FRIDAM Method to Calculate Blast Propagation, Building Damage, and Injuries from Small Internal Explosions

Chuck Oswald
Protection Engineering Consultants, USA  coswald@protection-consultants.com

Abstract
Internal explosions cause a shock wave and an overall quasistatic, or fill pressure in the explosion room. The shock wave and fill pressure will propagate outside the explosion room through any openings or failing walls. There has been much study and numerous fast-running methods developed to predict the shock pressure histories and quasistatic pressures in the explosion room. These methods have evolved from simple, single room codes developed for explosive safety design work into larger, multi-room codes, such as the BlastX [1] and VAPO [2] codes, which calculate blast loads for a fixed multi-room geometry. There has been very limited development of fast-running codes that integrate blast load propagation and structural response to calculate blast propagation outside the explosion room through failing walls and doors. Recently, the Defense Threat Reduction Agency (DTRA) and the Air Force Research Laboratory (AFRL) in the U.S. and the German government have sponsored test programs to investigate internal blast propagation through failing walls. Also, DTRA has sponsored development of FRIDAM (Fast-Running Internal Damage Assessment Methodology) to predict blast pressures, building damage, and occupant injuries in buildings from internal explosions. FRIDAM is a semi-empirical approach with coupled blast load and structural response calculations that has been developed using the test data from thirty-one internal detonation tests sponsored by DTRA and AFRL with charge weights up to 25 lb. (11.4 kg) TNT in multi-room test structures with internal walls that have typical building construction.

TEST DATA
Three test series have been conducted by DTRA in multiple room concrete test structures. Two test series were conducted in the Distinct Cobra (DC) test structure; Series I with three identical test rooms all in-line with the explosion room [3], and Series II with additional test rooms and non-uniform room dimensions [4]. The test structures used for the DCI and DCII tests series are shown in Figure 1 and Figure 2, respectively. The basic internal wall configuration in Figure 2 was modified in several of the DCII tests to include long hallways, large L-shaped rooms, and explosion rooms at different locations in the test structure. A total of 16 tests were conducted in Series I and 9 tests in Series II. The charge weights ranged from 1 lb. (0.45 kg) to 5 lb. (2.3 kg) equivalent TNT and the internal walls were either “heavy walls”, which were primarily 6 inch thick unreinforced concrete masonry unit (CMU) walls weighing 30 lb/ft² (146 kg/m²), or “light walls”, which were 4 inch thick light stud walls with 0.5 inch (12.5 mm) thick gypsum board on each side weighing 3.5 lb/ft² (17 kg/m²). Based on this selection of test walls and an assumption that they represent the large majority of internal walls in typical buildings, the methodology in FRIDAM categorizes internal walls as either “heavy” or “light” walls and some of the empirical parameters for blast load calculations are based on these wall categories. Many of the test walls had openings, including wood and steel doors, uncovered door openings, and uncovered plenum space openings at the top of the test walls.

The third test series was conducted in the Distinct Hornet (DH) test structure shown in Figure 3 [5]. These tests had larger charge weights of 10 lb. (4.5 kg) and 25 lb. (11.4 kg) TNT and only one test room. The same test wall types from the DC test series were used, including two walls with small uncovered openings. In addition to these tests, DTRA sponsored one additional internal detonation test with a 25 lb. (11.4 kg) TNT charge weight in AFRL’s ReUsable Test (RUT) structure with 9 test rooms. This test had a combination of 8 inch lightly reinforced CMU test walls separating some test rooms, including those closest to the charge, and open doorways between other test rooms. The measured blast loads and test wall response from these thirty-one internal detonation tests were used to develop FRIDAM. After this development was almost complete, AFRL provided data from five internal detonation tests they conducted with the German government as part of the MOUT test series [6]. These tests had an explosion room and one test room divided by test walls including thick adobe walls, CMU walls, and light stud walls. The TNT equivalent charge weights ranged from 5.7 lbs. (2.6 kg) to 22 lbs. (10 kg).

Many of these internal detonation tests were conducted at small scaled standoffs causing breaching of the test wall in the explosion room (Wall 1). Wall 1 failed catastrophically due to a combination of shock and quasistatic pressures in the explosion room in every test except one. The large majority of all test walls failed. The failure
mechanisms ranged from breakup of the test wall into very small pieces to walls that failed in flexural response and connection failure. All light metal stud walls failed, where many of these walls furthest from the explosion room failed at their connections to the floor and ceiling with very little wall breakup. Nearly all of these tests had explosion venting to the atmosphere through an uncovered opening in the explosion room and an open or failed door opening in at least one test room. The loading densities in the explosion room ranged from 0.0004 lb/ft\(^3\) (.0064 kg/m\(^3\)) to 0.005 lb/ft\(^3\) (.08 kg/m\(^3\)) in the DC tests and from 0.012 lb/ft\(^3\) (.19 kg/m\(^3\)) to 0.03 lb/ft\(^3\) (.48 kg/m\(^3\)) in the DH and RUT tests.

**Figure 1. Plan View of DCI Test Structure**

**Figure 2. Plan View of DCII Series Test Setup**

**Figure 3. DH Series Test Setup**

**METHODOLOGY AND COMPARISON TO TEST DATA**

FRIDAM calculates the blast pressures and wall response from an internal detonation with a time stepping method starting in the explosion room [7]. The peak quasistatic pressure and the average shock pressure history are calculated on all the walls, including a fictitious very early time pulse from a cased weapon, if applicable, at each gage point with an impulse equal to that from surrounding fragment impacts. The shock pressure, and quasistatic pressure considering venting through uncovered openings and any failed wall openings, are input blast loads into
single-degree-of-freedom (SDOF) analyses of each wall at each time step. After any calculated wall response exceeds response criteria from PDC-TR 06-08 Rev. 1 [8] for Heavy damage, walls are considered to be failed. Doors are assumed to fail when the net pressure exceeds limit values based on measured loads causing door failures in static tests. Wall and door movement after failure is calculated assuming they are rigid bodies accelerated by the net pressure acting calculated for the rooms on both sides. A flow area through each failed wall and a volume compression of the room behind each failed wall are calculated using semi-empirical equations. The calculated change in air mass and volume in each room at each time step, assuming they are adiabatic, are used to calculate the new overall room fill pressure. The net fill pressure is used as the applied blast load on each wall at each time step after blast pressure propagates out of the explosion wall. If fill pressure is underpredicted or overpredicted in a given time step, the wall movement and mass flow in the next time step will partially offset this by being larger, or smaller, respectively, than it would be if the calculation were more accurate in the previous time step. This is important because it allows fill pressures to be calculated with sufficient accuracy even though simplified methodologies are used to calculate the complex behavior of mass flow and room volume compression due to failing walls.

Empirically-based equations are used to calculate the shock propagation through failed walls. A separate semi-empirical approach is used to calculate shock propagation through uncovered wall openings from the explosion room based on the effective yield method [9]. The method has been modified and extended in FRIDAM to apply to image charges representing shock wave reflections in the explosion room and in adjacent rooms. This method is also used to calculate shock propagation through covered openings (e.g. closed doors) with a semi-empirical delay time to account for the time required for the door to fail and move far enough to provide a full opening area for shock propagation. The total calculated blast pressure at each point in each room is the sum of the calculated full pressure plus shock pressure. The response of walls outside the explosion room is based only on the calculated net fill pressure because trial calculations including calculated shock pressures did not correlate as well to test data. This is due, in large part, to the fact that the impulse from fill pressure in rooms outside the explosion room is much greater than that from shock pressure and the wall response is more sensitive to impulse than peak pressure. Also, the shock pressure calculations in FRIDAM may have more error than the fill pressure calculations.

The fill pressure in all rooms, including the explosion room, is calculated using Equation 1 based on the adiabatic change in air mass and volume of each room. The fill pressure in the explosion room, which is equal to the peak quasistatic pressure at time zero, decreases with time while the fill pressures in other rooms increase. Late in time, the fill pressures in all rooms with failed walls or openings tend to equilibrate. The total change in mass in each room is calculated at each time step with Equation 2, which is a theoretically-based equation for flow of an ideal gas through a nozzle. The flow area in Equation 2 is calculated for each wall at each time step with Equation 3, which is based on the calculated rigid body wall movement after failure and empirical factors.

\[
\frac{P(t)}{P_o} = \left( \frac{M(t)}{M_o} \right)^{1.4} \left( \frac{V_e}{V_o(t)} \right)^{1.4}
\]  

where:

- \( P(t) \) = Room pressure at time \( t \)
- \( P_o \) = Room pressure at time zero (zero in all rooms except peak quasistatic pressure in explosion room)
- \( M(t) \) = Mass of air in room based on summed mass flow through all failing walls of room
- \( M_o \) = Mass of air in room at time zero (plus mass of explosive in explosion room)
- \( V_e(t) \) = Effective volume of room (i.e. volume within room that is compressed/expanded by “effective” wall movement)
- \( V_o \) = Volume of room at time zero

\[
\Delta M(t) = \frac{dM(t)}{dt} \sum A_i(t)
\]

\[
\frac{dM(t)}{dt} = S \left[ \gamma - 7 \rho_i \rho \left( \frac{P_2}{P} \right)^{1.42} \right] \left( \frac{P_2}{P} \right)^{1.71} \leq \frac{dM(t)}{dt} \quad \text{for} \quad \gamma = 1.4
\]
where:
\[ \Delta M(t) = \text{total mass that flows through a failed wall surface during time step at time } t \]
\[ \frac{dM(t)}{dt} = \text{mass flow rate through openings a given wall surface from Room 1 into Room 2} \]
\[ \frac{dM_c(t)}{dt} = \text{mass flowing through openings with choked flow} \]
\[ S = \text{nozzle coefficient} = 0.62 \text{ for rough opening with no streamlining} \]
\[ P_1 = \text{higher room pressure acting on wall at time } t \]
\[ P_2 = \text{lower room pressure acting on opposite side of wall at time } t \]
\[ \rho_1 = \text{density in Room 1 (room with higher pressure) at time } t \]
\[ A_o(t) = \text{total area of opening(s) through wall surface for at time } t \text{ (see Equation 3)} \]
\[ \gamma = \frac{\text{ratio of specific heats}}{\text{for air}} = 1.4 \]

\[ A(t) = A_B + A_u(t) + A_p(t) + A_{wo} \leq A_{wo} \quad (3) \]

where:
\[ A_B = \text{breach area} \]
\[ A_u = \text{uncovered opening area in wall} \]
\[ A_o(t) = \text{flow area through failed interior wall debris} \]
\[ A_p(t) = \text{flow area around failed door or wall with perimeter venting} \]
\[ A_{wo} = \text{original wall area before failure} \]

The wall breach area in Equation 3, \( A_B \), is calculated with empirically derived equations only for walls in the explosion room where the explosive is close enough to the wall to cause a “breached” area to fail significantly before the rest of the wall. The flow area through failed wall debris in Equation 3, \( A_o(t) \), is based on a surface area for the wall debris that is determined from the calculated wall displacement after failure modified by an empirical factor \( K_d \) and an assumed, simplified shape function of the debris. The flow area is the difference between the surface area of the wall debris and the original wall area. The assumed surface areas, which depend on the wall boundary conditions, are illustrated in Figure 4. Debris from walls with flexural failure are assumed to have the first two shape functions, where the surface area is a function of the calculated displacement of the failed wall, \( d(t) \), and \( K_d \). \( K_d \) is a reduction factor that only applies to heavy walls in the explosion room that are overwhelmed by the blast load. The debris at the edges for these walls can have nearly the same displacement as the center of the wall. Comparisons to internal test data indicate that the wall displacement near the center is large enough compared to the edges such that the surface area for mass flow can be calculated assuming \( K_d \) is equal to 1.0 other cases. The last shape in Figure 4 is used for failed doors and exterior walls, where the primary flow area is around the perimeter. Figure 5 shows how the flow area is related to wall displacement for different assumed shape functions in Figure 4, plus the case where to wall tips over (i.e. all wall movement is based on rotation about the bottom support).

**Figure 4. Simplified Wall Openings for Failing Walls**
Figure 5. Opening Flow Area Ratio vs. Scaled Failed Wall Deflection for Different Failed Wall Debris Shapes

The effective room volume in Equation 1, $V_e(t)$, is the sum of the effective volume changes at each time step calculated with Equation 4. The volume change is based on “effective” incremental displacements equal to the total calculated incremental wall displacements multiplied by $K(t)$, which varies nonlinearly from 1.0 to zero as the total wall displacement after failure increases. $K(t)$ accounts for a failed wall initially acting as a nearly perfect piston to compress the room volume and cause pressure change (i.e. $K(t) = 1.0$), and then becoming a less effective piston as the sizes of openings in the failed wall increase as it displaces (i.e. $0 \geq K(t) > 1.0$). $K(t)$ is a function of the empirical factor $K'$, which is a function of wall type (i.e. heavy or light internal wall or exterior wall) and the explosive charge weight divided the volume of the explosion room and rooms between the wall of interest and explosion room. The detailed equations for $K'$ are presented elsewhere [7]. $K'$ varies from 1.0, for cases where the failed wall is a more effective piston (i.e. light walls far from the explosion room and heavy walls near the explosion room), to 0.05 for cases where the wall is not an effective piston (i.e. light walls in the explosion room or heavy walls far from the explosion room that tend fall down nearly in place). A very low value of $K'$ is also used for exterior walls moving into the atmosphere. Figure 5 shows how $K(t)$ and the summed effective displacement of a wall are affected by the empirical factor $K'$. The right side plot in Figure 5 also shows that the summed effective wall displacement, which causes calculated compression of the room volume, has a maximum value of 67% of $H'$.

$$\Delta V_e(t) = \sum \Delta d_e(t) A_w$$

where $\Delta d_e(t) = \Delta d(t) K(t)$

$$K(t) = \left[ 1 - \left( \frac{d(t)}{K' L'} \right)^2 \right] \geq 0$$

where:
- $\Delta V(t)$ = room volume change during time step based on summed effective incremental displacements of all walls of room
- $\Delta d_e(t)$ = “effective” incremental displacement of wall during time step
- $\Delta d(t)$ = total incremental displacement of failed wall during time step
- $d(t)$ = total rigid body displacement of failed wall at time step
- $K(t)$ = fraction of incremental wall displacement calculated causing room volume change (equal to 1.0 at time zero and decreasing to zero when $d(t)=K' L'$)
- $K'$ = effective factor based on wall type (light or heavy) and explosive room loading density
- $H'$ = characteristic length based on largest dimension of failed wall, but not larger than room dimension behind failing wall
- $A_w$ = original wall area
Measured blast loads from the internal detonation tests showed that there was shock propagation from the explosion room through failing heavy and light walls and through wall openings in addition to fill pressures. Significant shock pulses through failed heavy walls of the explosion room were only measured in tests rooms adjacent to the explosion room. These shock loads are calculated in FRIDAM as a single pulse with a right triangular shape that “leaks” through the failed heavy wall at a relatively late time (i.e. after the fill pressure has begun). The peak pressure, duration, and leakage time of the shock pulse through failed heavy walls were determined for each relevant internal detonation test by fitting these three parameters to the measured blast loads and then correlating the fitted parameters for each relevant test to the loading density in the explosion room, whether the charge breached the wall, the number of failing walls in the explosion room, and the size of the adjacent room in each test. The curve-fit equations of these correlations are used in FRIDAM to calculate the parameters defining the shock pulse in the room adjacent to the explosion room through a failed heavy wall. This approach was generally used to develop all the empirical factors in FRIDAM. Figure 7 shows an example of the curve-fit equation used in FRIDAM to calculate the baseline peak pressure of the shock pulse from the loading density in the explosion room scaled by the weight of the failing heavy wall relative to the baseline weight in most of the internal detonation tests (i.e. 30 lb/ft$^2$ or 146 kg/m$^2$).

Figure 8 and Figure 9 show comparisons of blast loads calculated with FRIDAM and measured blast loads in test rooms from Test DC 11 and the RUT test, respectively. The DC test has three test rooms in-line with the explosion room all separated by 6 inch (152 mm) ungrouted CMU walls. The RUT test has 8 inch (203 mm), light reinforced CMU walls separating some test rooms near the charge and uncovered openings into other test rooms (total of 9 test rooms).

Figure 7. Curve-fit of Measured Peak Pressure Parameter ($P'$) to Scaled Loading Density in Explosion Room

The shock pressure from the explosion room through a failing light wall is idealized in FRIDAM as a shock wave in the adjacent room caused by the sudden velocity of the failed wall acting as a piston. The velocity of the failed light wall is equal to the calculated shock impulse on the wall from the explosive charge divided by the wall’s mass per unit area. The peak shock pressure and duration of this square shock wave with a linear decay at the end of its...
duration are calculated with equations from one-dimensional shock tube theory based on the calculated wall failure velocity. This theoretical shock wave is used with some empirical factors to represent the shock wave from the explosion room through failed light walls in FRIDAM. In contrast to failing heavy walls, the calculated shock load from a failed light wall arrives in the adjacent room before the fill pressure and it propagates into many rooms surrounding the explosion room until the ratio of the explosive charge weight divided by the volume of rooms with the propagated shock exceeds an empirical limit value.

Also, a separate, additional late time, high pressure shock pulse was measured in the room adjacent to the explosion room in almost all of the DC and DH tests with light test walls. This shock pressure pulse was attributed to the fact the explosion rooms had heavy concrete construction that confined the shock wave that initially propagated away from the test wall and redirected this shock back into, and through, the test wall into the test room adjacent to the explosion room. This shock pulse would not necessarily occur in a typical building where the explosion room is not built as a reusable test room, but it was important to have an empirical method to calculate this type of shock load in order to more closely predict the measured blast loads in the DC and DH tests. Therefore, a prediction equation was developed to calculate a right triangular shaped shock history from a free-field, surface burst with an effective charge weight that was increased to account for the confinement of the explosion room and a standoff that included twice the length of the explosion room plus the distance from the explosion room wall to the gage in the test room of interest. Figure 10 shows comparisons of blast loads calculated with FRIDAM at five gages in the test room of Test DH21, which had a light test wall, and measured blast loads at these gages. The gages are shown in the legend of Figure 10 in the order of their distance from the failed test wall. FRIDAM calculates an initial shock wave from the light wall failure that propagates the length of the test room, past each gage, and reflects. It also calculates a late time right triangular shock pulse from the confined shock wave in the explosion room and fill pressure.

The largest shock loads outside the explosion room in the internal detonation tests were measured behind test walls with uncovered openings and initially covered (i.e. with a failing door) openings. These shock loads are calculated in FRIDAM with an “effective yield”, which is a reduced charge weight to account for the percentage of the total charge energy that is transmitted through an opening [9]. This method is used to calculate shock load through an opening in VAPO and BlastX only for the incident shock wave without any reflections of the transmitted shock within the room of interest. This approach did not calculate the many shock pulses that were measured through uncovered openings at gages in the internal detonation tests. Therefore, the effective yield approach was extended in FRIDAM to be applied to shock reflections within the explosion room (i.e. an effective yield was calculated for each image charge representing a reflected shock wave in the explosion room) and image charges were created in the room of interest for the transmitted shock pulses to blast load from reflections of the transmitted shock waves in the room of interest. The calculated shock pulses were added using the non-linear Lamb shock additional rules used in BlastX at the gage point in the room of interest. Additionally, it was necessary to delete the relatively large calculated negative phase portions of each shock pulse before adding the shock pulses. This extension of the effective yield approach calculates shock loads that are very much better than the original approach based only on the incident shock wave, but this method can be improved with further study. Detailed equations for all shock load calculations in FRIDAM are presented elsewhere [7].

The measured blast loads through heavy test walls with failed doors showed that a significant part of shock load predicted assuming an uncovered door opening was measured. Therefore, the prediction method in FRIDAM for covered openings is based on calculating the shock load at the gage point assuming the opening is uncovered and then deleting an initial portion of the calculated shock load based on the calculated failure time of the door. When the room of interest is separate from the explosion room by two heavy walls with failing doors, less shock load is deleted because much of the shock that would arrive before the second door failure is only delayed by the door failure, rather than redirected so that it does not go through the door opening. Shock loads are not calculated in FRIDAM through doors in light walls because doors fail at approximately the same time as light walls. Figure 11 shows a comparison of measured blast loads and blast loads calculated through failed doors (in test walls into Rooms 1 and 2) in Test DC14. The measured pressures histories from all the available internal detonation tests have been compared to calculated pressure histories with FRIDAM [7]. Table 1 shows a summary of the ratios of peak calculated to measured blast load and wall response parameters from these tests.

Injuries from blunt trauma caused by failing walls in rooms outside the explosion room are calculated in FRIDAM using a method adopted from BICADS methodology [10]. The maximum calculated velocity of each failed wall in the building is multiplied by the wall mass per unit area to calculate the maximum momentum of the failed wall.
debris. Empirical correlations were developed separately for heavy walls (masonry, brick) and light walls (stud walls with gypsum board, wood walls) between momentum of wall debris and four injury levels using data from the London Blitz and the U.S. atomic bomb attacks on Japan during World War II, the Khobar Towers and Murrah Building bombings, and blast tests where ATDs (Anthropomorphic Test Devices) were subjected to failed wall debris. These correlations determine the percentage of exposed room occupants with each of four injury levels from each failed wall and door (i.e. injury source) thrown into the room. The percentages of room occupants with each injury level are determined by summing the injury effects from each injury sources assuming they are independent events and “removing” the percentage of room occupants with more severe injury levels before summing to determine less severe injury levels.

Table 1. Average Ratios of Calculated to Measured Peak Values from Internal Detonation Tests

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Compared Measurements¹</th>
<th>Peak Pressure Ratios (P_{calc}/P_{meas.})</th>
<th>Peak Impulse Ratios (I_{calc}/I_{meas.})</th>
<th>Peak Velocity Ratios (V_{calc}/V_{meas.})</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCI</td>
<td>45</td>
<td>1.0</td>
<td>1.2</td>
<td>0.8</td>
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<tr>
<td>DCII</td>
<td>60</td>
<td>1.05</td>
<td>1.07</td>
<td>0.8</td>
</tr>
<tr>
<td>DH</td>
<td>50</td>
<td>1.06</td>
<td>1.04</td>
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<tr>
<td>MOUT</td>
<td>5</td>
<td>0.87</td>
<td>1.0</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Note 1: Number of compared blast load measurements

SUMMARY

This paper describes FRIDAM, which is a fast-running, time-stepping methodology that predicts blast loads, wall response, and injuries from an internal explosion. This method uses a SDOF-based approach to calculate wall response and failure and a combination of a simplified first-principles based equations and empirical factors to calculate blast loads in the explosion room and blast load propagation outside the explosion room into surrounding rooms. This method is limited to a maximum charge weight of 30 lbs. (13.6 kg) TNT. It was developed using data from thirty-one internal detonation tests, which had a maximum charge weight of 25 lbs. (11.4 kg) TNT. Calculated blast loads and wall response with FRIDAM compare well to this test data. Calculated blast loads and wall debris velocities with FRIDAM also compare well to test data from the MOUT internal detonation tests, which were only used to develop a small part of the FRIDAM methodology related to test wall weights different than those used in the other internal detonation tests.

REFERENCES


ACKNOWLEDGEMENT

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Figure 8. Predicted and Measured Pressure Histories in Test Rooms with Heavy Walls For Test DC11 (5 lb. TNT)

Figure 9. Predicted and Measured Pressure Histories in Test Rooms with Heavy Walls For RUT Test (25 lb. TNT)

Distribution A: For Public Release
Figure 10. Predicted and Measured Pressure Histories at Gages in Test Room Behind Failing Light Wall in Test DH21 (10 lb. TNT)

Figure 11. Predicted and Measured Pressure Histories in Test Rooms with Steel Doors in Heavy Walls For Test DC14 (2 lb. TNT)