A Fast Running Model for Accurate Time-Dependent Post-Shock Gas Flow

Keywords: Confined Airblast, Explosive effects, Blast Model, Numerical Analysis

Pietro Gheorghiu[1], Joseph Abraham[2], Casey Meakin[3], Simon Fu[4]

[1] Karagozian & Case, Inc., 700 N. Brand Blvd., Suite 700, Glendale, CA 91203, USA (gheorghiu@kcse.com)

[2] Karagozian & Case, Inc., 700 N. Brand Blvd., Suite 700, Glendale, CA 91203, USA (abraham@kcse.com)

[3] Karagozian & Case, Inc., 700 N. Brand Blvd., Suite 700, Glendale, CA 91203, USA (meakin@kcse.com)

[4] Karagozian & Case, Inc., 700 N. Brand Blvd., Suite 700, Glendale, CA 91203, USA (simon@kcse.com)

Abstract

The gas pressure and heat resulting from a munition detonated within a structure often contributes significantly to the damage imparted to a target. Therefore, an accurate prediction of weapon effects under these circumstances requires modeling the pressure and thermal loads acting on structural members which will depend on the process by which gas pressure is equilibrated throughout the interior of the structure by sound waves and advection as well as conductive and radiative heat transport. Although fast-running models (FRMs) exist to treat these processes, their formulations are incomplete. A common approach involves modeling the interior structure of buildings as a network of locally equilibrated rooms or compartments connected by vents (e.g., ducts, open doorways, breach holes, etc.) through which gases can flow and pressure can eventually equilibrate globally. While this approach is computationally efficient and allows for various levels of fidelity with regards to calculating the flow rate driven by differential pressure between rooms, the assumption of instantaneous equilibration within a room or compartment can significantly undermine accuracy for a large number of scenarios of interest. Examples which are poorly handled by these approximations include breach holes which span a significant fraction of a wall as well as structures containing large rooms or hallways for which the sound crossing time can be significant. In order to address these issues, a mass, energy, and momentum conserving gas-flow model has been developed which employs a set of orthogonal planforms to represent sub-room structure and provides a means to capture the finite sound and gas flow speeds that drive equilibration. The model is fast running, unconditionally stable, and employs an implicit integration scheme to handle the stiff equation set. The model can evaluate complex high explosive compositions, afterburn energy, dynamic energy release rates, dynamic breach/vent openings, dynamic increases in room volume, and room vent activation based on sound crossing time. Results are provided which demonstrate the calculational efficiency of the model as well as

improvements in accuracy and precision over locally equilibrated models through comparisons with numerical and experimental data.

Introduction

Existing blast engineering tools or FRMs can be used to approximate blast loads inside of a structure. Typical blast calculations with these engineering tools require as little as a few minutes to setup and execute a problem of interest. This computational efficiency is achieved by leveraging reasonable engineering assumptions which are used to derive the formulations implemented in these FRMs. Due to the engineering assumptions that undergird these models, each of these FRMs has limitations and a parameter space that the software analyst must observe to obtain accurate results.

Common tools and methods used in the blast community to estimate the gas pressure in confined structures include: the UFC manual tables (UFC 3-340-02 2008), ConWep (Defense 1998), BlastX (Britt 2001), and MBLM (Pierce and Donovan 2012).

BlastX and MBLM provide an ability to define complex multi-room structures with consideration of venting at each of the room connections (i.e. doors, windows, etc.). Tools such as BlastX and MBLM typically consider conservation of mass and energy to estimate the fluid flow through a room connection or outlet but not conservation of momentum. Instead of solving the momentum equations, well known equations for nozzle flow are used to approximate the fluid flow between each room. While this approach works considerably well for scenarios where a vent is sufficiently small relative to the size of the room to be approximated as a nozzle, there are scenarios commonly encountered in weaponeering and explosive safety applications where this assumption does not hold true. For example, in many scenarios, a long hallway or an L-shaped room may require the analyst to parse the structure into two rooms which are connected by an opening of the same size as the entire cross-section of the room. Utilizing the assumption of nozzle flow for these scenarios is not appropriate but this approach is often used by analysts due to the lack of other suitable approaches in the available engineering tools. In these scenarios, an expensive computational fluid dynamics (CFD) simulation may be required to adequately represent the fluid-flow and venting throughout the structure.

The FRM described in this paper, was designed to address such limitations and enable analysts to accurately predict the gas pressure throughout a complex target or explosive facility. The capabilities developed in this new algorithm address complex structures with large and small vents but also lend themselves to accurate load estimation for structures where entire walls or large vents are opened dynamically due to failure. This capability makes the code suitable for coupling with structural response solvers in a loosely-coupled time-stepping manner.

The proposed model calculates the time-varying, quasi-steady blast environment in a confined structure, defining the thermodynamic state at each time-step. It is an unconditionally stable fast running model for solving the time-depended post-shock gas flow environment. Chemical models for the combustion of reactants consider the oxygen depletion in the room. The model also considers the travel time of the gas pressure wave propagation based on the speed of sound from

the burst point to each of the vent openings. Lastly, the model is capable of updating the gas pressures and the venting dynamically during run-time based on changes to the control volumes and openings sizes.

The model presented in this paper is currently implemented as a standalone software called GFLOW. The methodology used by GFLOW as well as practical examples are provided in this paper.

Theoretical Model for Gas Pressure Calculation

The proposed model is based on a control volume approach which utilizes the conservation of mass and the conservation of energy (1st law of thermodynamics) to solve a set of equations for an arbitrary number of rooms and openings. A control volume is defined as a confined volume in a space of interest for the analysis. The control volume can have any arbitrary geometry and comprised of surfaces which are referred to as control surfaces. Within a control volume, all the thermo-physical properties are evaluated. The control surface of a control volume can be fixed in space, or it can be free to move as a function of the time. That is, the control volume can change in volume, and with it, all the thermo-physical properties. A feature of the control volume approach is that mass, heat and work can cross the control surface. The exchange rate permitted by the control surface can be fixed or can be a function of time as well. The control surface can be selective, e.g. it can take the form of an impenetrable membrane if only heat can cross the interface or be completely isolating to any property. The transport of mass and energy across the control surfaces is obtained by either: 1) a set of global equations for conservation of momentum, or 2) the classical fluid-dynamic nozzle equations for isentropic flow. The coupling of these two approaches aims to expand the range of applicability of the methodology to practical scenarios. The model, according to the topology of the control surface with respect to the control volume, can infer whether to use an approach over the other, then calculates the transported properties either with the use of a global momentum conservation approach or a localized solution of the fluid-dynamics nozzle equations.

Typically, each control volume represents a room within the structure. The control surfaces provide a representation of the walls and openings. Mass flow is only allowed if there is an opening between two different control volumes. To allow the mass transfer, the wall must be equipped with an opening. An opening is an entity provided with the following information:

- A surface area;
- Location coordinates relative to specific reference system;
- The two rooms the opening connects.

Each control volume can have an arbitrary number of openings which may connect to one or more neighboring control volumes.

In Figure 1, the control surface of a control volume is shown as a dashed line. In this case, the control volume represents a room with three openings. The control surface can change shape and size as the control volume expands, contracts, and/or deforms due to the blast loads. For example,

Figure 1 shows the original control volume at time t on the left and the deformed control volume after a failed wall component is removed at a later time, $t + \Delta t$.

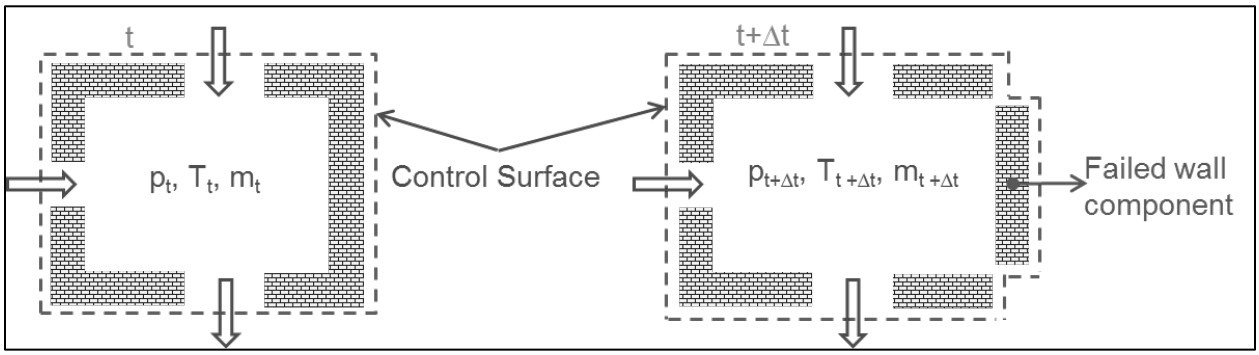

Figure 1. Expansion of a control surface.

The control volume approach is suitable for changes in room volumes and changes in vent area size. As shown in Figure 1, it is also suitable for problems with large displacements of wall components.

For an arbitrary control volume, j, with an arbitrary number of inlets, L_j, and an arbitrary number of outlets, H_j, the conservation of mass equation for the j^{th} control volume can be expressed as:

$$\frac{dm_j}{dt} = \sum_{k=1}^{L_j} \dot{m}_{in(j,k)} - \sum_{k=1}^{H_j} \dot{m}_{out(j,k)} \qquad \text{Eq. 1}$$

Where m_j refers to the total mass of air and detonation products in control volume j, $\dot{m}_{in(j,k)}$ is the mass flow rate from an inlet opening, and $\dot{m}_{out(j,k)}$ is the mass flow rate from an outflow opening.

Similarly, from the conservation of energy equation, we can express the following governing equation for the j^{th} control volume:

$$\frac{dE_j}{dt} = \dot{Q}_j - \dot{W}_j + \sum_{k=1}^{L_j} \dot{m}_{in(j,k)} \left(u_{\alpha,k} + \frac{v_{\alpha,k}^2}{2} + \frac{p_{\alpha,k}}{\rho_{\alpha,k}} \right) - \sum_{k=1}^{H_j} \dot{m}_{out(j,k)} \left(u_{j,k} + \frac{v_{j,k}^2}{2} + \frac{p_{j,k}}{\rho_{j,k}} \right) \qquad \text{Eq. 2}$$

where E is the total energy in control volume j, $\dot{Q}_j$ is the rate of heat in the control volume that may be generated (due to energy release from explosive) or lost to the surroundings, $\dot{W}_j$ is the work performed by or on the control volume (due to expansion/contraction). The variables $u_{\alpha,k}$, $v_{\alpha,k}$, $p_{\alpha,k}$, $\rho_{\alpha,k}$ refer to the internal energy, velocity, pressure, and density from control volume α which is connected to control volume j by the k opening. For the inlet, the properties from control volume α are used since the carrier fluid going to control volume j is originating from control volume α.

Similarly, $u_{j,k}$, $v_{j,k}$, $p_{j,k}$, $\rho_{j,k}$ refer to the internal energy, velocity, pressure, and density of the fluid exiting control volume j.

For solving the transport of properties across control volumes the combination of two approaches is presented. The output of the resolution of the transport equations is the variation of mass and variation of energy exchanged across two connecting control volumes. In the next paragraph, the two implemented strategies are explained in detail.

For solving the above set of equations, the following assumptions have been made. To close the system of equations and provide a relationship between pressure and temperature, the ideal gas equation of state (EOS) is used, $P = \rho RT$. The ideal gas EOS provides a good approximation for air up to pressure of 10 MPa. The relationship between temperature changes and the change of internal energy in the control volume is defined using constant volume specific heats for air as follows:

$$du = C_v dT \qquad \text{Eq. 3}$$

where $C_v = f(T)$ and the values of C_v are provided for a range of temperatures from 250 K to 3500 K by a specific heat capacity table for air (Cambridge 2000).

For the calculation of the energy released by the detonation, a chemical model has been developed and is presented in the "Energy Release Model" section. Also, a preliminary gas pressure rise time model is implemented, and described in the "Gas Pressure Rise Time in the Burst Room" subsection.

The propagation of the gas pressure across each control volume in the structures is determined according to a novel methodology presented in the subsection "Gas Pressure Propagation through Rooms".

Mass Flow Through Connections

The control volumes connect with each other through vents. Vents are treated as connections between two control volumes that allow mass and energy to be exchanged. After updating the thermo-physical properties for each control volume, the new control volume pressure values are used to update the flow direction for each opening. From the pressure difference between the two control volumes, updated velocity and mass flow rates are calculated.

A dual approach is adopted for the calculation of the properties transport across connecting control volumes. For most of the cases, the steady-state isentropic compressible flow equations are used to solve the velocities. In the case the venting area has a comparable size with the entire size of the wall in the room on which it is located, the nozzle equation is not suitable for calculating an accurate venting velocity. For that case, a momentum equilibrium is enforced for the two rooms, relying on the control volume approach. Thus, the conservation of momentum equations Eq. 11, Eq. 12 and Eq. 13 are adopted. This approach allows two control volume to equilibrate very quickly almost as if the two control volumes were one large control volume.

The steady-state isentropic compressible flow equations used (Shapiro 1953) are for an opening area that is equal or smaller than half of the smaller wall between the inlet and outlet wall, that is, when the following relation is satisfied:

$$Vent\ Area \leq \frac{1}{2}(V_{room})^{\frac{2}{3}}. \quad \text{Eq. 4}$$

The equations adopted are the same as the nozzle equations documented in the MBLM manual (Pierce and Donovan 2012). Let us consider control volume 1 as the donor and room 2 as the receiver, the control volume configuration is showed in the sketch in Figure 2.

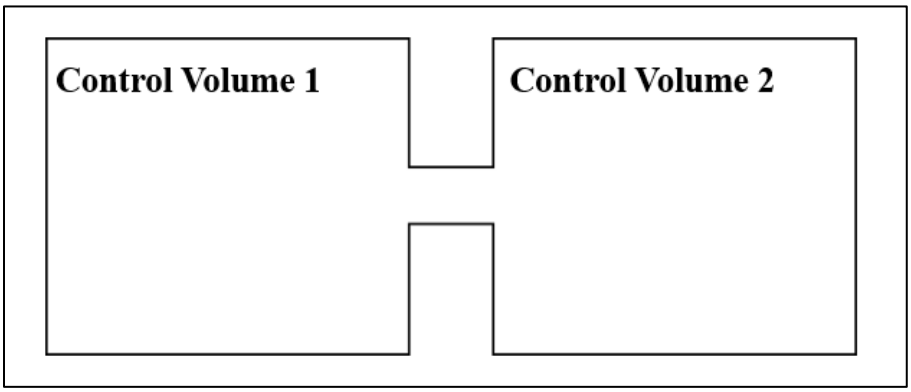

Figure 2. Illustration of two rooms connected by one vent.

The pressure difference between the two control volumes drives the velocity of the flow at the connection. As the pressure difference increases, when the sonic condition is matched, the relation between the exit plane pressure P_2 and the stagnation pressure in the donor control volume P_1 is

$$\left(\frac{P_2}{P_1}\right)_c = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \quad \text{Eq. 5}$$

where $\gamma = {C_p}/{C_v}$ is the ratio of the specific heats in the donor control volume. The subscript c designates the choked condition. When the flow is choked, the pressure ratio remains fixed according to equation Eq. 5. At this condition, the Mach number at the exit plane is $M_2 = 1$. For an unchoked flow, the local Mach number is given by:

$$M_2 = \sqrt{\left(\frac{2}{\gamma-1}\right)\left[\left(\frac{P_2}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}. \quad \text{Eq. 6}$$

The exit plane temperature can be calculated from:

$$T_2 = \frac{T_1}{1+\frac{\gamma-1}{2}M_2^2}. \quad \text{Eq. 7}$$

And from the isentropic relation, the pressure can be defined as:

$$P_2 = P_1\left(1 + \frac{\gamma - 1}{2} M_2^2\right)^{\frac{\gamma}{1-\gamma}}. \quad \text{Eq. 8}$$

Finally, for both the choked and unchoked flow the mass rate can be calculated from:

$$\dot{m} = \left(\frac{\gamma MAP}{c_s}\right)_2. \quad \text{Eq. 9}$$

where $c_{s=}\sqrt{\gamma RT}$ is the speed of sound.

Along with the steady-state isentropic compressible equation a discharge coefficient is used (Busemann 1937). Such coefficient is the ratio of the actual discharge to the theoretical discharge and can be calculated by the following equation, with the assumption of a sharp edge:

$$C_D = 0.60394 + 0.02824M + 0.088M^2 \quad \text{Eq. 10}$$

with dependency on the velocity of the flow, expressed by the Mach number in the equation. Multiplying the mass rate with the discharge coefficient provides the final mass rate through the vent.

For the scenario where the vent opening is comparable in size with the wall size, the conservation of momentum set of equations is solved. We can express the conservation of momentum equation in the x-direction for a j^{th} control volume as follows:

$$\frac{d(mv_x)_j}{dt} = \sum F_x + \sum_{k=1}^{L_j} \dot{m}_{in(j,k)}\, v_{x(\alpha,k)} - \sum_{k=1}^{H_j} \dot{m}_{out(j,k)} v_{x(j,k)} \quad \text{Eq. 11}$$

where $(mv_x)_j$ is the x-direction momentum of control volume j, $\sum F_x$ is the net force acting on the control surface in the x-direction and normally amounts to the pressure differential at all the inlet and outlets between control volume j and its neighboring control volumes that are connected by openings normal to a unit vector in the x-direction. Lastly, $\sum_{k=1}^{L_j} \dot{m}_{in(j,k)}\, v_{x(\alpha,k)}$ and $\sum_{k=1}^{H_j} \dot{m}_{out(j,k)} v_{x(j,k)}$ account for the changes in momentum that is transported by the carrier fluid into and out of control volume j. Similar to equation Eq. 11, the equations for the y-momentum and z-momentum can be expressed by:

$$\frac{d\left(mv_y\right)_j}{dt} = \sum F_y + \sum_{k=1}^{L_j} \dot{m}_{in(j,k)}\, v_{y(\alpha,k)} - \sum_{k=1}^{H_j} \dot{m}_{out(j,k)} v_{y(j,k)} \quad \text{Eq. 12}$$

$$\frac{d(mv_z)_j}{dt} = \sum F_z + \sum_{k=1}^{L_j} \dot{m}_{in(j,k)}\, v_{z(\alpha,k)} - \sum_{k=1}^{H_j} \dot{m}_{out(j,k)} v_{z(j,k)} \quad \text{Eq. 13}$$

This set of equations can then be solved to obtain the velocity components.

Energy Release Model

The calculation of the energy released by the detonation is based on the theoretical models used in the INBLAST code (Proctor 1972) (Montanaro and Michael M. Swisdak 1990). A chemical combustion model is adopted where it is assumed that all the reactants fully react. In this scenario, it is assumed that all the reactants are perfectly mixed in each control volume. The chemical reaction of the explosion and mixing with air in a confined structure generates combustion products, the most common among High-Explosives are Al_2O_3, H_2O, CO, CO_2, C, Al, H_2, O_2, N_2. The assumption for the reaction chain is that there is a specific order based on priority for every chemical reaction. The following steps are used to determine the energy:

1. The Aluminum in the energetic material reacts with O2 to form Al_2O_3. If the oxygen is insufficient, the remaining Al is treated as a solid.
2. If there is sufficient oxygen, the formation of water occurs. H_2 molecules react with O_2 to generate H_2O. In case of insufficient oxygen, the remaining hydrogen is treated as H_2 gas.
3. If there is additional oxygen, the combustion reaction starts to form CO_2. If there is a deficiency of oxygen, two scenarios can happen: partial formation of CO and CO_2 and complete formation of CO.

As an example, the reactions taking place for TNT combustion in air are, in chronological order:

Aluminum oxidation:

$$2Al + \frac{3}{2}O_2 \rightarrow Al_2O_3 \qquad \text{Eq. 14}$$

Water formation:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad \text{Eq. 15}$$

Partial combustion (oxygen is the limiting agent and $O_2 < C < 2O_2$):

$$C + O_2 \rightarrow CO + CO_2 \qquad \text{Eq. 16}$$

Partial combustion (oxygen is the limiting agent and $C > 2O_2$):

$$C + O_2 \rightarrow CO + C \qquad \text{Eq. 17}$$

The initial composition of the air is $N_2 = 0.79$ and $O_2 = 0.21$ of air moles, and the HE composition varies according to its type.

The combustion model has been compared with the INBLAST code and validated with experimental data of explosion in closed chambers of TNT charges (Weibull 1968). Figure 3 shows the confined explosion peak gas pressure versus the W/V ratio (charge weight and confined volume ratio). The comparisons indicate that the GFLOW predictions are accurate.

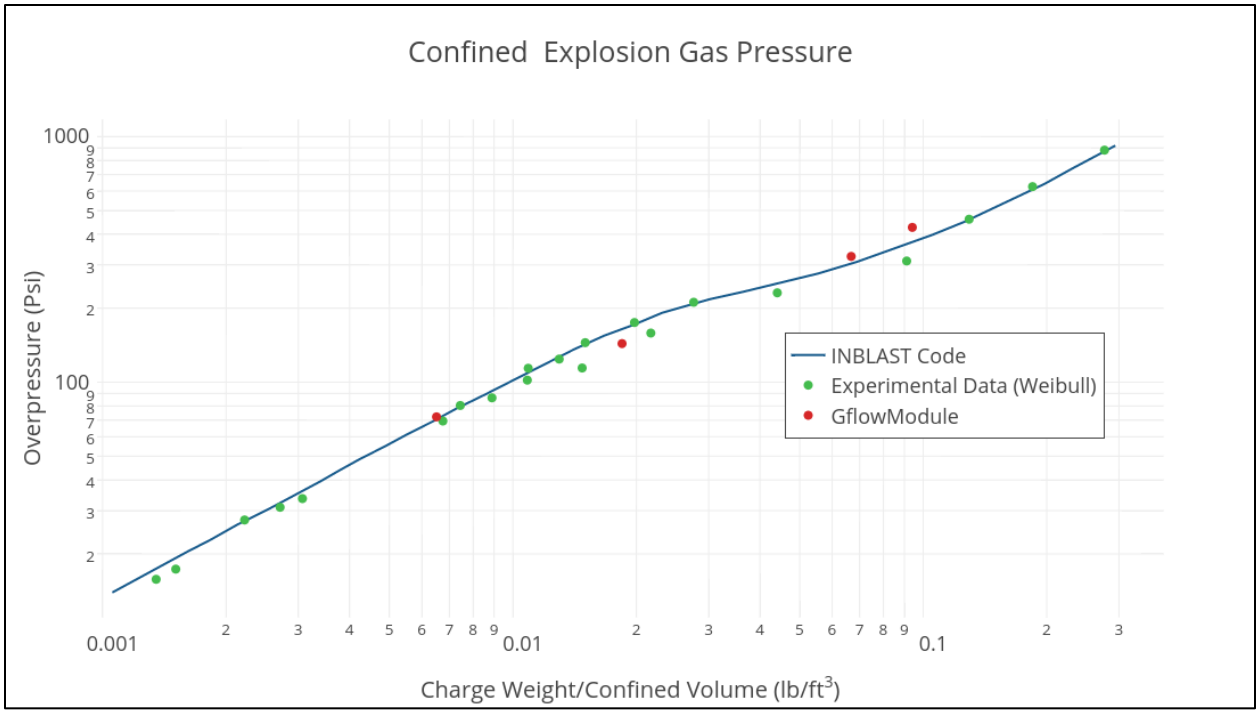

Figure 3. Comparison between GFLOW code and INBLAST code. Experimental data is provided.

Gas Pressure Rise Time in the Burst Room

When a charge detonates, the detonation front generates a high-pressure shockwave that propagates at speeds in excess of $M > 1$. If the detonation happens in a confined environment, the interaction of the shockwave with the walls introduce energy dissipation with formation of large amount of entropy. In this case, a fraction of the energy is transmitted to the walls, another fraction is dissipated into heat, and the rest is reflected back into the room, causing a reflected shockwave travelling in the opposite direction of the incident wave. Subsequently, the decomposed reactants begin to react with the oxygen in the room, which leads to the release of the remaining chemical energy. The production of heat in a confined environment causes a temperature increase followed by the building-up of pressurized air into the room.

The combination of these two phenomena, i.e., the shockwave reflections in the room and the heat released by combustion reactions, leads to the pressurization of the burst room. In the proposed model, a simplified methodology for tracking the rise-time of the pressure into a confined room is presented. The methodology follows guidelines presented in (Hager n.d.).

The energy released from the combustion process in the room is calculated as explained in the "Energy Release Model" section. For strong shocks, it has been observed that more than 90% of the maximum gas pressure is reached after 5 shock transitions, where a shock transition is defined as the time the shockwave takes for crossing the full length of the room. For weak shocks, the transition time is around 4. As a preliminary implementation in GFLOW, the time for the gas pressure to build-up into the room is assumed to be 5 transition times.

For the calculation, the speed of sound is calculated. Then, the characteristic time for the release of the total energy is

$$t_r = \frac{L}{c_s} \quad \text{Eq. 18}$$

Where L is the distance of the pair of closest opposite walls in the room.

Gas Pressure Propagation through Rooms

Complex structures with a large amount of rooms and connections are often encountered by analysts and in such scenarios, the timescale of the pressure propagation is important for the start of the pressurization in each control volume. In addition, less complex scenarios can be challenging to predict if the propagation of the gas pressure is not predicted accurately. For a structure with a large layout, the assumption of instantaneous equilibration of gas pressure is no longer valid and can affect the accuracy of the calculation. For this reason, a model for introducing a delay for the gas pressure propagation through each vent has been developed. The idea is to let the pressure information propagate with a finite velocity as opposed to an infinite propagation velocity. As a velocity reference, the speed of sound in the medium is considered, which varies according to the material composition of the gas and its thermodynamic state. For the speed of sound, the following equation is used:

$$c_{s=}\sqrt{\gamma RT}. \quad \text{Eq. 19}$$

Where γ is the specific heat ratio, R is the specific ideal gas constant and T is the temperature of the ideal gas.

Given the location of a generic point of the domain and the location of the detonation point, it is possible to calculate the time for the gas pressure to cover the distance between the two locations. The distance is calculated as the shortest distance among all the available paths that connect the detonation point to each vent. The schematic shown in Figure 4 is an example of the calculation of the shortest distance between two points. As shown in the figure, the building is outlined as a set of nodes and connections, where the nodes represent openings and connections represent available paths through which the gas can vent. The shortest path between the burst point and each control volume opening is then calculated with the Dijkstra's algorithm (Wikipedia 2018). The algorithm looks for paths through each node and iterates through each possible combination. At each step, the algorithm calculates the path that minimizes the distance between the charge and the vent under consideration.

Every time the algorithm advances, it stores the current distance and marks all the visited nodes. Every step updates D_{ai} (the distance from the starting point a, to a generic point) with the following equation:

$$D_{ai} = \min[D_{ai}, D_{ac} + l(c, i)] \quad \text{Eq. 20}$$

Where $l(c,i)$ represents all possible branches from the current position, and D_{ac} is the distance from the starting node to the last visited node. The algorithm stops once all the nodes have been visited.

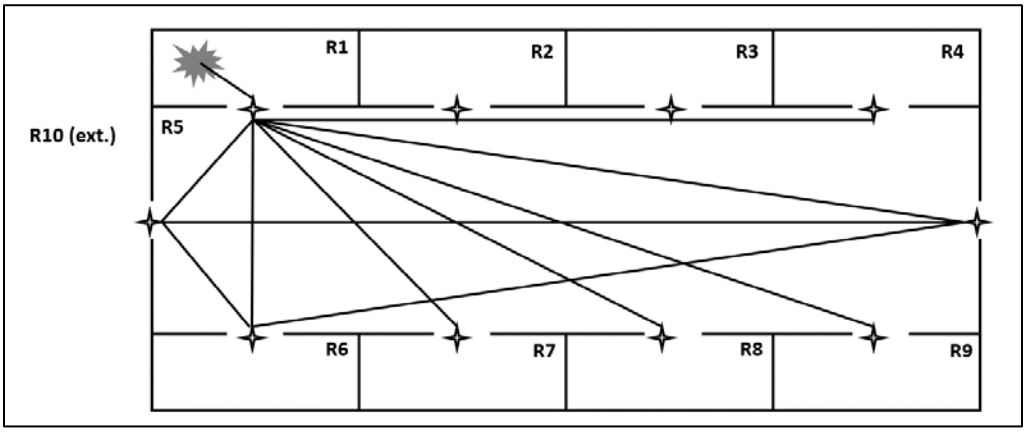

Figure 4. Schematic example for the connectivity network.

The time of propagation is finally calculated using the distance and the speed of sound of the medium as

$$t_p = \frac{D}{c_s}. \qquad \text{Eq. 21}$$

The time for the pressure wave to travel is then used for delaying the activation of the openings, to simulate the physical time for the propagation.

Results and Comparisons

In this section, results of the proposed methodology are shown. The gas pressure model is presented under the name of GFLOW, which is the software developed using this methodology.

The examples compare GFLOW with an Existing Blast Design Tool EBDT), and results are presented for various structure geometries. Capabilities and limitations of the code are described through the examples. The following assumptions are adopted for all the cases, for all the solvers:

- Ambient conditions: 25 °C and 1 atm.
- Rigid walls, the geometry configuration is fixed during the calculation evolution.
- Only gas pressure is considered (no shockwave effects).

Example 1: Linear Structure Configuration

The layout of the structure in this example is shown in Figure 5 on the right side. It consists of a series of rooms connected by openings, where the last in the series vents to the environment. A TNT charge is positioned in room 1, which is the room at the bottom of the diagram in Figure 5. This room is forced to vent only in room 2, through a single opening. Subsequently, room 2 will vent in room 3 and so on, until the last room which will then vent to ambient. In the pressure

history plot (Figure 5, on the left) a plot for each room is shown. Room 1 reaches the peak pressure approximately 8ms after the detonation. This is the time computed for the charge to release all its energy. The venting into each room starts after some delay: the pressure in room 2, 3, and 4 starts to rise after respectively ~7ms, ~19ms, and ~30ms since the pressure equilibration process is not instantaneous. In the final phase, all the rooms equilibrate to ambient pressure. Figure 6 shows the results from the same setup with the EBDT. Two main differences can be noticed: 1) GFLOW predicts the pressure rise time based on an energy release law, while the EBDT instantaneously releases all the energy (the simulation starts with the peak pressure); GFLOW predicts a delay for the pressure propagation across rooms, while in the EBDT calculation the gas pressure starts rising for all rooms at time zero.

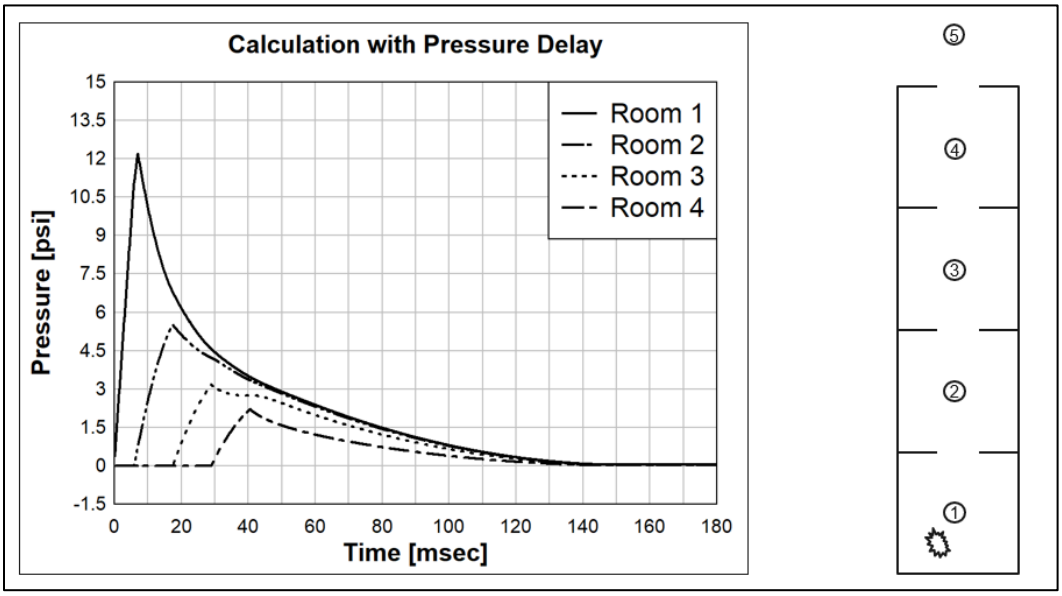

Figure 5. Pressure history for linear structure configuration example.

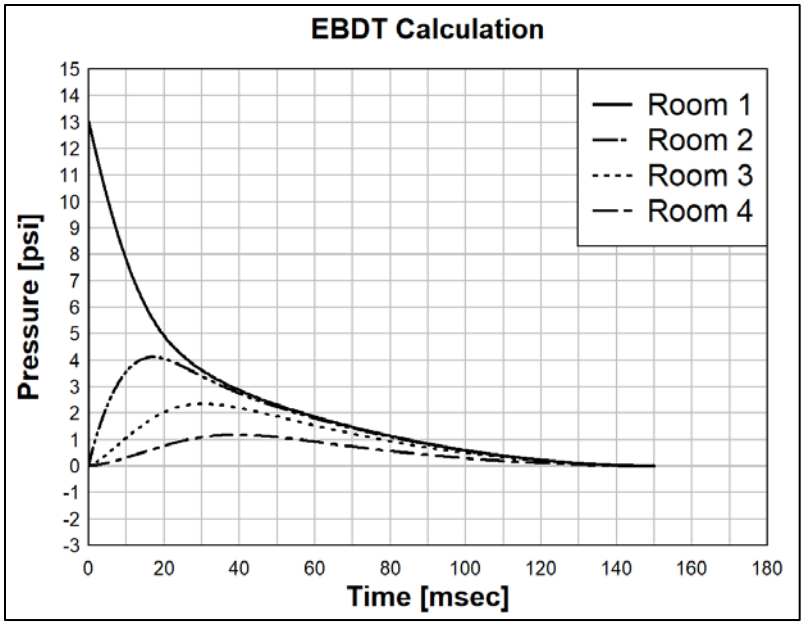

Figure 6. Prediction from typical existing blast design tool.

Example 2: Linear Structure Configuration with Complete Vent

Example 2 has a similar configuration to Example 1. The difference in the layout is in the connection between Room 1 and Room 2, which spans the entire cross-section of the room, (see Figure 7, layout on the right). In this example, Room 1 and Room 2 are still considered two separate rooms to assess the GFLOW venting algorithm for this configuration. The charge is positioned in Room 1. Figure 7 shows the gas pressure history for GFLOW and the EBDT respectively. The biggest difference is seen in the peak gas pressure. While the EBDT predicts ~13psi peak pressure, GFLOW's peak is ~7psi. That can be explained by two factors: First, GFLOW considers an energy release rate while the EBDT does not, second, GFLOW solves the rooms by equilibrating the pressure while the EBDT still applies the nozzle equation. As can be logically expected, the GFLOW gas pressure in Room 1 and Room 2 are nearly identical since they are pressurized as if they are one large room.

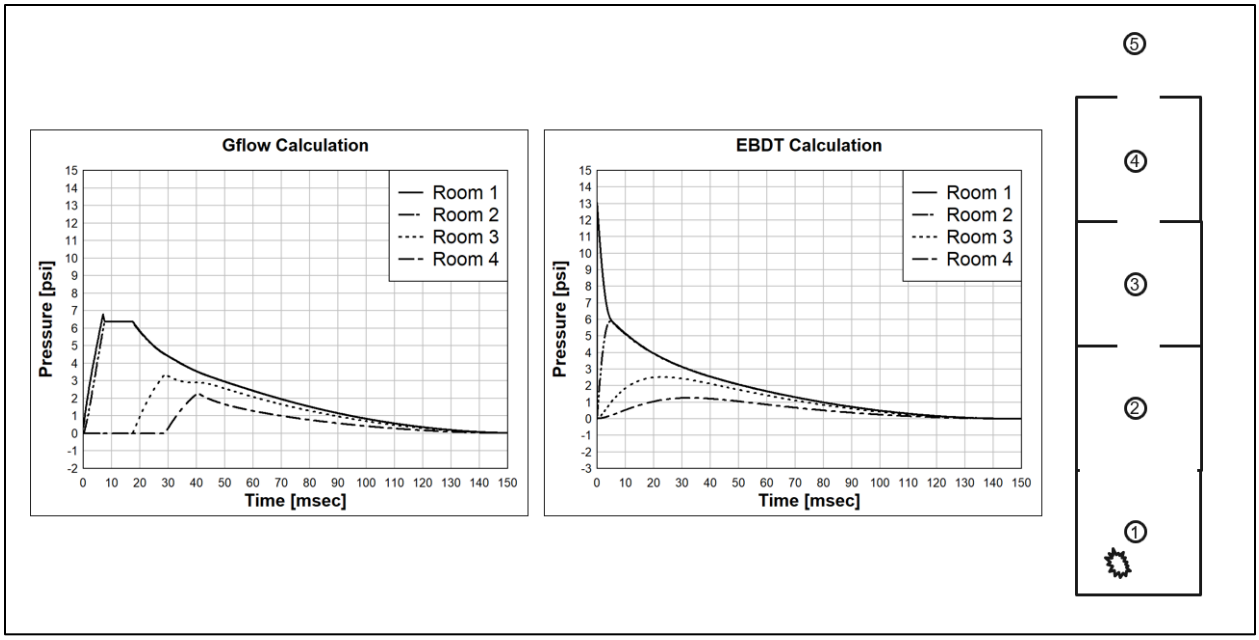

Figure 7.Comparison between GFLOW and BlastX prediction.

Example 3: Structure with Hallway

In this example, a six-rooms building is analyzed. The structure is composed of six rooms, where room 2 is a hallway with multiple connections. A TNT charge is positioned in room 1 which can directly vent only to room 2. Subsequently, the gas flow will propagate from room 2 to the rooms 3, 4, and 5 and then from room 5 to room 6. Figure 8 shows the GFLOW pressure history plots for each room. Room 1 reaches the peak pressure ~6ms after the detonation. This is the time for the charge to release all its energy. As expected, the venting to room 2 starts first, followed by room 4, then room 5, then room 3, and finally to room 6. Figure 9 shows the results from the same setup with the EBDT which provides a very different loading time-history for each room. K&C has found that the structural response of the wall in each room is sensitive to the pressure time-history predicted by GFLOW versus other EBDT applications, especially when considering the pressure load applied to each wall component from rooms on opposite sides.

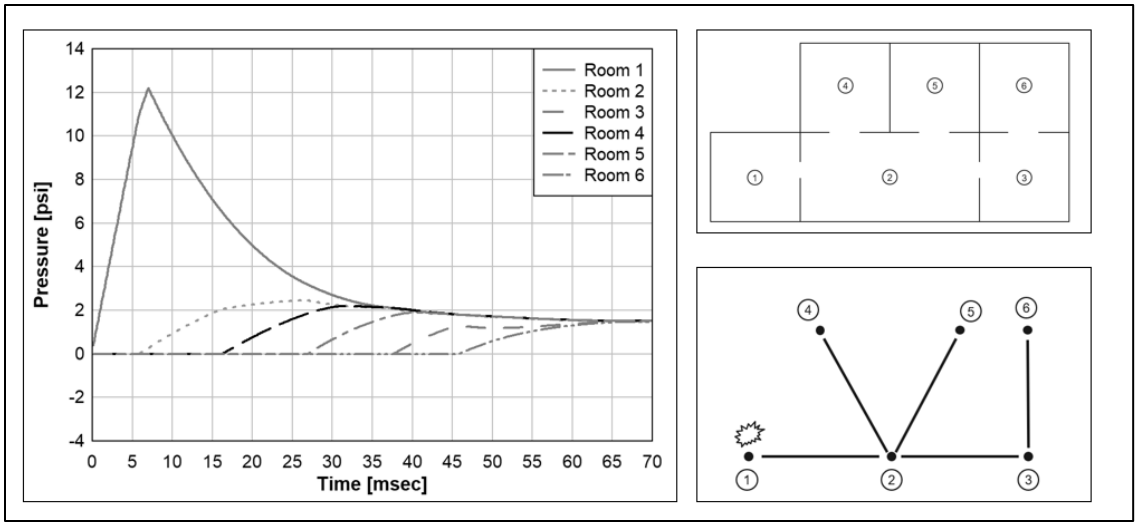

Figure 8. GFLOW Pressure history(left), structure geometry (right).

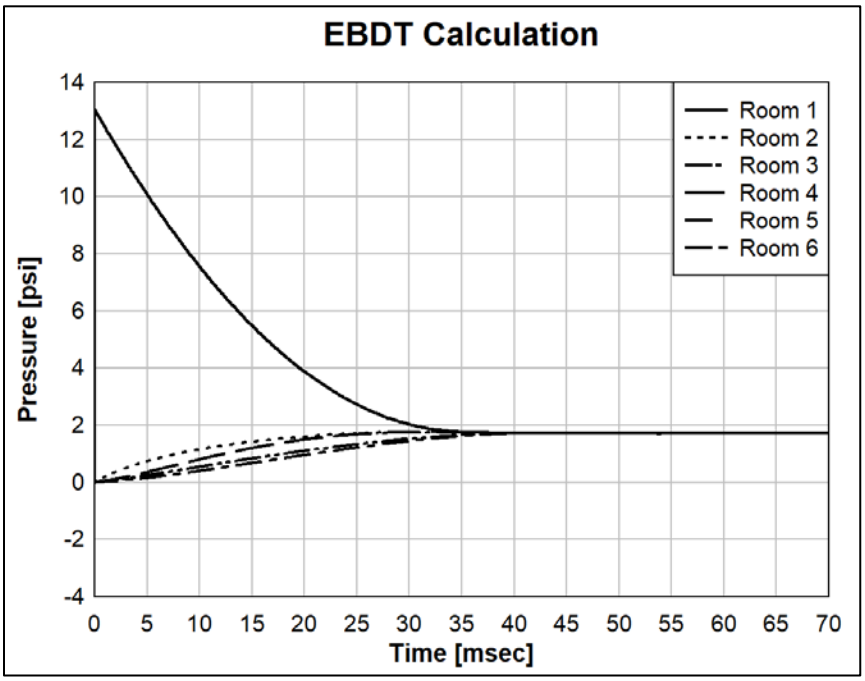

Figure 9. Prediction from EBDT.

Example 4: Comparison with Other Engineering Tools

In this example, a simple geometry is used to compare GFLOW with the engineering tool BlastX (BlastX version 7.0.1). The geometry consists of a single cube-shaped room venting to open air through an opening. The charge is located in the center of the room. Only gas pressure is considered for the calculation. Figure 10 shows the normalized pressure history comparison for the different codes. The peak gas pressure matches for both the GFLOW and BlastX. The pressure time-history has the same shape for both for GFLOW and BlastX.

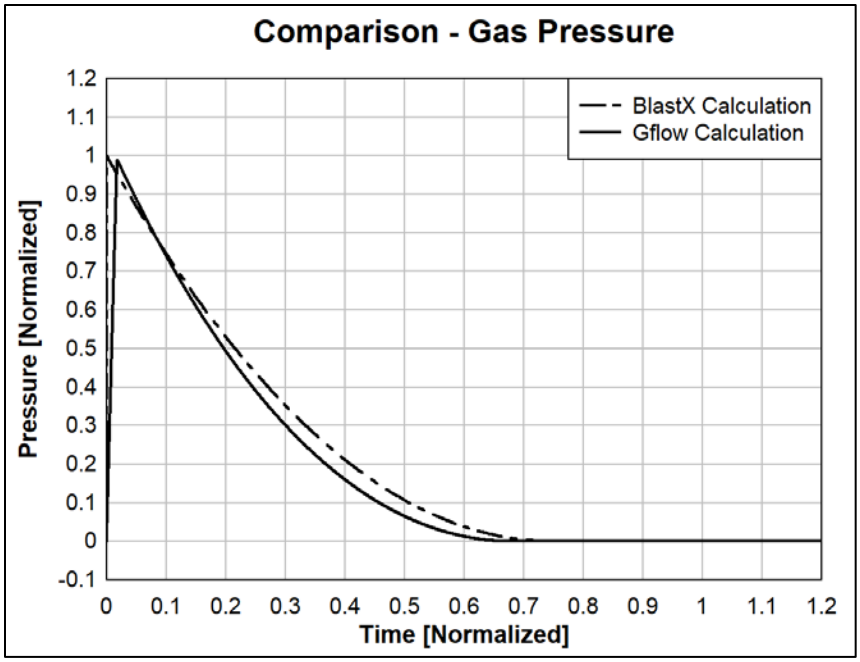

Figure 10. GFLOW comparison with BlastX.

Conclusions

A novel methodology for the prediction of blast effects in confined environments has been developed. It introduces a technique that combines two algorithms for solving the transport of properties across rooms, increasing the prediction accuracy for cases where the structure geometry requires an analyst to parse the structure into control volumes connected by large openings. The model also considers the spatial distance of each vent from the burst point to compute a delay time for the activation of each vent. In future studies, additional algorithms will be investigated for the burst room pressurization rate as well as the vent activation time delay based on documented used by other gas flow codes.

Bibliography

Britt, J. Robert, Dale E. Ranta, and Charles E. Joachim. *BlastX code, version 4.2, user's manual.* Vicksburg, MS: ERDC/GSL TR-01-2, US Army Engineer Research and Development Center, 2001.

Busemann, A. *Hodographenmethod der Gasdynamik.* Z.a.M.M, 1937.

Cambridge, University of. *Cambridge University Press.* 2000. www.cambridge.org/us/download_file/212545/ (accessed Nov 2016).

Defense, Department of. "Design and analysis of hardened structures to conventional weapons effects." 1998.

Hager, Kevin. *Algorithm for Calculating Gas Pressure Rise-Time for Confined Explosions.* Port Hueneme, CA: Naval Facility Engineering Service Center, n.d.

Kingery, C.N., and G. Bulmash. *Airblast parameters from TNT spherical air burst and hemispherical surface burst.* Aberdeen Proving Grounds, MD: U.S. Armcy Armament Research and Development enter, Ballistics Research Laboratory, TR ARBRLTR02555, 1984.

Montanaro, Paul E., and Jr. Michael M. Swisdak. *INBLAST - A New and Revised Computer Code for the Prediction of Blast Inside Closed or Vented Structures.* Silver Spring, MD: Naval Surface Warfare Center, 1990.

Pierce, T. H., and M. T. Donovan. *MULTI-CHAMBER BLOWDOWN MODEL (MBLM).* San Diego, CA: SAIC, 2012.

Proctor, James F. *Internal Blast Damage Mechanism Computer Program.* WHITE OAK, SILVER SPRING, MARYLAND: NTIS, 1972.

Shapiro, A. H. *The Dynamics and Thermodynamics of Compressible Fluid Flow.* New York: Ronald Press, 1953.

UFC 3-340-02. *Structures to Resist the Effects of Accidental Explosions.* Department of Defense, 2008.

Weibull, Hans RW. *Pressures recorded in partially closed chambers at explosion of TNT charges.* Annals of the New York Academy of Sciences , 1968.

Wikipedia. *Dijkstra's algorithm.* Wikipedia. July 10, 2018. https://en.wikipedia.org/wiki/Dijkstra%27s_algorithm (accessed July 11, 2018).