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CFD Analysis of Blast Venting from a Magazine into a Chamber

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Abstract

UFC 3-340-02 [1] outlines methods for calculating blast loads due to an internal detonation within a single room as well as wraparound pressure escaping from three-sided and four walled cubicles. However, UFC does not provide a methodology for blast escaping an enclosure that is itself located within another enclosure. A recent project required design for just such a scenario: magazines were to be placed inside a chamber to protect personnel within the larger building in the event of an accidental explosion. The cylindrical magazines are designed to contain blast loads from an internal detonation. However, if that detonation occurs when the magazine's door is open, the chamber must contain the escaping blast pressures. Loads on the wall that the magazine door faces will be amplified due to the magazine focusing the blast on that wall. Due to the complex geometry of the magazine and because the magazine is enclosed within the chamber, the analytical methods of UFC seemed inadequate and highly approximate. Therefore, a high-fidelity computational fluid dynamics (CFD) analysis was performed using Viper::Blast (Viper) [2].

Design blast loads obtained from Viper are compared against results using engineering methods to determine if they would lead to a significantly different result. One approach is to ignore the magazine and use the SHOCK [3] and FRANG [4] models in the ConfinedBlast code. Another is to use the leakage pressure curves in the UFC and apply appropriate reflection factors. Both methods were shown to be reasonable with regard to shock pressure on the front wall, but conservative to highly conservative for shock pressure on the roof. And the gas pressure from FRANG was seen to be very conservative as well.

This paper will discuss the assumptions, methodology, and results of the different approaches to calculating the internal blast pressure and their effects on the front wall and roof design of the chamber.

Introduction

Designing a containment structure for an internal explosion requires calculation of internal shock and gas pressures. These can be easily calculated using SHOCK and FRANG models within ConfinedBlast [5] for a standard room. However, this assumes a charge is unconfined within the cuboid shaped room. If a charge is partially confined but fully vented (e.g., three-sided cubicle with one venting wall), leakage pressures are enhanced in the direction of venting and reduced to the side or back of the cubicle, as compared to a free-air explosion. When the charge is located in a partially vented cubicle (e.g., four-walled cubicle with venting), the leakage pressures to the front may or may not be enhanced depending on the size of the vent opening. If a charge is partially confined within two nested containment structures, these effects should be considered when determining the design loading. Unfortunately, such complex geometry cannot be accommodated by either ConfinedBlast nor by the engineering methods in UFC for leakage pressures; hence, we turn to high fidelity modeling.

This paper discusses a case study in which a design was developed for a containment chamber housing three magazines, each of which houses explosives. Blast pressure exits the magazine through its open door, fills the containment chamber, then propagates to the exterior via vents in the chamber. Blast loads calculated using a computational fluid dynamics (CFD) model were used for the design, and in this paper we compare those loads to ones generated using two engineering methods: (*a*) ConfinedBlast, and (*b*) leakage pressure curves in UFC. The lessons learned provide useful guidance regarding the benefits of using high-fidelity modeling.

Case Study Design Basis

In a recent design project, a series of cylindrical magazines were to be located within a large building. The individual magazines are designed to contain an accidental explosion when the magazine door is closed. However, since the explosion could occur while explosives are being moved into or out of the magazine, a concrete containment structure was included in the design to protect personnel in the rest of the building. The floor plan of the concrete chamber is illustrated in Figure 1. The construction of the containment structure will be of reinforced concrete with the magazines sitting in a pit below floor level, as illustrated in Figure 2. Only a single magazine will be open at any time. Therefore, the magazine containing the largest charge weight (right-most magazine in Figure 1) was used for the design of the chamber. The design charge weight is 54 lb TNT equivalent located at the center of the magazine.

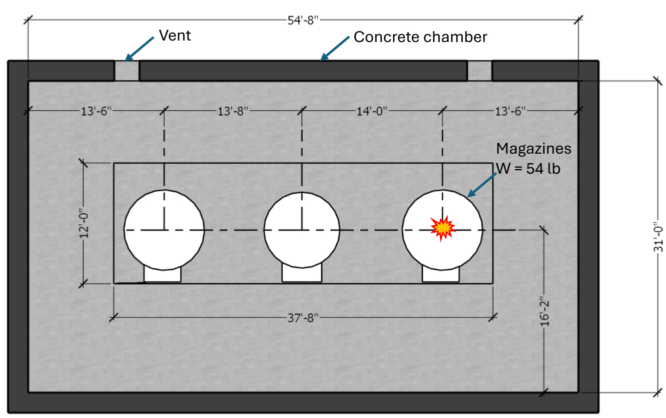

Figure 1. Floor plan of magazines inside chamber.

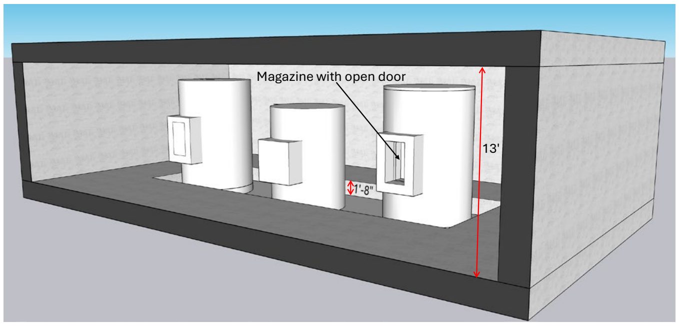

Figure 2. Isometric view of magazines in chamber.

Blast Loading

CFD Model Validation

Prediction of the pressures escaping the magazine and loading the chamber was performed with Viper::Blast (Viper) [2]. Viper is a high-fidelity CFD tool for simulating the airblast environment resulting from the detonation of high explosives and predicting the blast loads on complex structural geometry.

Viper had been validated in a previous study [6] against a set of two replicate experiments where a bare C4 charge was detonated in the center of a simple, square, non-responsive structure. Pressure histories were compared at eight different gauge locations within the room. An example comparison of histories between Viper and the tests are shown in Figure 3 for a single gauge. Viper was able to capture not only the initial (highest) shock but also several of the subsequent reflected pulses. However, by 10 ms the impulse has not kept up with that in the test and is visibly lower.

Key scalar metrics (peak pressure and impulse) were extracted and compared to the measurements to quantify the results. Peak shock pressure (P_r) from the first pulse, early-time impulse at 2 ms (i_2), and mid-time impulse at 15 ms (i_{15}) were determined at each of eight gauge location from both tests and averaged. The same parameters were extracted from the Viper results then normalized by the test value. This was done for for each metric. The individual gauge results were then averaged, with the mean values being plotted in Figure 4. In general, Viper slightly underpredicts shock pressure (by 10%) and impulse by a somewhat larger margin (20%). The underprediction of impulse 15 15 ms (i_{15}) is indicative of the gas pressure being a little low. The study demonstrates the calculational accuracy of Viper for that simple geometry and supports its use for the more complex geometry of current interest.

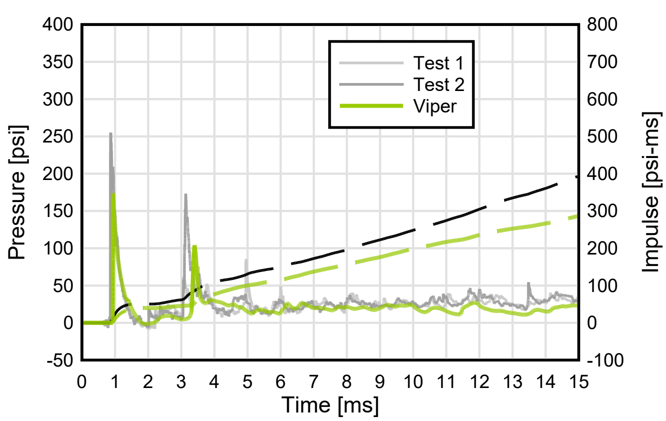

Figure 3. Viper pressure history comparison to tests.

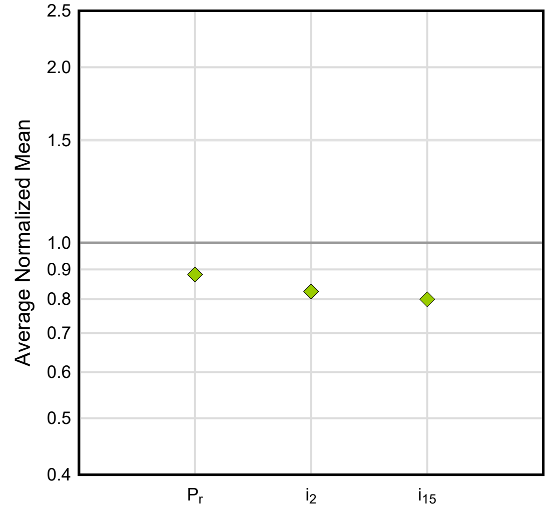

Figure 4. Viper average normalized mean for each key metric.

CFD Results

To optimize the Viper calculation, a 2-D axisymmetric model representing the interior volume of the magazine was first run to calculate the initial expansion of the shock wave. In this model, the high explosive was modeled as a sphere of TNT. The behavior of the TNT was controlled by the JWL equation of state. Parameters for the equation of state were taken from the LLNL Explosives Handbook [7]. The 2-D mesh had a very fine resolution with an element size of 0.1 inch by 0.1 inch. The shock wave was allowed to expand until it had nearly reached the wall of the magazine. At that point, due to the presence of the opening, the 2-D axisymmetric assumption is no longer valid and thus the pressures were mapped from the 2-D model to a full 3-D model before the simulation could continue.

Figure 5 shows the model with walls hidden to reveal the magazines within. The 3-D model of the chamber used 1-inch cubic elements to represent the air (in contrast to the 0.1-inch element size used within the magazine itself). Both magazines and the concrete chamber were treated as non-responding surfaces in the CFD model.

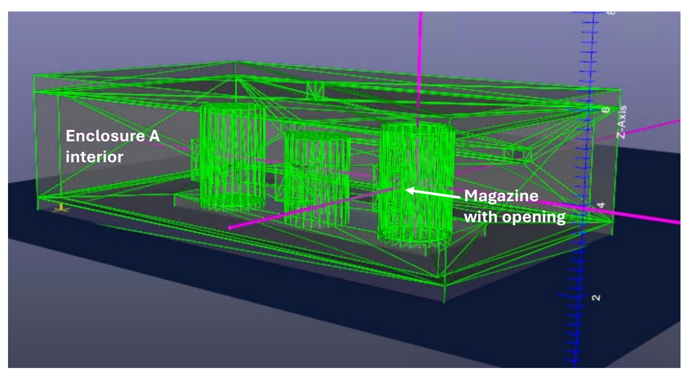

Figure 5. Model for chamber and magazines within.

A series of pressure fringe snapshots from the Viper simulation are presented in Figure 6. The view is taken as a plan section through the chamber. Eventually, as pressure propagates throughout the chamber, the outline of all three magazines can be seen; these are treated as rigid surfaces within the model. The images show the shock front exiting the magazine, reflecting off the front wall, and then generating numerous other reflections from the various internal surfaces of the room, as well as from the two other magazines.

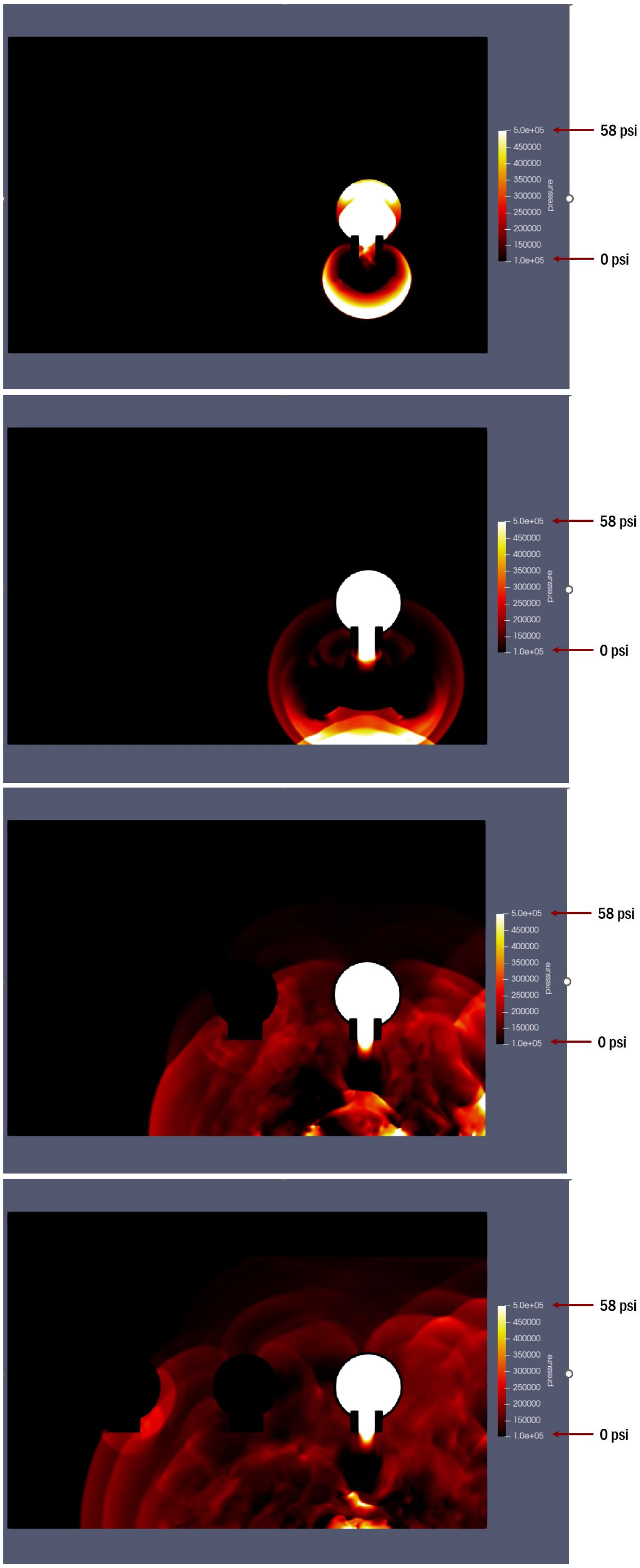

Figure 6. Pressure fringe snapshots from CFD analysis, taken along a horizontal plane through the mid-height of the chamber.

Pressure was measured at a number of locations within the chamber, but for this discussion the pressures (Figure 7) on the front wall directly in front of the opening of the magazine (red curve) and the roof (blue curve) will be of interest. These histories were conservatively used to design the concrete chamber wall and roof—conservative since the gauges represent the maximum values on the component of interest, while the actual pressure distribution will be non-uniform. The peak shock pressure at the roof is significantly lower than the front wall, which is expected given the front wall's position directly opposite the opening in the magazine.

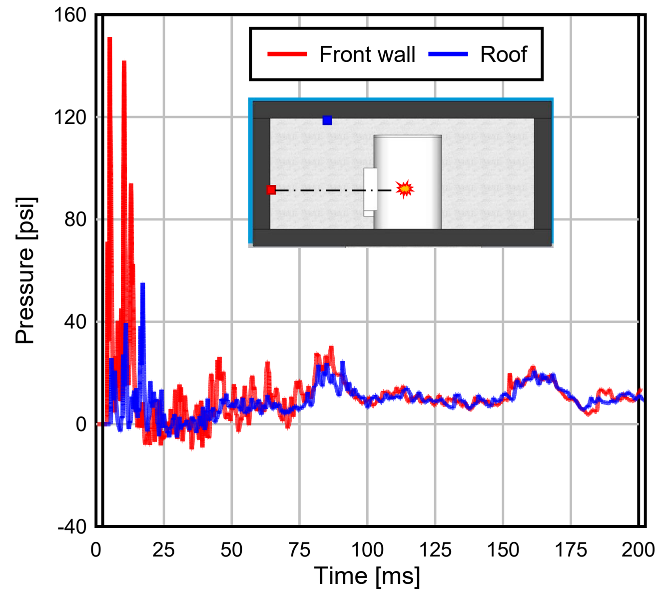

Figure 7. Viper pressure history at wall and roof of concrete chamber.

Multiple high shocks were observed due to the reflections coming from within the magazine as well as reflections from adjacent surfaces of the chamber. This can be observed at early-time in Figure 8. This is followed by a very long-lasting, late-time gas pressure phase with a magnitude of roughly 14 psi (Figure 9). To limit run time, the analysis was cut off at 400 ms, and a linear fit to the gas decay was performed; this linear fit was then extrapolated to define the gas pressure until the time of venting. The same was done for the roof.

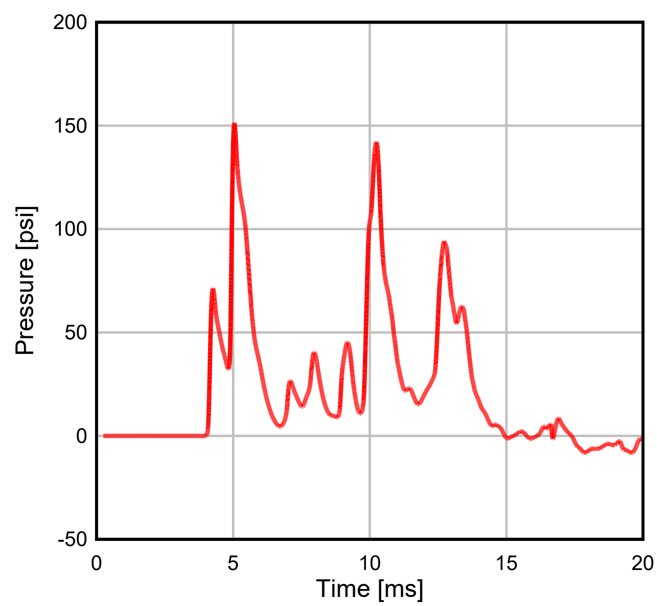

Figure 8. Early-time pressure history at front wall of concrete chamber.

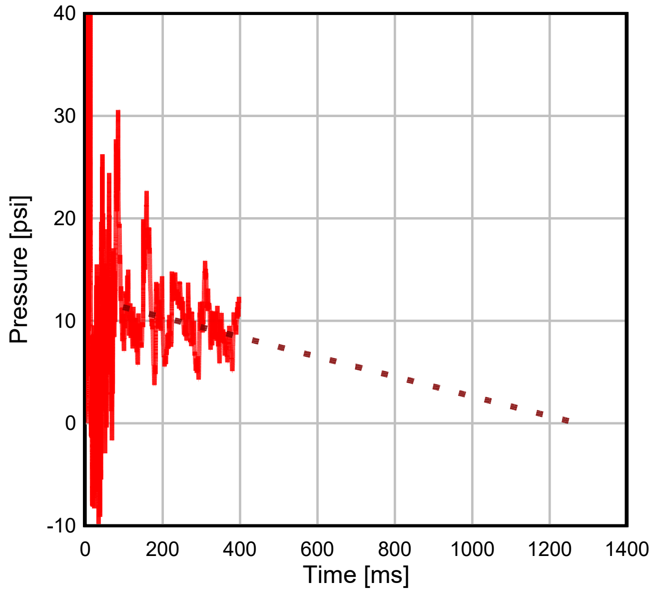

Figure 9. Late-time pressure history at front wall of concrete chamber.

CFD vs ConfinedBlast (SHOCK/FRANG)

If one were limited to using engineering methods for this problem, one certain simplifying assumptions would be required. One plausible approach would be to set up a model in the ConfinedBlast software with the same room dimensions and open vent sizes as the Viper model, but ignoring the pit in which the magazines sit and, more importantly, ignoring the presence of the magazine entirely (i.e., assuming the charge is openly located in the chamber). A schematic of the ConfinedBlast model is illustrated in Figure 10.

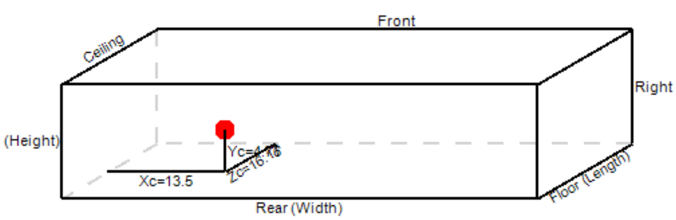

Figure 10. ConfinedBlast model.

Pressure was measured at the same two points (directly in front of the charge and on the roof). The shock pressure and gas pressure output were combined to obtain the bilinear pressure histories shown in Figure 11. The peak shock pressure is 156 psi for the wall and 296 psi for the roof. The peak gas pressure within the room is 29 psi and is completely vented by 1650 ms. Note that, where Viper predicted a higher pressure on the front wall than on the roof, ConfinedBlast predicts the reverse.

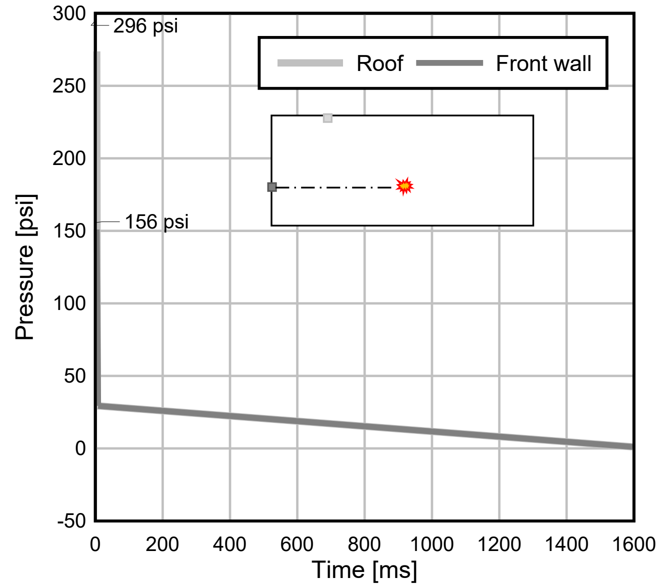

Figure 11. ConfinedBlast pressure history at wall and roof of concrete chamber.

The early-time pressure histories at the front wall are compared to what was obtained from Viper (Figure 12). The pressure is shown as solid lines while the impulse is shown in dashed lines. ConfinedBlast is unable to capture the multiple shock pulses like Viper does, but the peak shock pressure is almost identical for the two. Even though ConfinedBlast cannot capture the multiple peaks, it predicts a greater impulse than Viper, mainly because of the excessive gas pressure. Late-time pressure and impulse are provided in Figure 13 for the wall. The peak gas pressure and total impulse calculated using ConfinedBlast are approximately three times that of the Viper output.

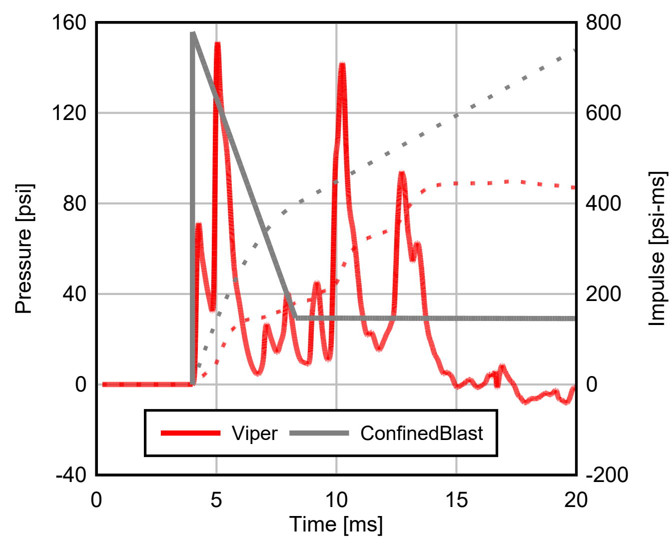

Figure 12. Early-time pressure and impulse comparison for front wall.

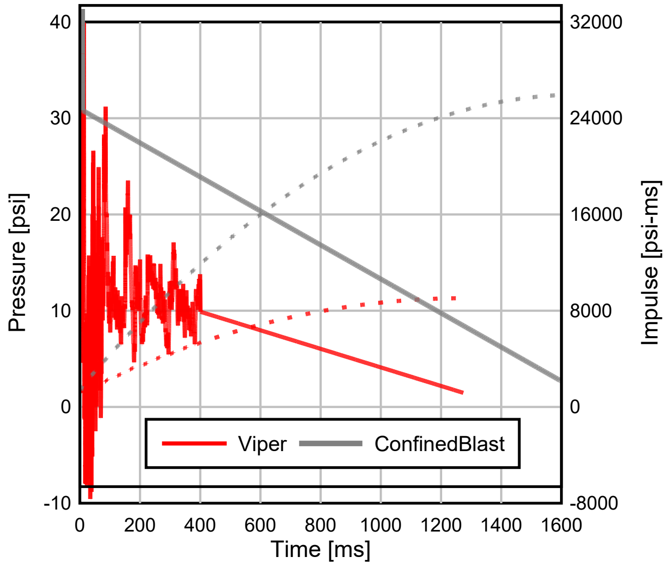

Figure 13. Late-time pressure and impulse comparison for front wall.

For the roof, the peak shock pressure from ConfinedBlast is an order of magnitude greater than that from Viper as can be seen in Figure 14. This results from the simplification that ConfinedBlast does not account for any confinement of the charge within the magazine. Once again, the peak gas pressure and total impulse from ConfinedBlast are around three times those from Viper (Figure 15).

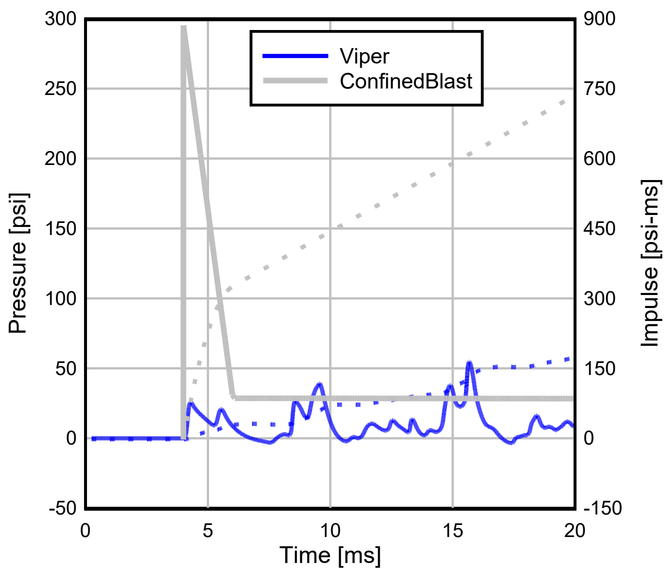

Figure 14. Early-time pressure and impulse comparison for roof.

The primary observations from these comparisons are that, first, ConfinedBlast is extremely conservative in its gas pressure prediction, with total late-time impulse being high by a factor of 3. Yes, Viper was seen to underpredict late-time impulse by about 20% when compared to tests, but the FRANG model's gas pressure is far higher than that margin, and the time to full venting also seems rather too long. These are well-known features of FRANG to those who have been accustomed to using its output as design loads, and been obliged to accept the resulting overdesign of facilities for these loads.

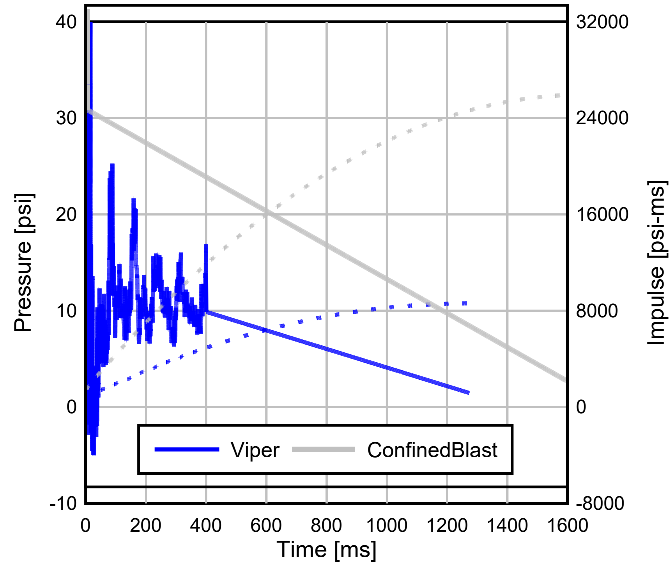

Figure 15. Late-time pressure and impulse comparison for roof.

Chamber Design Response

For our facility, the concrete wall and roof of the containment structure were designed using the blast loads from Viper. The selected design consisted of a 20-inch-thick wall with #5 reinforcement at 8 inches on center, at each face, spanning vertically. This design was obtained using single degree of freedom (SDOF) analysis to calculate response and comparing the support rotation to acceptable limits provided by UFC ($\theta \leq 2°$). The wall and roof responses were 0.2 and 1.8°, respectively; the design was thus controlled by the roof.

To evaluate the impact of the conservatism inserted into the design process by ConfinedBlast (or conversely, eliminated from the design process by Viper), the dynamic response of those same components were re-calculated, this tie using the ConfinedBlast loads shown earlier. The results are summarized in Table 1. The wall response increased five times but remained below the criterion of 2°; thus no change to the wall design would be needed. But the roof response is indicative of catastrophic failure, meaning that the roof would have to be redesigned with a greater thickness of concrete and additional steel reinforcement.

Table 1. Summary of wall and roof responses to blast loading.

Component	Support Rotation [°]	
	Viper	ConfinedBlast
Wall	0.2	1.0
Roof	1.8	>>12

Leakage Pressure Method

An alternative to using ConfinedBlast, if one is restricted to engineering methods to solve this problem, is to use the curves for leakage pressure found in UFC. A four-wall cubicle (Figure 16) is similar to the magazine in our design since it has one partial opening at one side, just like the magazine door. One could use the "front" direction curves to obtain the front wall pressure, and "side" curves for the roof pressure, as illustrated in Figure 17.

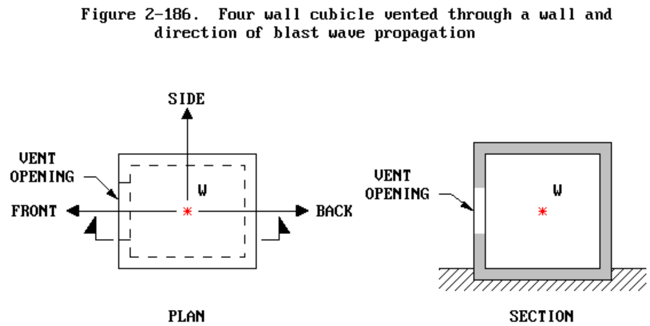

Figure 16. Four-wall cubicle definition from UFC 3-340-02.

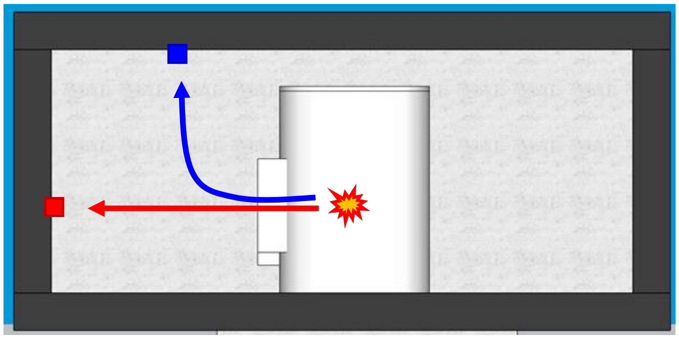
Figure 17. Front and side orientations as used with leakage pressure curves.

Using the appropriate curves from UFC, the *incident* pressure and impulse at the appropriate standoff were obtained. These were then converted to reflected pressure and impulse, since the wall and roof of the chamber provide reflecting surfaces.

Comparisons showing early-time histories from Viper, ConfinedBlast, and UFC blast leakage are presented in Figure 18 and Figure 19. Note that, were we to use the blast leakage method, we would need to combine its triangular waveform with a second triangle representing gas pressure, which would be the one from FRANG (ConfinedBlast), but for the present, our comments will be restricted to the early-time portion of the waveforms.

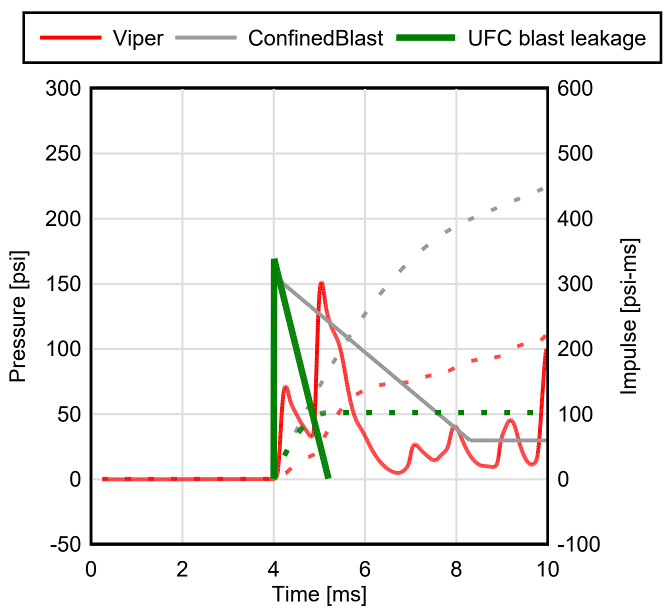

Figure 18. Pressure history comparison at front wall.

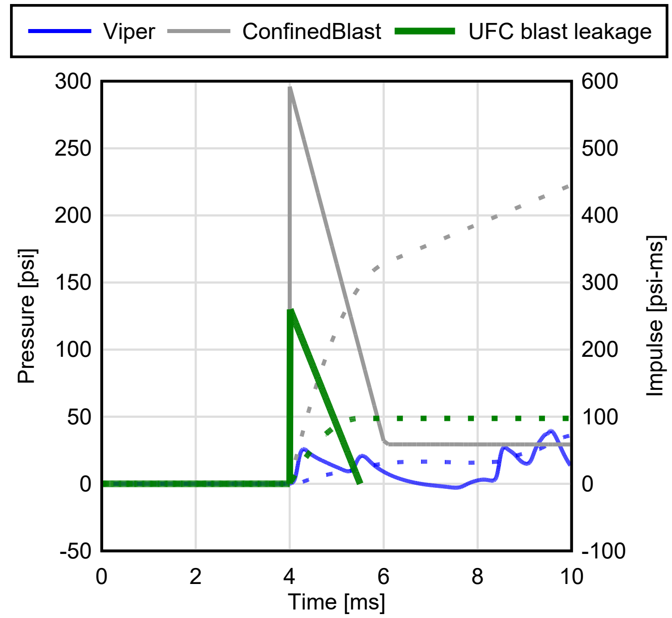

Figure 19. Pressure history comparison at roof.

At the front wall, the blast leakage does a creditable job in comparing to Viper, and in fact all three methods produce a very good match in peak pressure. However, the duration of the UFC shock pulse is rather too short, as may be expected since the leakage curves are meant to be applied in the open air and do not account for additional reflections from other surfaces.

At the roof, the leakage method is still high relative to Viper, but it is not as egregiously high as ConfinedBlast. The duration is moderate, and the impulse at the end of the leakage pulse is about three times higher than that from Viper. Overall, though, this is an improvement over ConfinedBlast.

Summary/Conclusions

From these results, the following conclusions are drawn:

1. Using a validated, commercially available CFD code provides a useful and practical method of calculating blast loads from complex geometries such as those where a magazine vents into a confined space.
2. Engineering methods could be substituted for the high-fidelity model, but only at the cost of significantly greater conservatism in the design blast loads. In the present instance, this increased conservatism factor ranged from 2 to about 10.
3. Of the two engineering methods attempted, ConfinedBlast proved to be the more conservative. The gas pressure waveform in particular is higher in magnitude and longer in duration than that calculated by the CFD code. The leakage pressure curves performed reasonably well for the front wall but were still several times too high (in early-time shock) at the roof.
4. When applied to the design of the concrete structure, these overly conservative loads lead to either (*a*) greater response of a given design, and/or (*b*) requirements for heavier construction to meet response criteria. The latter results in unnecessarily high construction costs that, in many cases, more than offset the added analytical cost of high-fidelity modeling.

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