame temperature, T_{flame} . With these assumptions it is possible to derive an equation specifying the gas pressure in the closed bomb as a function of time. If one takes account the mass of the solid propellant at a given instant in time (this is important because as the solid propellant burns there is more volume from the propellant gas to expand into) the governing equation for a closed bomb can be written as (EQ-5):

$$P(t) = \frac{R \left[\frac{\rho_{initial} \left(V_{bomb} - \frac{m_{prop,ori}}{\rho_{prop}} \right) T_{initial} + \left[\int_0^t \dot{m}_{prop,gas}(t) dt \right] T_{flame}}{\rho_{initial} \left(V_{bomb} - \frac{m_{prop,ori}}{\rho_{prop}} \right) + \int_0^t \dot{m}_{prop,gas}(t) dt} \right]}{\left[\frac{\rho_{initial} \left(V_{bomb} - \frac{m_{prop,ori}}{\rho_{prop}} \right) + \int_0^t \dot{m}_{prop,gas}(t) dt}{V_{bomb} - \frac{m_{prop,ori} - \int_0^t \dot{m}_{prop,gas}(t) dt}{\rho_{prop}}} \right]^{-1} - b} \quad EQ-5$$

Note that the accumulation of propellant gas into the closed bomb is expressed by the integral $\int_0^t \dot{m}_{prop,gas}(t) dt$. Implicit in evaluating this integral is that the rate of propellant gas generation at an arbitrary time is a function of pressure (i.e. the burn rate of the propellant is pressure dependent). Mathematically, this implies $\int_0^t \dot{m}_{prop,gas}(t) dt = f(P(t), t)$. Assuming that the closed bomb is not rigid, it becomes clear that the rate of gas generation is dependent on the structural behavior of the closed bomb since any deformation or structural failure will change the volume available to the propellant gas or allow mass flow out of the control volume, which in turn affects the gas pressure. This interdependency of propellant burn models, gas dynamics, and structural mechanics in this type of problem is why fully-coupled methods are required in a simulation.

If the volume of solid propellant is much smaller than the volume of the closed bomb then $V_{bomb} \gg \frac{m_{prop,ori}}{\rho_{prop}}$. This leads to the following approximations (EQ-6):

$$V_{bomb} - \frac{m_{prop,ori}}{\rho_{prop}} \approx V_{bomb} - \frac{m_{prop,ori} - \int_0^t \dot{m}_{prop,gas}(t) dt}{\rho_{prop}} \approx V_{bomb} \quad EQ-6$$

The governing equation for the gas pressure inside of the closed bomb then simplifies to (EQ-7):

$$P(t) = \frac{R \left[\frac{\rho_{initial} V_{bomb} T_{initial} + \left[\int_0^t \dot{m}_{prop,gas}(t) dt \right] T_{flame}}{\rho_{initial} V_{bomb} + \int_0^t \dot{m}_{prop,gas}(t) dt} \right]}{\left[\rho_{initial} + \frac{\int_0^t \dot{m}_{prop,gas}(t) dt}{V_{bomb}} \right]^{-1} - b} \quad EQ-7$$

Since this implementation of coupling pressure dependent burn models with inflator nodes neglects solid propellant effects, it will not yield accurate transient behavior if there is too much solid propellant present in the control volume. FIG 3 illustrates how the accuracy of a simulation can be impacted as solid propellant effects become significant for a generalized closed bomb problem. Depending on the problem specification the volume of the solid propellant can be assumed to be negligible but not always.

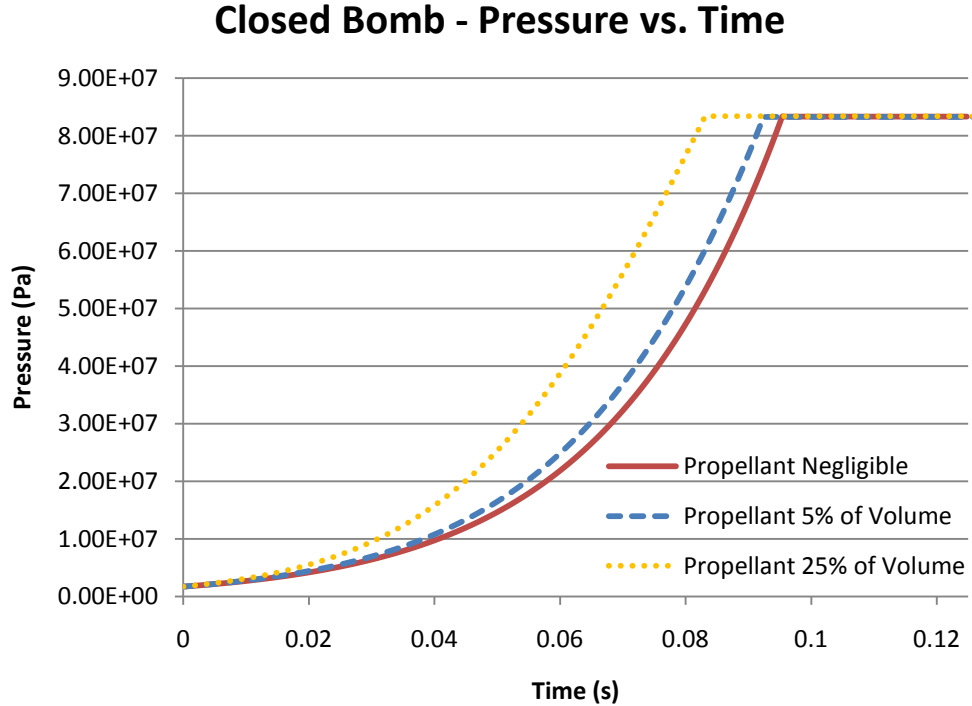


Figure 3. Effect of propellant initial volume on closed bomb transient pressure.

Given the arbitrary parameters used in FIG 3, when solid propellant is 5% of the closed bomb volume, accounting for its volume can be neglected. However, this is not true when the solid propellant takes up 25% of the volume or more. Although the equilibrium state will be

identical, the transient behavior will change dramatically. Though, for analyses that look at the transient response for a time short compared to the burn out time of the propellant, larger propellant volume ratios will yield reasonably accurate results. Unfortunately, there is no general method to determine when the volume of solid propellant must be accounted for. This percentage varies given the problem type, as well as its governing parameters. However, it is valid to neglect the volume for many practical problems, especially when the control volume is venting (as this mitigates the solid volume effect). Techniques to accurately integrate solid propellant behavior in conjunction with inflator nodes are presently being investigated by the authors.

2. Model Definition

2.1 Problem Definition

A steel ammunition container with the approximate dimensions of 500 mm x 400 mm x 250 mm was considered as it is representative of typical geometry. To simplify the analysis, modeling a lid with a corresponding latching system was omitted. Instead, the ammunition container was treated as being perfectly sealed (except for vents). The container was assumed to be devoid of any packaging products and only included an initial mass of 8 kg of propellant. The properties used in modeling the propellant were representative of typical propellants used in military and commercial applications. At the start of the analysis, it was assumed that all the propellant present in the container uniformly ignited.

Two venting cases were considered which included 175 mm x 90 mm cutouts centered on the largest faces of the container. In the first design, these vents were completely unobstructed. That is, they are essentially large holes put into the container. The second design included sheet metal burst plates, which obstructed any flow of gas out of the container. These plates were intended to fail after an initial build up of pressure in the container. Upon failure of the plates, the venting process would occur unimpeded.

2.2 Model

Due to the problem definition, the analysis could be modeled using one-eighth symmetry, which greatly reduced the required computational overhead. Additional computational cost was saved in modeling the container and burst plate with continuum shells. A very fine mesh was required for the Eulerian domain in order to correctly resolve the contact between the container walls and the propellant gases. The mesh for the Eulerian domain required over half a million elements, which stresses the advantage of being able to apply one-eighth symmetry. The overall assembly is summarized in Figure 4.

Approximately 20,000 inflator nodes were defined over the majority of the interior volume of the ammunition container. From a modeling standpoint, this abstracted the 8 kg of solid propellant as being very finely distributed through most of the interior. In order for the propellant to modeled correctly, it is important that the volume occupied by the inflator elements is on the

same order of (or larger than) the volume occupied by the actual solid propellant (excluding its packing volume). If this is not done the flow out of an inflator element can become choked, which results in inaccurately higher pressure acting on the element. Since the propellant burn rate is dependent on pressure, such an effect causes artificially high gas generation. Note that in this problem the volume occupied by inflator elements is several orders of magnitude larger than the minimum requirement. This over-conservative allocation of volume has no adverse impact on the analysis results.

3. Analysis

3.1 Open Vent Design

When considering an open vent design, it is necessary for the container to have appropriately sized vents. If the area of the vent is too small, the gaseous products generated from the solid propellant combustion will be produced at a greater rate than they can flow through the vent. This will lead to a pressure increase in the container and, since the burn rate is pressure dependent, the rate of gas production will accelerate. As a result the propellant may enter a runaway reaction and cause a catastrophic failure of the container. However, it is also not advisable to make the vent arbitrarily large as this will begin to affect the structural integrity of the container, eliminating its functionality. In essence, sizing the vent becomes an optimization problem.

FIG 6 chronicles the pressure development within the container using the fully-coupled approach with an open vent design. As can be seen, upon ignition of the propellant the pressure rapidly builds inside the container and within five milliseconds a potentially dangerous condition is present in the vent. From inspection of the contour plots, the flow out of the container is severely choked. This is problematic as it indicates the vent is being used to its capacity (i.e. it can't allow the propellant gas to flow any faster out of the container). A situation like this does not necessarily indicate that a failure is eminent as the state of the propellant (for instance how much has already burned) becomes a factor.

Within seven milliseconds it becomes apparent that the propellant burn rate was low enough to prevent a runaway reaction from occurring and the vent is sized sufficiently. Within ten milliseconds, the pressure within the container is not too far above ambient levels and the container is no longer in danger of catastrophic failure. At this stage the propellant is burning gradually and a steady burn will ensue for several seconds (much like if you burned a propellant that wasn't enclosed). From a design standpoint, this open ventilation configuration was successful.

3.2 Burst Plate Design

A burst plate design behaves similarly to that of an open vent design except that a pressure build up in the container is required to fail the burst plate, which will then allow venting to occur. Consequently, a burst plate design will be identical to a corresponding open vent design except that the initial pressure preceding the venting process will be substantially higher. Additionally, if

this pressure is severe enough, the container walls may deform appreciably to expand the overall internal volume (i.e. the control volume changes).

The pressure contours of the Eulerian domain of the burst plate design, as well as the corresponding von Mises stress distributions of the container just before and right after the burst plate fails are shown in FIG 7. At three milliseconds into the analysis, the structural integrity of the burst plate has not been compromised (although failure will occur within another millisecond) and the ammunition container is behaving much like a closed bomb. At five milliseconds, the burst plate has completely separated from the container and is being ejected from the Eulerian domain. At this point the physics governing the container will be the same as in the open vent design. It is interesting that as a result of this rapid pressure decrease, the container walls will engage in vibration modes (i.e. the structure “rings”). This phenomenon was not present in the open vent design. Continuing the analysis to determine if the newly opened vent is adequate in preventing a catastrophic failure reveals that the container does vent properly (FIG 8). By ten milliseconds, the pressure inside of the container has decreased substantially and by twenty milliseconds the internal pressure is almost at ambient conditions.

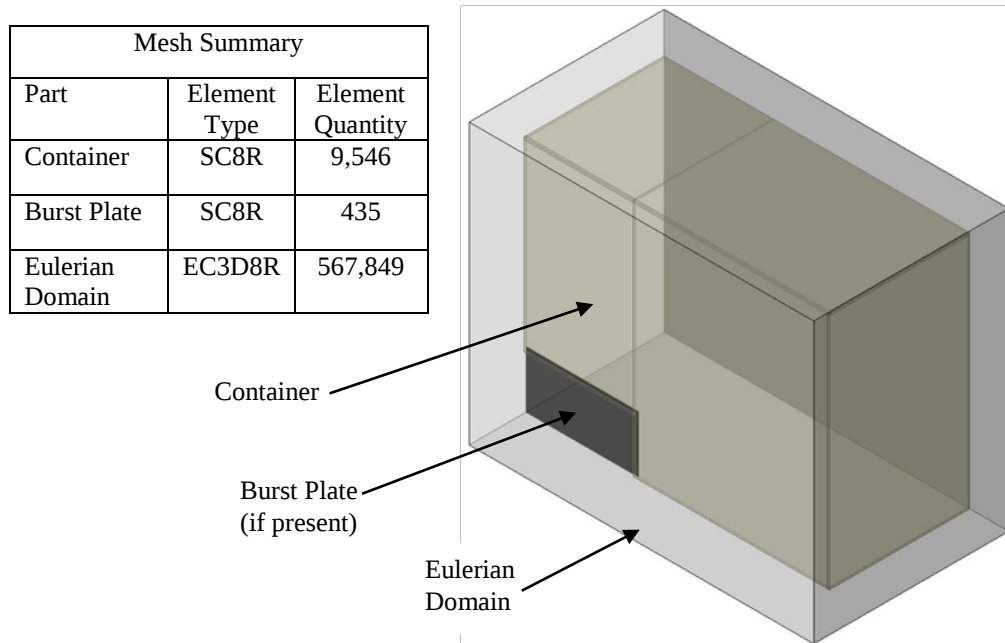


Figure 4. Assembly Overview and Mesh Summary.

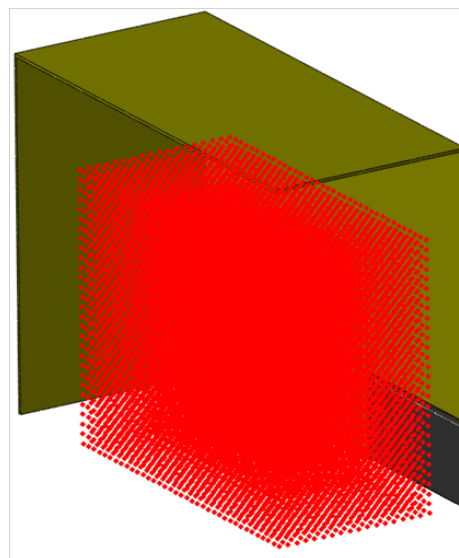


Figure 5. Inflator Node Definition

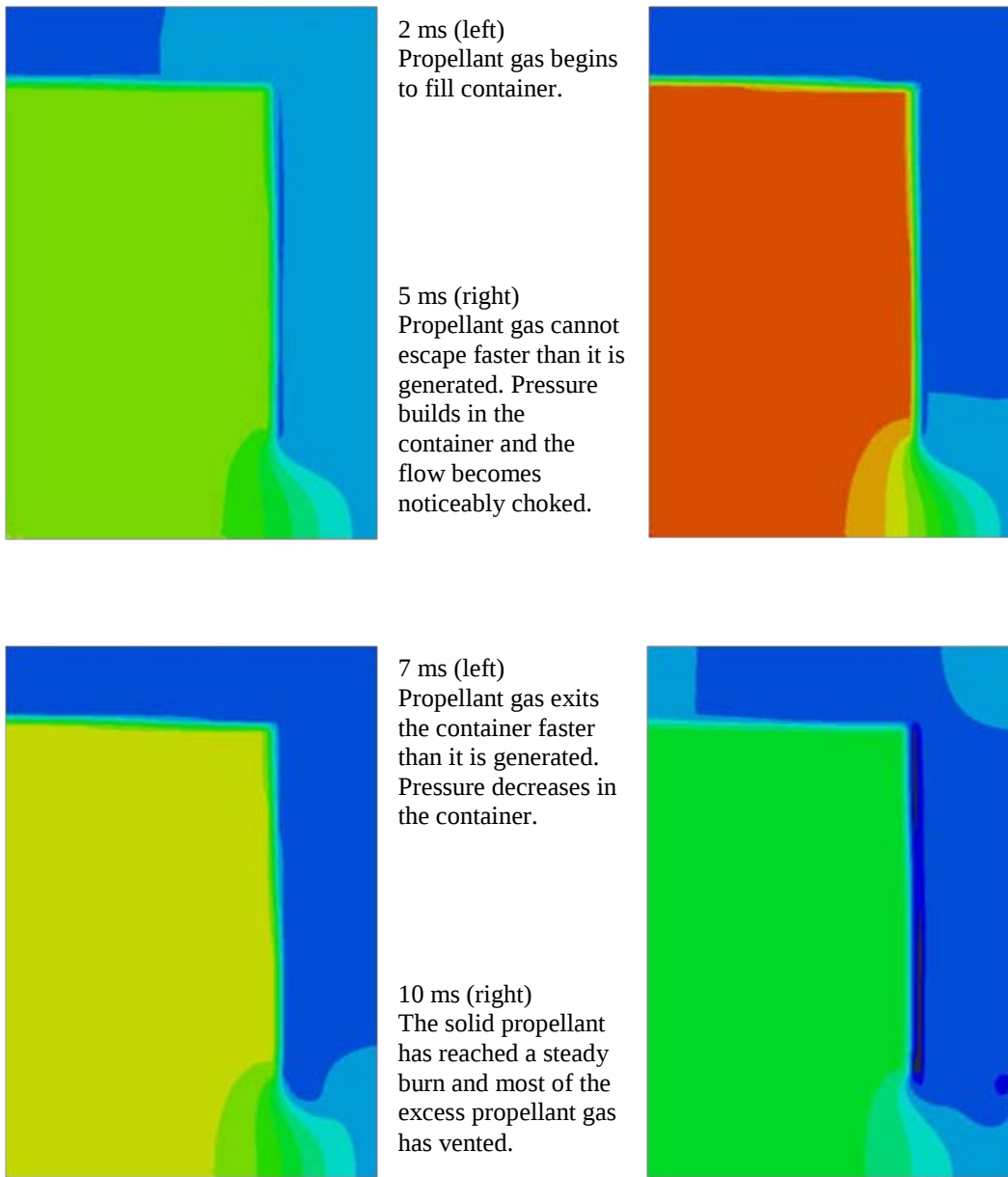
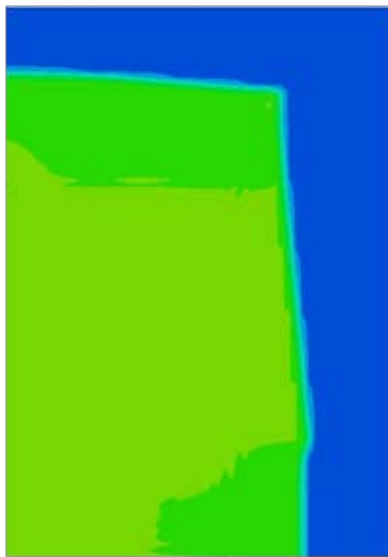
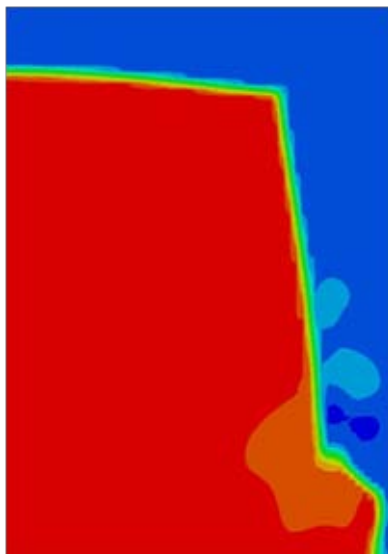
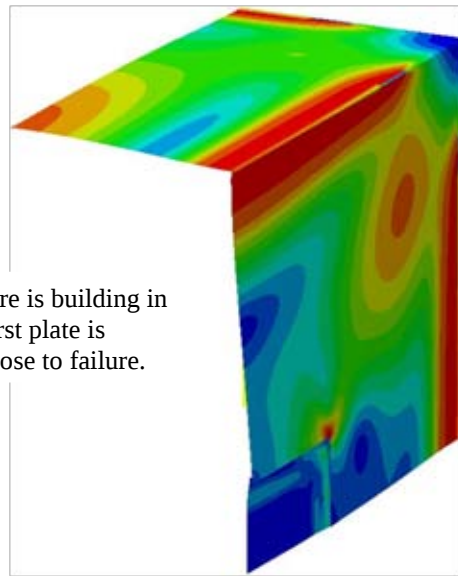


Figure 6. Pressure Contours During Open Venting



3 ms – Pressure is building in container. Burst plate is holding but close to failure.



5 ms – Burst plate has failed and is being propelled away from container. Propellant gas begins to escape.

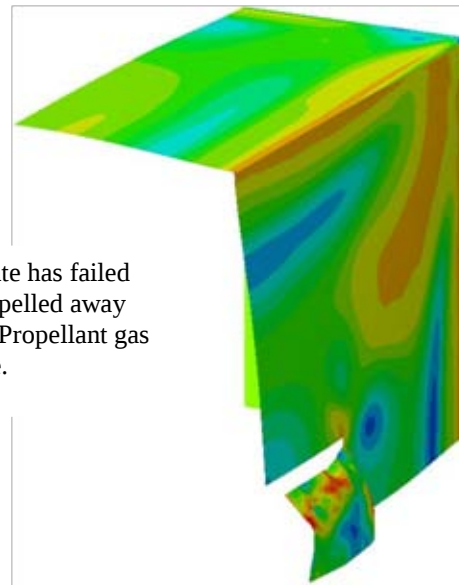


Figure 7. Pressure and Stress Contours Capturing Failure of Burst Plate

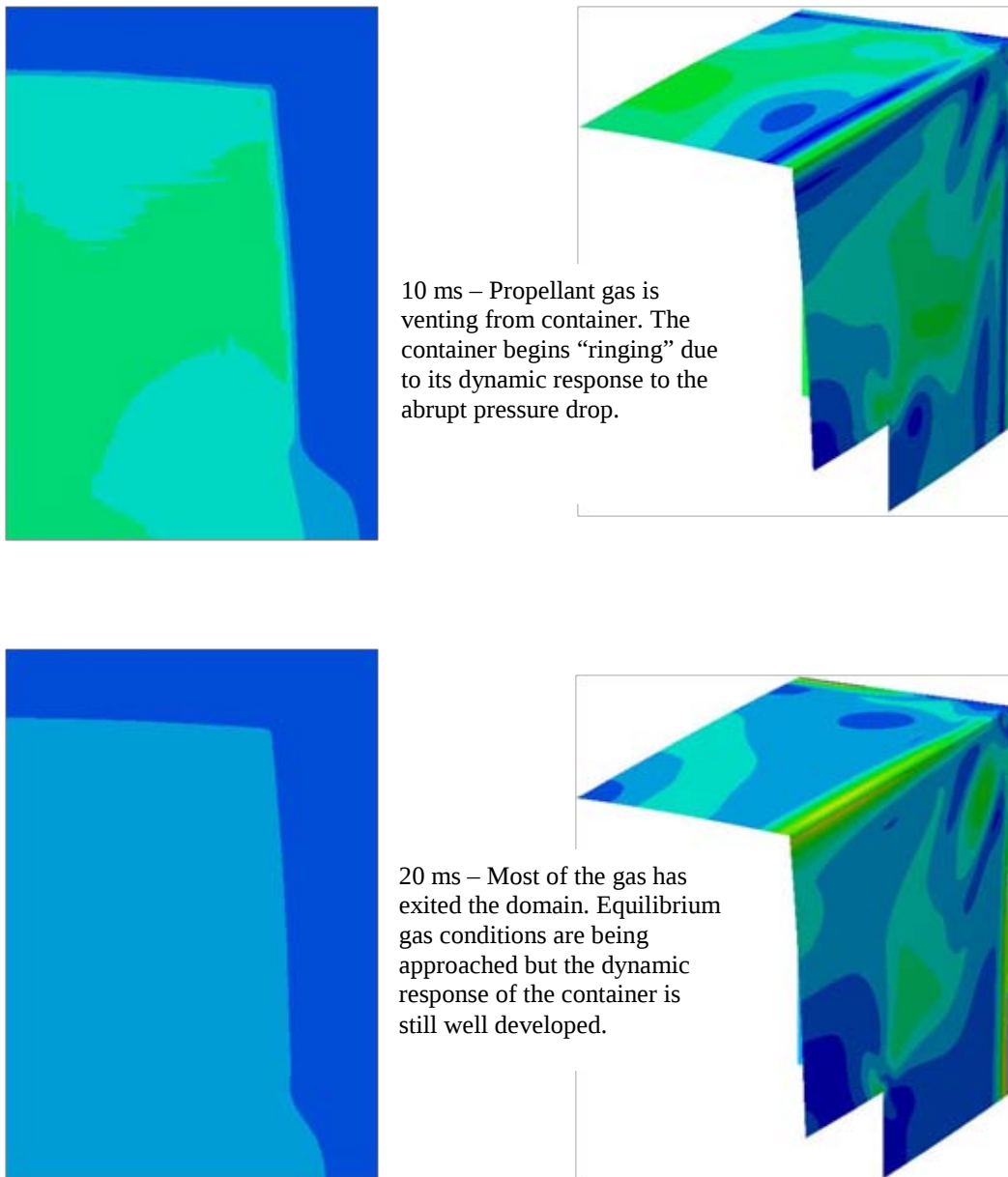


Figure 8. Pressure and Stress Contours Capturing Venting

4. Discussion

4.1 Breakdown of the Closed Bomb Assumption

Recall that the governing equations for a rigid closed bomb are accurate in describing sealed ammunition containers until there is a significant change to the control volume or the system becomes open. Two common modes of this include the expansion of container walls due to a high pressure build up (this can be significant when the container is made out of ductile material) or the process of venting. For the analyses considered, the onset of venting is the primary reason closed bomb calculations become inaccurate. However, from a theoretical standpoint, the closed bomb calculations should be accurate up until the burst plate fails. An additional analysis of the burst plate design was conducted in which a predefined mass flow rate vs. time curve was imposed upon the inflator nodes. This curve was produced from analytical closed bomb theory (EQ-5). In this way, a direct comparison could be made between this “one-way” modeling approach and the fully-coupled approach.

FIG 9 compares the pressure contours of the one-way approach vs. the fully-coupled approach at two milliseconds after propellant ignition. Since there is negligible distortion in the ammunition container and the burst plate is well intact, it is expected that both approaches would produce identical results. This is indeed the case. There is no appreciable variation between the two models. Additionally, since both approaches produced the same result and the one-way calculations took into account the volume occupied by the solid propellant (whereas the fully-coupled approach did not), the modeling assumption to neglect solid propellant effects is proven to be valid.

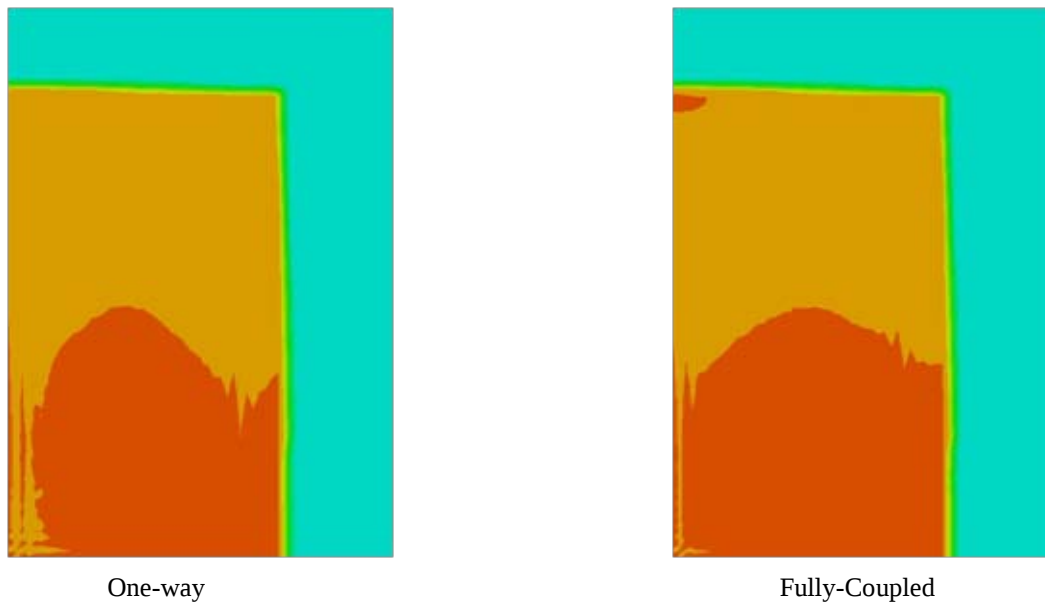


Figure 9. Pressure Comparison at $t = 2$ ms

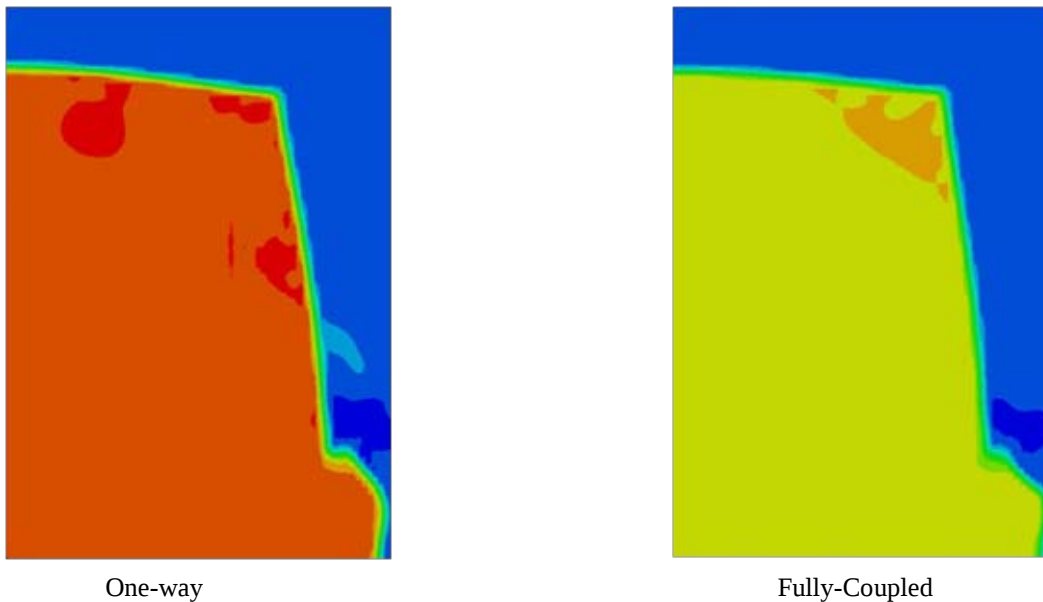


Figure 10. Pressure Comparison at $t = 5$ ms

Four milliseconds after the pyrotechnic is initiated, the pressure inside the ammunition container is severe enough to fail the burst plate. At the point of failure, the container has expanded considerably as a result of containing the propellant gas. A millisecond later, the burst plate has been completely ejected and gas is venting. This event marks the breakdown of the one-way modeling approach as the underlying assumptions behind the closed bomb approximation are no longer valid. As a result it would be expected that from this point forward, the one-way approach would over-predict the true pressures since the theory does not account for volume expansion or venting (both processes reduce the internal pressure). FIG 10 shows exactly this behavior. Notice that from a qualitative standpoint the deviation is not too severe and may even be appropriate from an engineering standpoint.

However, continuing the one-way model beyond this time only exacerbates this error and the fully-coupled approach becomes required for an accurate simulation. FIG 11 shows that by eight milliseconds into the analysis the one-way approach significantly deviates from the fully-coupled approach. From an analysis standpoint this error is completely unacceptable and the model results are of little engineering value. In fact by the time the analysis has reached twenty milliseconds (not shown) the one-way model predicts a catastrophic failure of the container, whereas the fully-coupled approach predicts the gas pressure to be at nearly ambient conditions. Essentially, the one-way approach in this particular problem predicted the failure of a design that was actually acceptable.

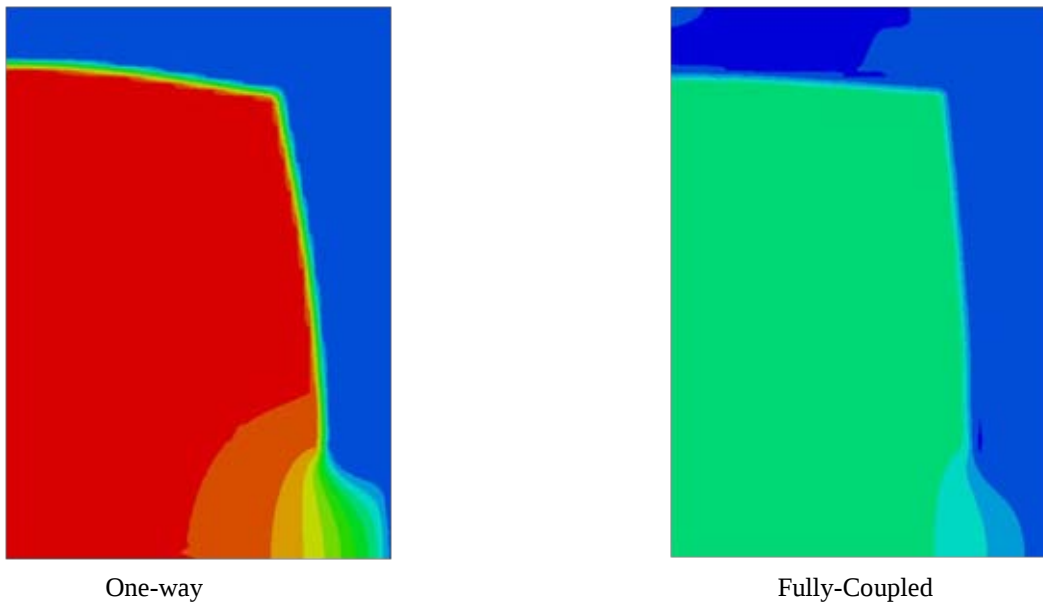


Figure 11. Pressure Comparison at $t = 8$ ms

5. Conclusions

In simulating the ignition of pyrotechnic materials inside of a sealed container, it is clear that incorporating the fluid-structure interaction of the produced gases with burn models for the pyrotechnic is necessary for an accurate analysis. It has been demonstrated that the present capabilities of Abaqus Explicit – CEL are sufficient to accurately incorporate the required physics of this process into a finite element model. Therefore, Abaqus can be used as a predictive tool in the design of sealed containers that are packaged with pyrotechnics, or other combustible products. This modeling capability has great potential for packaging engineers in the military and commercial sectors. Due to the complexity and highly coupled nature of the physics involved in these types of events, there exists a substantial knowledge gap in packaging engineering. As a result, much information relating to a package design is inferred qualitatively through costly testing. It is hoped that the insights provided by using Abaqus as a research tool will bridge this gap.

6. References

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