Development and Validation of a Rapid Threat Assessment Simulation

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ABSTRACT

A capability for Rapid Threat Assessment (RTA) due to explosive threats is presented in this paper. The audience for the RTA are non-technical users who can utilize the generated information for security planning. The RTA determines the maximum pressure load applied on building structures from an explosion in an urban environment and the lethal regions from the detonation of a threat that combines an explosive and projectiles. The former functionality considers a couple of alternative layouts for the urban environment and allows a user to select the type of layout, the main dimensions of the layout, the size of the explosive and its relative placement with respect to the buildings. This information is used for determining the blast loads applied on the buildings from an explosion. A regression approach is used for developing the predictive models for the pressure loading and the maximum pressure load from a modest number of high fidelity simulations that have been completed for each layout. The main dimensions of each layout, the size of the explosive, and its relative placement varied in each high fidelity simulation. The results are used for training a regression model which is then utilized for predictions within the RTA tool. Simulation results are validated through comparison to published test data for two urban configurations. The second functionality of the RTA utilizes semi-empirical expressions for determining the initial velocity of projectiles and a numerical solution to a system of ordinary differential equations for determining their trajectories. The lethality of the projectiles is determined from their energy and their trajectory time histories. The lethal region from the blast pressure is based on semi-empirical equations for peak pressure loads and an iterative solution that determines the limit of the lethal distance. The theoretical background, the validation, and the value of the RTA capability are presented.

ABOUT THE AUTHORS

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INTRODUCTION

The RTA capability has two functionalities; computing the loads from the detonation of an explosive on the adjacent buildings for two types of urban settings and determining the lethality regions for humans from the detonation of an explosive that includes projectiles. In the former functionality it is necessary to capture the blast loads determined on the surface of the buildings. Reflections from the ground and from the buildings of the urban configuration influence the results. In the past a phenomenological model (Larcher, 2010) has been used for determining the blast load due to its simplicity and then it was combined with a computational fluids dynamics (CFD) solver for determining the blast wave propagation over a complex landscape (Valsamos, 2021). Commercial software with a Lagrange Euler solver such as AUTODYN and LS-DYNA have been used for high fidelity blast simulations in the vicinity of buildings. Representative applications are discussed in (Seman, 2022) and (Zhou, 2021), respectively. The formation of the pressure wave from the detonation of the explosive and its propagation throughout the domain of interest are simulated. In this work LS-DYNA is used for populating the sample space when developing the regression models for the blast pressure computations in the RTA. Semi-empirical blast models based on spherical propagation with linear reflectance have been employed for blast simulations in urban environments (Liu, 2010). Such models work well for air blasts near the explosive since they are developed from experimental data in the vicinity of the detonation. In this paper they are utilized for the latter functionality of the RTA, when determining the lethal regions from a charge that includes both explosive and projectiles. The intent of the two RTA functionalities is to provide estimates about the maximum blast pressure on buildings from an explosive representative of a car bomb; or the lethal distances from an explosive representative of a smaller explosive device. The RTA is not expecting the user to have any knowledge about explosive simulations. The user only needs to provide information about the size of the explosive and its relative placement within the environment of interest.

A regression approach is used for developing models for the load (including the maximum load) on the buildings from a modest number of high fidelity simulations. Each high fidelity simulation is carried out in LS-DYNA using the Multi-Material Arbitrary Lagrange-Eulerian (MM-ALE) solver with 1D-to-2D-to-3D mapping (Hallquist, 2006), (Schwer, 2010). The mapping offers considerable reduction in computational time with no degradation in simulation accuracy when populating the sample space used for developing the regression models. The pressure loading information generated by the RTA can then be used in conjunction with the ASCE 59-11 (ASCE, 2011) or the CSA S850-12 (CSA, 2012) for assessing the potential damage on the buildings. The work presented in this paper focuses only on determining the loads from the blast; a discussion on how such information is used for determining what happens to a building is summarized well in (Abedini, et al, 2018).

The lethality region from the blast pressure of an explosion is determined using the Kingery-Bulmash (K-B) equations for the peak blast pressure (Kingery, 1984) and (US Army TM5-855-1, 1986) and the threshold value of 40psi suggested by (Baker, 1980). The K-B equations are modified using an image approach for accounting for reflections from any hard walls. An iterative solution determines the lethal distance from the explosive based on the threshold pressure value. The lethality assessment from the projectiles, which are part of the explosive threat, is done by first deriving an initial velocity for the projectiles using the Gurney equation (Gurney, 1982) and (Kennedy, 2019). Then, trajectory computations are performed for determining when the kinetic energy of the projectiles reaches the lethality

threshold value of 58 ft-lb (~78J) (US Department of the Army, 1990). These calculations determine the range that the projectiles are lethal. For different trajectories a different lethal distance is determined since the gravity load differs between trajectories.

The modeling approach utilized in this work for conducting the LS-DYNA simulations and comparisons between computations and test data for the two road configurations of interest are presented first. The development of the regression models from the LS-DYNA simulations is discussed. Predictions from the regression models are compared to high fidelity LS-DYNA simulations for representative configurations that are not part of the sample space used in developing the models. The methods used for determining the lethality regions due to the blast pressure and the projectiles from an explosive device are presented in the last Section of the paper.

BLAST SIMULATION USING MM-ALE WITH MAPPING

MM-ALE is a finite-element solver provided by LS-DYNA for computing explosive blast loads on buildings and structures (Hallquist, 2006). For air blast simulations with the MM-ALE solver, both the explosive and the air need to be meshed. A sufficiently fine discretization is required for the MM-ALE solver to obtain a reasonably accurate solution. The number of elements required for the MM-ALE solver increases rapidly for wider streets and for a road configuration involving multiple streets like cross-roads configuration. Direct use of the MM-ALE solver, therefore, is often restricted to near field blast analyses (Schwer, 2010) and (Medyanik, 2018).

An analysis strategy available in LS-DYNA to reduce the computational cost associated with the MM-ALE solver is mapping one-dimensional (1D) or two-dimensional (2D) ALE simulation results to a three-dimensional (3D) ALE model (Aquelet, 2008). LS-DYNA provides mapping commands to make it possible to simulate the initial detonation of a charge and formation of air blast waves using a dense 1D (or 2D) ALE mesh and then map the 1D (or 2D) solution to a coarser 3D ALE model as an initial condition. Depending on problem configurations one can use either 1D to 3D or 2D to 3D or 1D to 2D to 3D mapping approach. ALE analyses in lower dimensions are made possible by means of symmetry. The 1D ALE solver performs spherically symmetric analyses; 2D ALE solver makes use of axi-symmetry. 1D or 2D ALE analysis is much quicker for a same mesh resolution than a 3D ALE simulation. Therefore, this mapping approach can save significant computational effort while accomplishing the same level of accuracy in results. Cheaper computational expense with 1D or 2D ALE simulations, furthermore, allows for using denser mesh to achieve more accurate prediction of peak pressure.

In this work 1D ALE analysis is performed for the spherically symmetric region between the explosive charge and the ground (Figure 1.a); 2D ALE analysis for the axi-symmetric region from the explosive location to the closest wall (Figure 1.b and 1.c); and 3D ALE analysis for the rest of the analysis domain. Appropriate boundary conditions (symmetry and rigid boundary conditions on walls and pressure boundary conditions on free surfaces) are applied as shown in Figure 1. In 1D ALE analysis, spherically-symmetric solid elements needed to discretize the sphere whose radius is equal to the charge-to-ground distance are defined using two-node beam elements. Their section properties, which control the type of formulation used for the elements, are defined using SECTION_ALE1D keyword in LS-Dyna. Particularly, two parameters ALEFORM and ELFORM of the SECTION_ALE1D keyword are used to request 1D (spherically-symmetric) multi-material ALE formulation. 1D multi-material ALE analysis using 1D beam elements are designated below as 'ALE1D'. After the last time step of the 'ALE1D' analysis, 1D ALE simulation results are written into a binary file specified by the 'map' command in LS-DYNA. This binary file, which contains 1D analysis data, will be mapped to a 2D ALE model, using the same 'map' command when running the 2D ALE analysis.

The 2D ALE mesh consists of axi-symmetric solid elements that model the axi-symmetric region defined between the explosive and the closest building boundary. The axi-symmetric solid elements are defined in the same format as three or four node shell elements. Axi-symmetric multi-material ALE formulation required for the 2D ALE mesh is specified through SECTION_ALE2D card in LS-DYNA, and the 2D ALE analysis is referred to as 'ALE2D' in the figure below. Once the 2D ALE model is submitted along with 'map' commands, the 1D solution is first mapped to the 2D ALE model as an initial condition, and the 'ALE2D' simulation proceeds from there. After the last time step of the 'ALE2D' simulation, the 2D analysis data are written to the file specified with the second 'map' command.
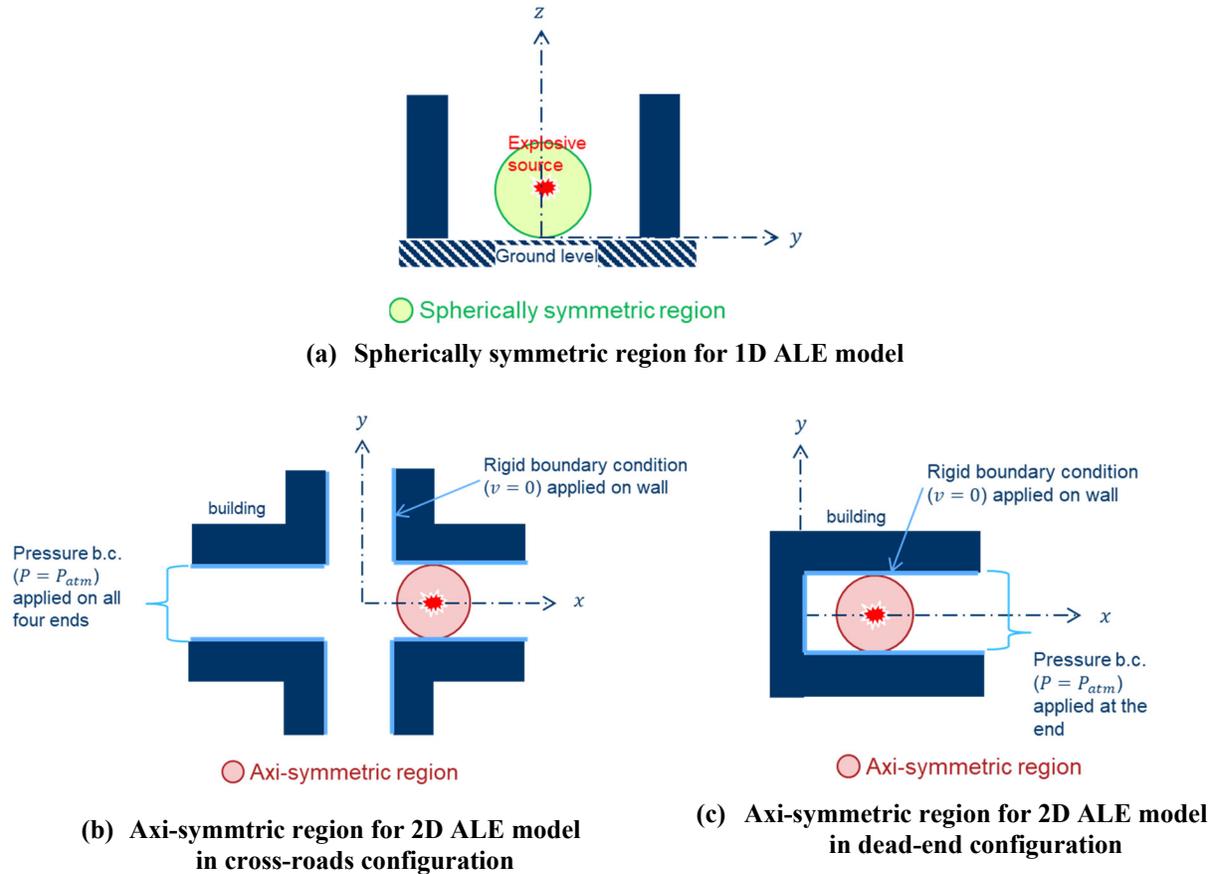
(a) Spherically symmetric region for 1D ALE model

(b) Axi-symmtric region for 2D ALE model in cross-roads configuration

(c) Axi-symmetric region for 2D ALE model in dead-end configuration

Figure 1. Spherically-symmetric and axi-symmetric regions for ALE blast simulations in urban street configurations

The rest of the domain of interest must be modeled with a 3D ALE mesh. The 3D ALE mesh contains four node tetrahedral, six node pentahedral, and/or eight node hexahedral solid elements, whose element formulation (multi-material ALE formulation) is defined by SECTION_SOLID card. Initial condition of the 3D ALE model is specified through 2D to 3D mapping, where the 2D solution is mapped to the 3D ALE model before 3D ALE analysis (denoted below as 'ALE3D') initiates.

Figure 2 illustrates a sequence of the three-step blast wave simulation process, including 1D to 2D and 2D to 3D mapping. A very dense mesh for spherically symmetric region (5 mm line elements for ALE1D), a dense mesh for axi-symmetric region (50 mm quad elements for ALE2D), and a coarse mesh (0.5 m cubic elements for ALE3D) enable efficient and relatively accurate blast wave simulations within a reasonable amount of computation time. The blast wave simulation procedure through mapping is illustrated in Figure 2.
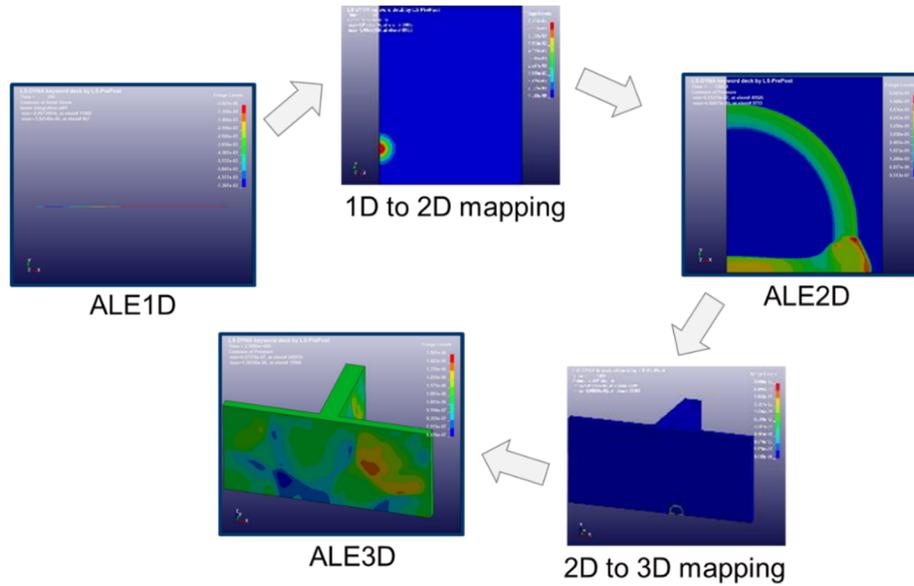
Figure 2. Three-step blast wave simulation procedure through mapping in LS-DYNA

Comparison of MM-ALE with Mapping and Test Data

The MM-ALE mapping approach is validated by comparing simulation results to experimental data from (Rose, 2001). In the experiments, a 1/50th scale model for a cross-road configuration was built using steel plates. The test setup considered a street width of 15 m at full scale and a uniform height for the buildings of 50 m at full scale. The explosive charge corresponded to a vehicle bomb of approximately 1625 kg TNT. A plan view of the blast test configuration used in (Rose, 2001) is shown schematically in Figure 3. An explosive being located at the center makes the model symmetric and thus only a 1/8th of the entire domain, the area enclosed by a blue rectangle in the figure, is modeled for MM-ALE simulations. A side-view schematic of the experimental set-up and the pressure gauge locations used in the experiments is also shown in Figure 3. There are three arrays of gauges attached to the side wall: 4 horizontal (H1 to H4), 4 vertical (V1 to V4), and 4 on a diagonal line at 45 degrees (D1 to D4), making a total of 10 gauge points since locations of gauges H1, V1, and D1 coincide.
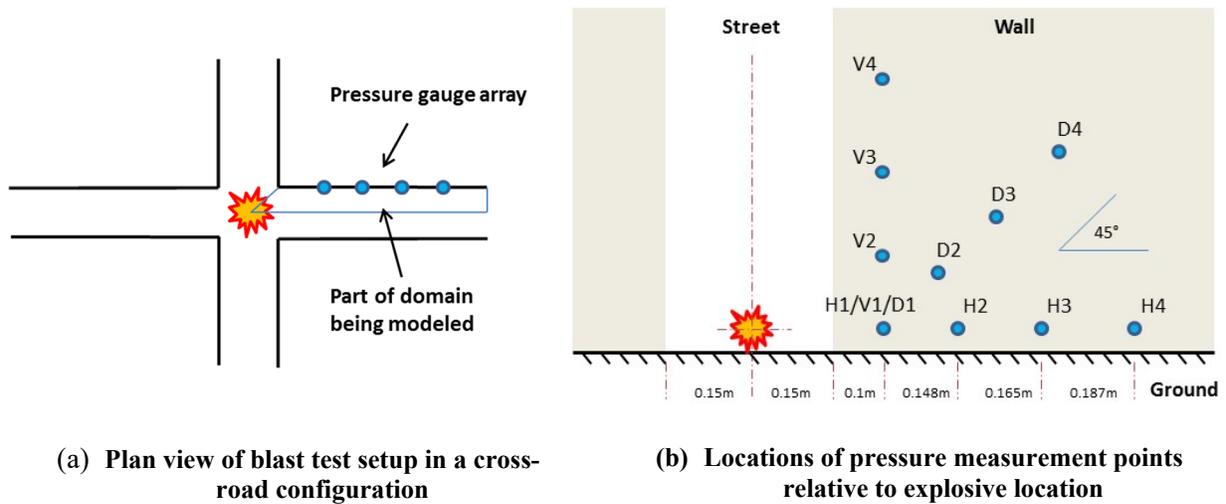

(a) **Plan view of blast test setup in a cross-road configuration**

(b) **Locations of pressure measurement points relative to explosive location**

Figure 3. Schematics of blast test setup in a cross-road configuration from (Rose, 2001)

With the mapping approach we utilized spherical symmetry (1-D ALE simulation) and axi-symmetry (2-D ALE simulation), and then modeled 1/4th of the domain using 3-d elements (using 5mm mesh in the vicinity of explosive and then 10mm mesh for the rest). The simulation required only about 30 min for the 1/4th of the domain. Peak pressure is measured at the pressure gauge locations and the test data are listed in Table 1, together with simulation results. It must be pointed out that the experimental results were collected by conducting three separate tests. During each test results were collected for gages "V", "D", and "H". The pressure measurement points, H1, V1, and D1 are located physically at the same position and therefore the same level of pressure is expected for all three of them. The peak pressure values recorded at the three pressure gauges, however, differ and vary from 2281-3613 kPa, which amounts to approximately 48% variations around its mean value of 2775 kPa. Taking into account the variability within experimental data it is deemed that the simulation results are in a good agreement with the experimental data.

Table 1. Comparison in peak pressure of blast simulation and experiment for crossroads configuration

Results / Location	Peak Pressure (kPa)	
	Analysis	Experiment
H1	2324	2281
H2	782	728
H3	398	312
H4	303	224
V1	2324	2432
V2	1310	1272
V3	723	472
V4	359	252
D1	2324	3613
D2	920	921
D3	505	402
D4	332	238

A similar comparison between simulation results and test data was completed for the dead-end road configuration depicted in Figure 4. All set-up parameters were the same except for the road configuration. The comparison between test and simulation is presented in Table 2. Given the variance which is present in the test data (pressures for points H1/V1/D1 varying from 2,612 kPa – 3,476 kPa the correlation between simulation and test is also considered to be good for the second road configuration.
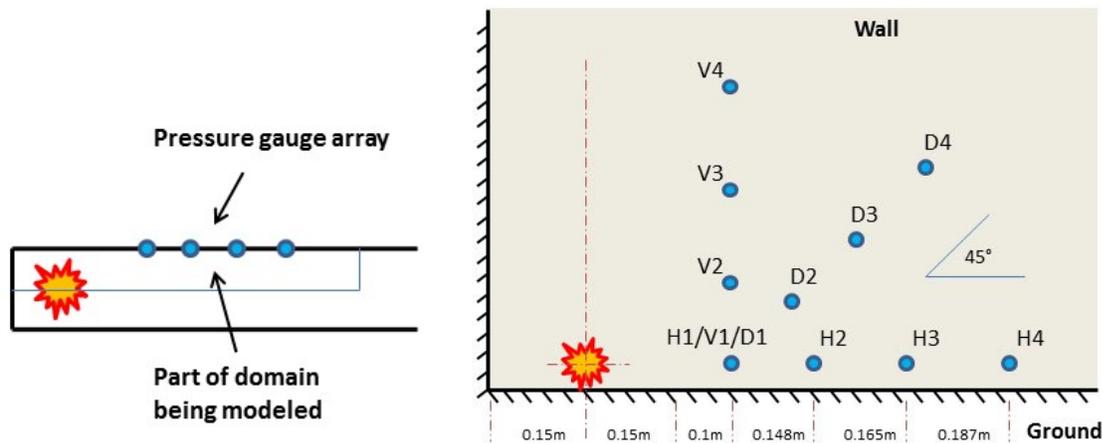

Figure 4. Schematics of blast test setup in a dead-end road configuration from (Rose, 2001)

Table 2. Comparison in peak pressure of blast simulation and experiment for dead-end configuration

Results Location	Peak Pressure (kPa)	
	Analysis	Experiment
H1	3157	3210
H2	884	1352
H3	443	570
H4	318	363
V1	3157	3476
V2	1560	1672
V3	674	679
V4	545	760
D1	3157	2612
D2	1166	1297
D3	524	468
D4	334	398

DEVELOMENT OF REGRESSION MODEL FROM MM-ALE SIMULATIONS

Blast simulations, even with the mapping approach, are an expensive computational endeavor and therefore it usually takes a long time to evaluate blast loads on the building structures of an urban environment. Lack of symmetry with respect to the placement of the charge and the surrounding buildings makes the simulations even costlier since symmetric boundary conditions cannot be considered. A fast running computational model is a necessity for rapidly calculating the blast loads in the RTA tool. In the past regression models were developed from a limited number of high fidelity explosive simulations when considering the impact of uncertainty in the soil properties to the loads developed on the lower extremities of occupants of a vehicle subjected to the detonation load from a buried explosive (Sun, 2006). Regression models were also developed when determining the dynamic response of a ground vehicle to a buried explosive for many different combinations of depth of burial, relative placement of the explosive with respect to the vehicle, size of the explosive, and ground clearances (Li, 2013). In this work regression models are developed for the peak pressure with respect to the input parameters that a user of the RTA utilizes for defining the environment to be analyzed. These input variables include the street width SW, the size of the explosive W, the location of the explosive $\mathbf{x}_W = (x_W, y_W)$, and the type of street configuration (cross-road intersection and dead-end street). Figure 5 illustrates the input variables for the cross roads configuration.
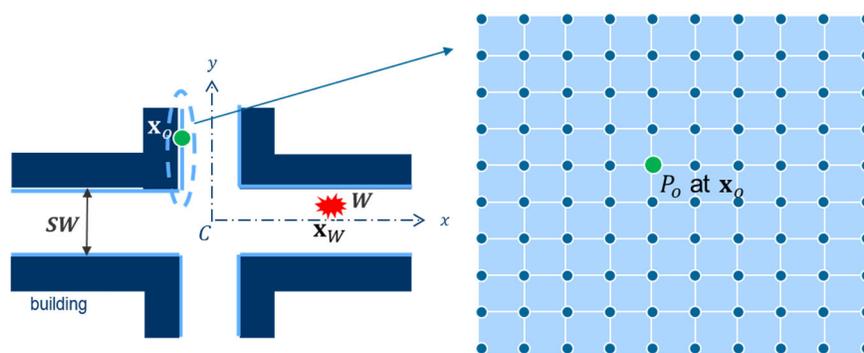

Figure 5. Input variable to the RTA model and grid points for retrieving the pressure

An additional parameter which is not specified by the user but considered in the regression analysis, is the observer location $\mathbf{x}_o = (x_o, y_o)$ where the numerical value of the peak pressure is computed. In this work we consider an equal-distant 10×10 grid on each wall surface along each street side, i.e. a total of 100 observer grid points on each side, as also shown in Figure 5. Each grid point is used as a tracer point in LS-DYNA to track the blast pressure. For example, a time history of blast pressure $P(t, \mathbf{x}_o)$ is recorded at the grid point located at $\mathbf{x}_o$ during the high fidelity blast

simulation and its peak pressure value P_o is used for the subsequent regression model development. These grid points also constitute a mesh used for displaying the results.

The regression model comprises a mathematical expression for the output variable (peak pressure) based on input variables (explosive weight, street width, charge location, observation location, and type of urban configuration). In regression models developed for an airblast above a surface within a free domain, the distance was converted to a non-dimensional parameter (Kingery, 1984) and (US Army, TM5-855-1, 1986). Following such an approach, the physical input parameters: W, SW, $\mathbf{x}_W$, $\mathbf{x}_o$(depicted in Figure 6) are first converted to the following set of non-dimensional parameters for developing and using the regression model: scaled street width, $\frac{SW}{W^{1/3}}$; scaled distance from charge to observation position $\frac{D}{W^{1/3}}$ where $D = |\mathbf{x}_o - \mathbf{x}_W|$; and angle between charge and observation position $\theta = \cos^{-1}\frac{\mathbf{x}_o \cdot \mathbf{x}_W}{|\mathbf{x}_o||\mathbf{x}_W|}$. The first two parameters, $\frac{SW}{W^{1/3}}$ and $\frac{D}{W^{1/3}}$, are used to associate the explosive weight, the street width, and the observer location relative to the explosive location. The third parameter θ measures the degree to which the blast wave is concentrated in a single street wall on which the observer point lays. For the cross-road configuration in Figure 6, it is anticipated that the walls along the street where the explosion occurs will experience higher blast loads than the walls along the other three streets. Parameter θ, is used to account for the fact that the blast wave energy is not equally transferred in all four streets due to the presence of buildings in some of the paths.
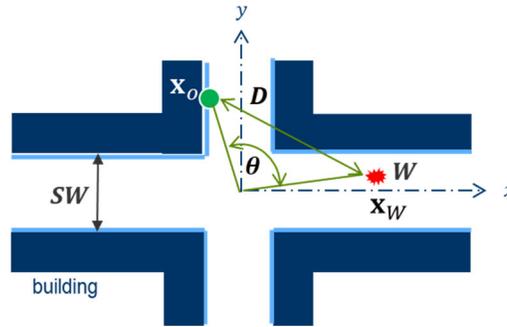

Figure 6. Input variables to RFA and their conversion to the input parameters to the regression model

These input parameters are used to develop a regression model based on minimizing the average root-mean-squared (RMS) difference defined as:

$$\frac{1}{N}\sum_{i=1}^{N}\sqrt{\left(\frac{P_s^i - P_p^i}{P_s^i}\right)^2} \tag{1}$$

where N is the total number of observation wall grids and P_s^i and P_p^i are pressure values at wall grid i obtained from simulation and predicted using regression analysis, respectively. A separate regression model is developed for each road configuration. For each configuration five discrete street widths are considered (10m, 15m, 20m, 25m, and 30m) and five different sizes of TNT charges (1,000kg, 1,500kg, 2,000kg, 2,500kg, and 3,000kg). For each combination of street width and TNT charge 10 different locations $\mathbf{x}_W$ for the explosive are considered. A total of 250 high fidelity simulations are conducted for generating the sample space used for creating the regression models. The ranges for the user defined parameters for which the regression models are valid are summarized in Table 3.

Table 3. Ranges for Input Data to Regression Models

	Cross-road	Dead-end
Street Width, SW (ft)	10 m ≤ SW ≤ 30 m	10 m ≤ SW ≤ 30 m
Explosive Weight, W (lb)	1000 kg ≤ W ≤ 3000 kg	1000 kg ≤ W ≤ 3000 kg
Explosive's X-location, x (ft)	0 ≤ x ≤ (50-0.5*SW) m	0 ≤ x ≤ (50-0.5*SW) m
Explosive's Y-location, y (ft)	0 ≤ y ≤ 0.5*SW m	0 ≤ y ≤ 0.5*SW m
Explosive's Z-location, z (ft)	z set to 1.25 m	z set to 1.25 m

Validation of Regression Models

Results for two configurations where the location of the explosive was not used in the sample space that generated the regression models are presented in Figures 7 and 8 for the cross road and the dead-end road configurations respectively. In each case a high fidelity simulation using LS-DYNA is also performed in order to compare the regression results against the actual simulations. In both cases the average RMS difference is small and the pressure patterns on the walls match well between the actual simulations and the regression models.
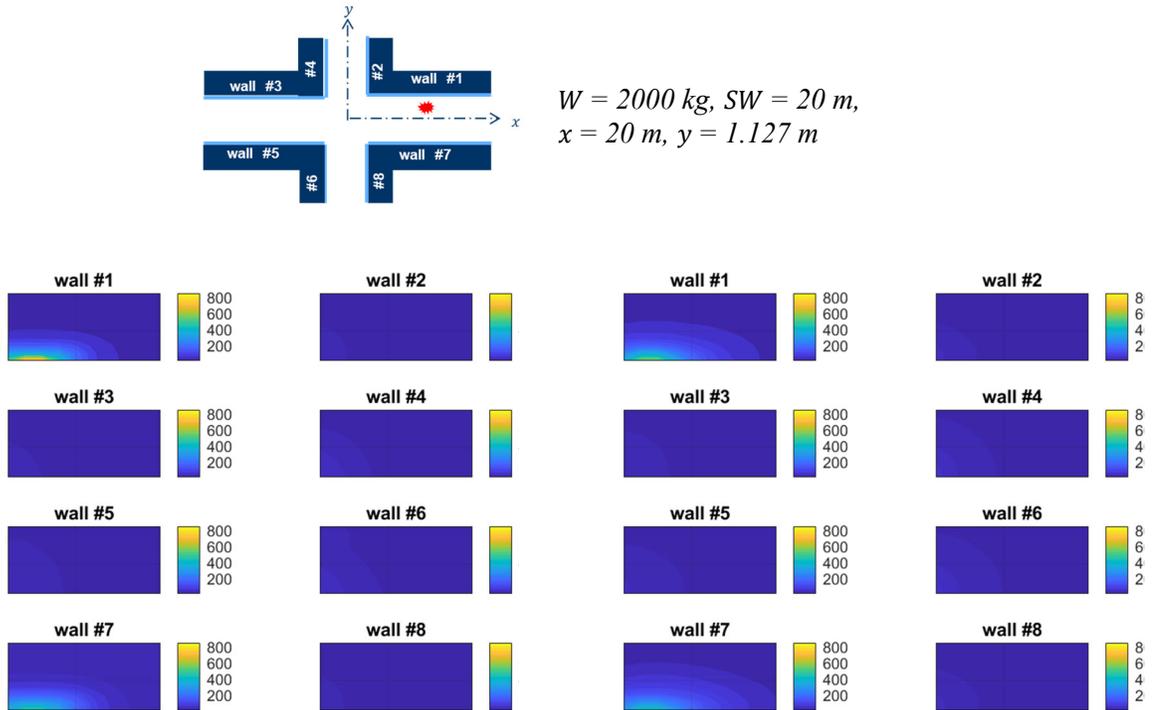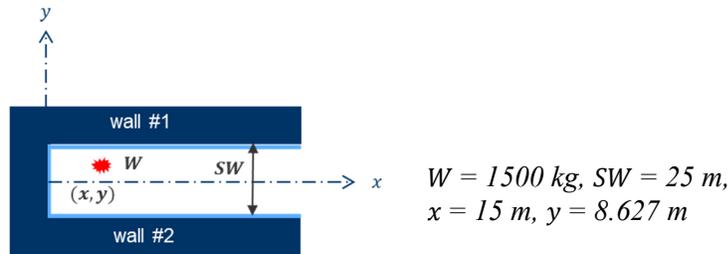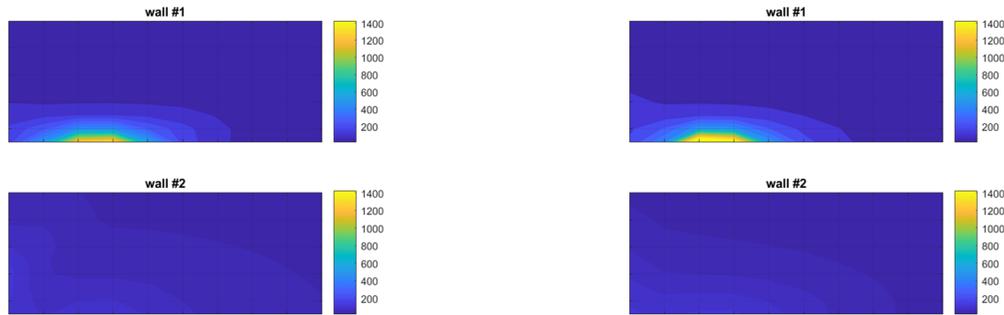
$W = 2000\ kg,\ SW = 20\ m,$
$x = 20\ m,\ y = 1.127\ m$

(a) Pressure (psi) obtained from simulation   (b) Pressure (psi) predicted using regression model
**Figure 7. Comparison between high fidelity simulations and the regression model for the cross-roads;
resulting RMS difference = 0.0076**

$W = 1500\ kg,\ SW = 25\ m,$
$x = 15\ m,\ y = 8.627\ m$

(b) Pressure (psi) obtained from simulation (left) and using regression model (right)
Figure 8. Comparison between high fidelity simulations and the regression model for the ded-end road; resulting RMS difference = 0.026

LETHALITY ASSESMENTS

In this Section the work done for evaluating the lethality range due to the blast pressure and the energy of the projectiles from the detonation of a small explosive is presented.

Blast Pressure Lethality Assessment

First the peak pressure of the blast wave is estimated using the K-B equations which originate from curve fitting numerous test data obtained from air and surface blast experiments (Kingery, 1984) and (US Army TM5-855-1, 1986). Through curve-fitting (Kingery, 1984) expressed the common logarithm of the peak blast pressure P as a polynomial function of the common logarithm of scaled distance $Z = R/W^{1/3}$, where R is the distance from an explosive to a point of interest and W is the explosive weight. The K-B equations can be conveniently expressed in the form of :

$$Y = C_0 + \sum_n C_n U^n \tag{2}$$

where $Y = \log_{10} P$ is the logarithm of peak blast pressure P and $U = K_0 + K_1 \log_{10} Z$ is a linear function of the common logarithm of scaled distance Z. Constants $K_{0,1}$, C_0, and C_n are all given as a result of curve fitting pressure data. The order of the polynomial is dependent on the type of blast test. If there is an explosion in an environment that contains nearby walls, then the reflections must be considered. These reflections enhance the amplitude of peak blast pressure so that the combined pressure of incident and reflected blast waves are greater than the incident wave pressure amplitude. In order to account for the existence of walls, the image method is used where the blast wave reflected from walls is considered originating from imaginary sources. The location of an imaginary source can be readily computed by identifying the explosive location normal to wall and by considering the wall as a plane of symmetry. Multiple planes of symmetry can be accounted by the image method.

The implementation of the aforementioned calculation method is validated through a comparison to LS-DYNA simulation results. The Load Blast Enhanced (LBE) approach in LS-DYNA uses the same empirical models with the K-B equations to calculate key blast parameters (peak pressure amplitudes, positive phase duration, etc.) and eventually creates a pressure time history using the Friedlander expression. The empirical models used in the LBE theory consist of a suite of polynomial functions of logarithmic variables, each of which was constructed to have the best fit to a set of data points obtained from free or surface air blast tests. For a target located at a distance R from a charge weight, W, this empirical air blast model is very quick and easy to use as it takes the scaled distance $R/W^{1/3}$ as input and calculates blast parameters from associated polynomial functions. Then the time-variant blast load at the target is expressed using Friedlander's exponential function.

A comparison is done between the two solutions by considering an explosive detonating on the ground. In the RTA computation the plane of symmetry is the ground surface and thus a single imaginary source of the same size as the

explosive is placed at the ground along with the explosive source. The LBE LS-DYNA results are compared in the Figure 9 with the RTA results with excellent agreement. This verifies the implementation of the K-B equations in the RTA.
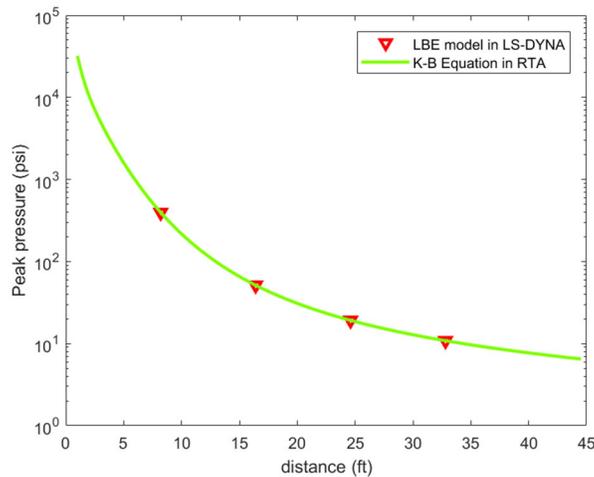

Figure 9. Comparison between the K-B Equation in RTA and the LS-DYNA LBE results

By considering the blast pressure wave evaluated by the K-B equations to be spherical, the radius of the spherical lethal region is evaluated based on the threshold pressure value associated with fatality. The blast over-pressure value of 40 psi (~ 276 kPa) is used as threshold fatality pressure level as suggested in (Baker, 1980). Given the threshold pressure level determining the range at which the blast pressure is equal to the threshold value is not straight forward as the K-B equations provide the blast pressure as a polynomial function of scaled distance (or range). Therefore, a bisection method is employed for computing the lethal range. Depending on the size of the explosive and the number of reflective surfaces the lethal range will change.

Shrapnel Lethality Assessment

The lethality of the projectiles is determined by computing first the initial velocities of the projectiles and then solving a system of nonlinear ordinary differential equations that provide the velocity along the trajectory of the projectiles. The initial velocity of a projectile is determined using the Gurney equation (Gurney, 1982) and (Kennedy, 2019). The Gurney equation provides an initial velocity of a fractured metal casing of an explosive for the initial velocity v_o:

$$v_o = \sqrt{2E} \cdot \left[\frac{C/M}{1 + \alpha(C/M)} \right]^{1/2} \tag{3}$$

Here, $\sqrt{2E}$ is the squared root of explosive energy per unit mass and is given by 8000 ft/s for TNT. In the equation above, C/M is the explosive to shrapnel mass ratio, which is in the range of $0.1 \leq C/M \leq 5.0$, and α accounts for shape of explosive and is given as α=0.6 for spherical explosive and α=0.5 for cylindrical explosive. In his study, Gurney showed that his equation is in a good agreement with measured data. Figure 10 presents a figure from (Kennedy, 2019) showing the correlation between Equation (3) and measurements.
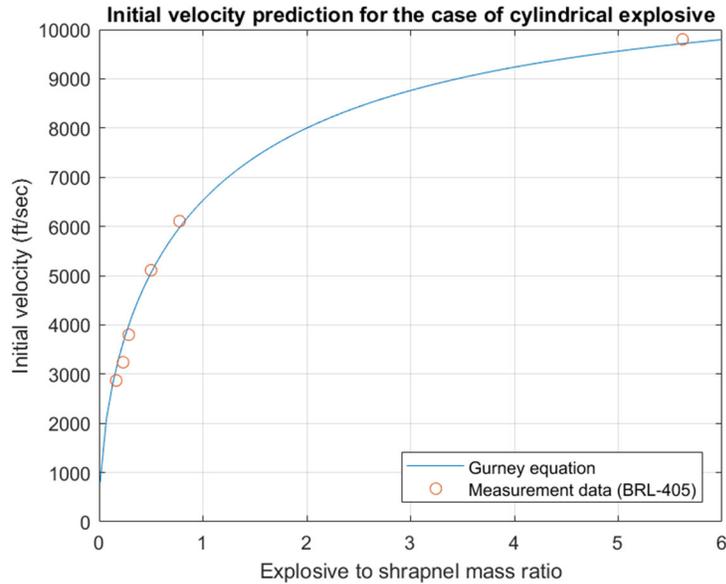
Figure 10. Comparison of Gurney's equation with measured data (Kennedy, 2019)

Once the initial velocity v_o of a projectile is determined, the differential equations for the vertical and horizontal components of its velocity, respectively, are given by :

$$\frac{dv_z}{dt} = -g - \frac{\rho_o C_d A}{2m}|v|v_z \tag{4}$$

$$\frac{dv_h}{dt} = -\frac{\rho_o C_d A}{2m}|v|v_h \tag{5}$$

The air resistance has been considered in deriving the equations. The equations are non-linear ordinary differential equations for the projectile velocity v, and in its horizontal and vertical components, v_h and v_z. Other parameters in the equations include the drag coefficient C_d, the air density ρ_o, the gravitational acceleration g, the projectile mass m and the cross-sectional area of projectile A. These non-linear system of ordinary differential equations are solved numerically to compute the trajectory profile.

The lethal region associated with a shrapnel is determined up to the range at which the shrapnel kinetic energy reaches the value of 58 ft-lb (~ 78 J) (US Army, 1990). In the RTA implementation the user defines the weight of the explosive, the weight of each projectile, the projected area of each projectile, and the number of projectiles (all projectiles are assumed to have the same weight and the same projected area). This information is converted to the parameters needed in Equations (3) – (5). As an example, for a shrapnel of mass 0.015 oz, an initial velocity of 8,000 ft/s, projected area of 1.8614e-04 ft^2 (a spherical shrapnel of 0.185" diameter), and launch angle of 45 degrees the following are the associated lethality region calculations. With the threshold kinetic energy value of 58ft-lb, the distance of shrapnel lethality region is determined to be equal to the range at which the kinetic energy of the shrapnel reaches the threshold value. In this case the shrapnel is following the trajectory obtained from numerical solution of the system of ODEs given in Equations (4) and (5). After launching with initial velocity of 8000 ft/s the shrapnel decelerates rapidly due to air resistance and its kinetic energy becomes less than the threshold value of 58 ft-lb in just 37 msec. At time 37 msec, it is found that the shrapnel is flying at the velocity of 1995 ft/sec and the distance that the shrapnel travelled amounts to 137 ft. The travelled distance of 137 ft is considered to be the distance determining the lethal zone.
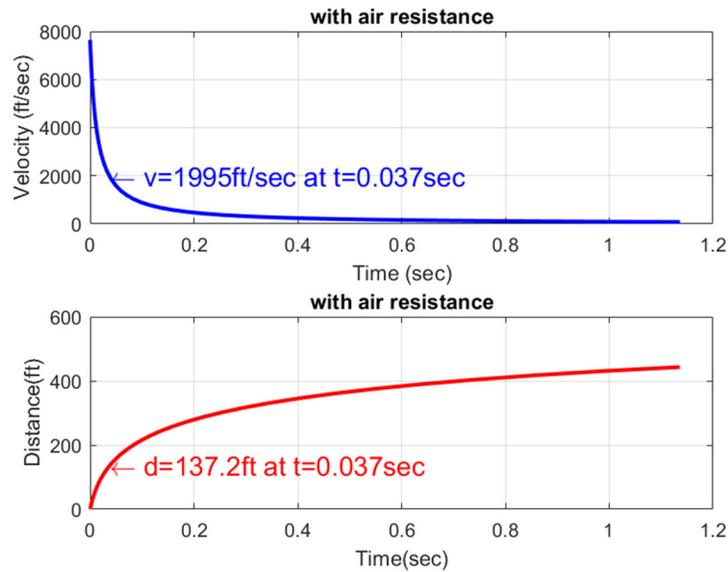
Figure 11. Calculation of velocity and lethal range of shrapnel through the numerical solution of trajectory equations

SUMMARY

The RTA allows a user without specialized knowledge on explosive simulations, to obtain basic information for determining the threat level on buildings and humans from the detonation of explosives in an urban environment. A regression model is used for determining the maximum pressure load applied on building structures from the detonation of an explosive. A semi-empirical approach is used for determining the lethal regions from the detonation of a threat that combines an explosive and projectiles. The theoretical background implemented in the RTA is presented in this paper for completing the understanding of how the new simulation tool works. Results computed by the RTA are verified either through comparison to test data from the open literature or by comparison to other simulation tools. In the future regression models for additional urban road configurations can be added to the RTA using the established methodology.

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