Development of a Regression Model for Blast Pressure Prediction in Urban Street Configurations

Sungmin Lee
Michigan Engineering Services, LLC

Nickolas Vlahopoulos
University of Michigan

Syed Mohammad
Department of Homeland Security

Abstract

Structural damage assessment due to explosive detonations in an urban setting requires a prediction tool for air-blast loads on buildings within the region. In this study, dead-end and cross-roads configurations are considered for blast wave simulations using Multi-Material Arbitrary Lagrange-Eulerian (MM-ALE) with mapping, with aim at developing a prediction model using regression analysis. Variations in street width and charge size and location are considered in constructing these street configurations. For all simulation models we use the uniform building height of 50 m and the identical street length of 50 m, and assume a vehicle bomb, meaning that a charge is carried by a vehicle such as pickup truck and detonates 1.25 m above ground. MM-ALE simulations with mapping, which is available in LS-DYNA®, will be used to achieve accuracy with reasonable amount of computational efforts. Mapping of solutions from 1D to 2D and then from 2D to 3D constitutes our three-step multi-material ALE simulation approach. 1D ALE analysis is performed for the spherically symmetric region between the explosive charge and the ground; 2D ALE analysis for the axi-symmetrical region from explosive location to closest wall; and 3D ALE analysis for the rest of the analysis domain. The ALE mapping approach is validated by comparing its simulation results to experimental data from literature. For the development of a fast running blast model we use regression analysis to estimate the relationship between an important blast simulation output variable (peak pressure) and input variables including street width, explosive size, explosive location, and type of street configuration. Regression analysis results are compared with actual simulation results.

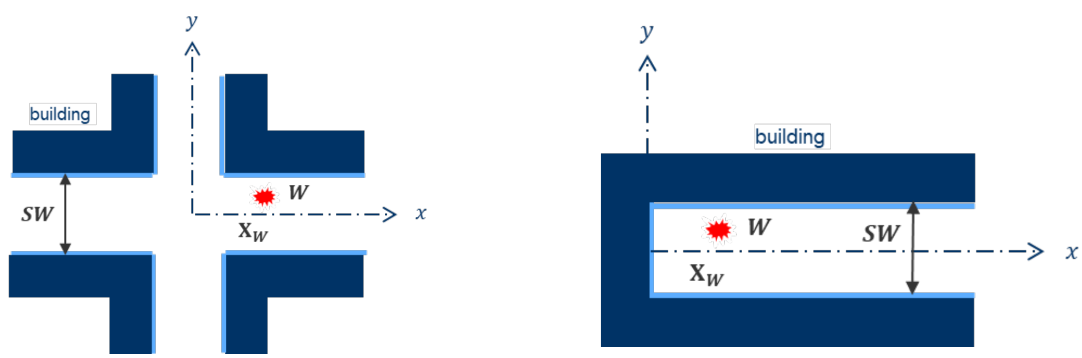
Introduction

In this study, we present a blast pressure prediction model for quick evaluation of air-blast loads on buildings in urban street configurations. The prediction model is developed by applying regression analysis to peak pressure results gathered via extensive blast wave simulation of various vehicle bomb detonation scenarios in dead-end and cross-roads configurations. The blast wave simulation was carried out in LS-DYNA using the Multi-Material Arbitrary Lagrange-Eulerian (MM-ALE) solver with 1D-to-2D-to-3D mapping, through which we have achieved considerable reduction in computation time with nearly no degradation in simulation accuracy. The mapping is available in LS-DYNA and was applicable by leveraging symmetry in the blast model for vehicle bomb detonation in either type of street configuration. In what follows we first present the MM-ALE blast simulation process in more detail, along with descriptions on input and output variables and their range of variation. The mapping technique used to achieve accuracy with reasonable amount of computational efforts is also elaborated. It is followed by a discussion on the development of the regression model. The proposed fast-running blast-pressure prediction model is validated by comparing to other computational simulation results, which is reported at the end.

Blast Simulation in Urban Street Configurations 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 [1]. In air blast simulations with the MM-ALE solver, both explosive and 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 [2, 3].

An analysis strategy available in LS-DYNA to reduce the computational cost associated with using the MM-ALE solver is mapping one-dimensional (1D) or two-dimensional (2D) ALE simulation results to a three-dimensional (3D) ALE model [4]. 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.



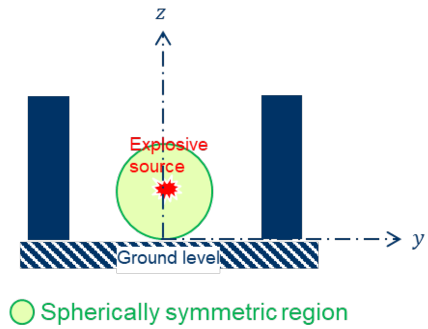
(a) Blast in crossroad-road street intersection (b) Blast in dead-end street

Figure 1. Urban blast configurations and input variables used for blast simulations

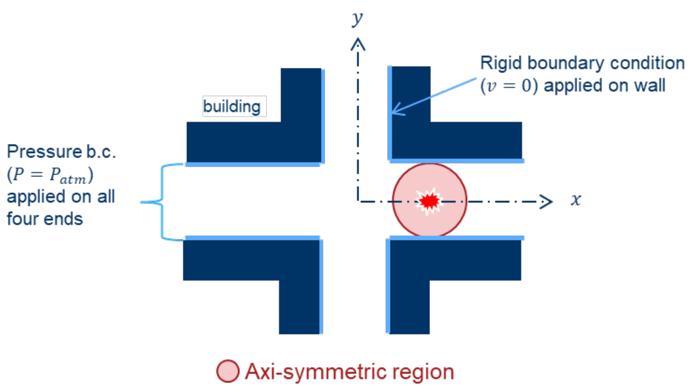
Figure 1 shows dead-end and cross-roads configurations considered for blast wave simulations to develop a fast-running prediction model using regression analysis. In constructing these street configurations we will use every combination of five discrete street width *SW* (10 m, 15 m, 20 m, 25 m, and 30 m) and five different sizes of TNT charge *W* (1000 kg, 1500 kg, 2000 kg, 2500 kg, and 3000 kg), resulting in a total of 25 disparate analysis cases. For all simulation models we use the uniform building height of 50 m and the identical street length of 50 m, and assume a vehicle bomb, meaning that a charge is carried by a vehicle such as pickup truck and detonates 1.25m above ground. With the coordinate system defined as in Figure 1, location of the vehicle bomb, $\mathbf{x}_W = (x_W, y_W)$, will change discretely over the region of positive x and y. Due to symmetry of the model about the x-axis (also y-axis for cross-roads configuration), the same simulation results obtained for each bomb location can be reused for the situation where a bomb is located opposite across the street.

The aforementioned multi-material ALE simulations with mapping, which is available in LS-DYNA, will be used to achieve accuracy with reasonable amount of computational efforts. Mapping of solutions from 1D to 2D and then from 2D to 3D constitutes our three-step multi-material ALE simulation approach. 1D ALE analysis is performed for the spherically symmetric region between the explosive charge and the ground (see Figure 2.a);

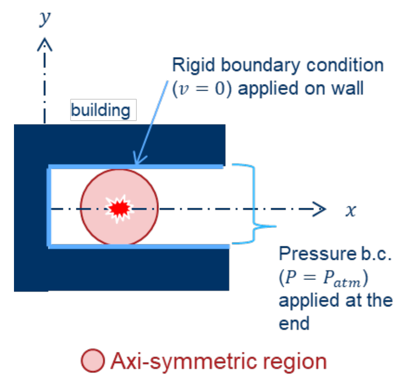
2D ALE analysis for the axi-symmetrical region from explosive location to closest wall (see Figure 2.b and 2.c); and 3D ALE analysis for the rest of the analysis domain. Appropriate boundary conditions (symmetry and rigid boundary conditions on walls and pressure boundary conditions on free surfaces) are applied as shown in Figure 2.



(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 2. Spherically-symmetric and axi-symmetric regions for ALE blast simulations in urban street configurations

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, and their section properties, which controls 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 '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 2D ALE analysis.

The 2D ALE mesh consists of axi-symmetric solid elements that is used to model the axi-symmetric region defined by half the street width. 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 (name of the file used for mapping is specified by the first 'map' command), 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.

Exactly the same 'ALE1D' and 'ALE2D' analyses can be carried out for both dead-end and cross-roads configurations, as long as the street width is identical. 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. The figure below 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 the figure below.

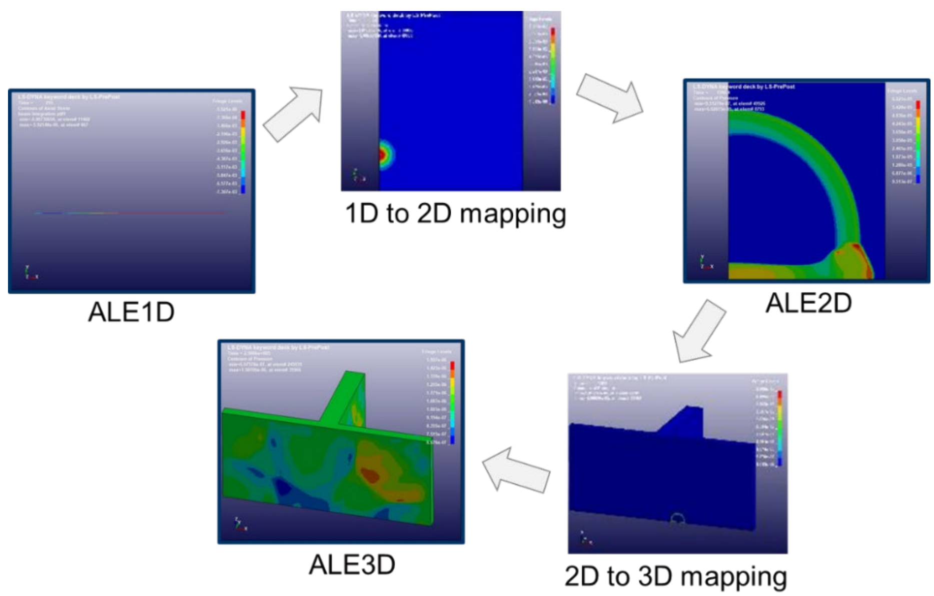
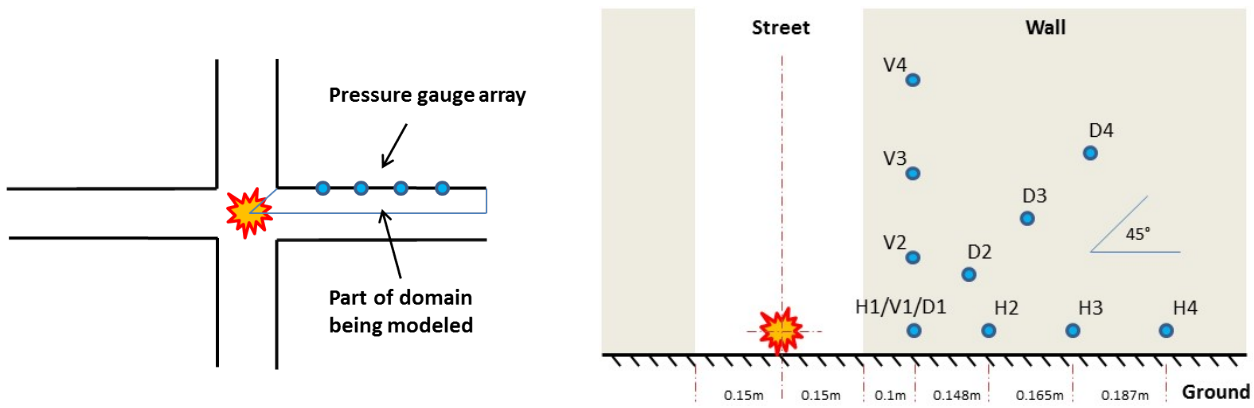


Figure 3. Three-step blast wave simulation procedure through mapping in LS-DYNA

Comparison of LS-DYNA blast simulation results to test data

The MM-ALE analysis with 1D to 2D to 3D mapping described in the previous section is applied to modeling an air blast event in a cross-road street configuration. The ALE mapping approach is validated by comparing its simulation results to experimental data from literature [5]. A series of experiments of blast events for a cross-road configuration have also been conducted and reported in [5]. In the experiments, a 1/50th scale model was built using steel plates. The test setup assumed the street width of 0.3 m (corresponds to 15 m at full scale) and the buildings height of 1 m uniformly along the street. The applied explosive charge was 11.13g SX2 plus approximately 1g detonator, which is equivalent to about 12-13 g of TNT, and was detonated at 25 mm above ground, which at a full scale would correspond to a vehicle bomb of approximately 1625 kg TNT.
A plan view of the blast test configuration used in [5] is shown schematically in the figure below. 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 pressure gauge locations used in the experiments is also shown in the figure. 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 4. Schematics of blast test setup in a cross-road configuration.

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). This took only about 30 min to conduct LS-DYNA simulations for the 1/4th of the domain. Peak pressure is measured at the pressure gauge locations and the test data are listed in the table below, together with simulation results obtained from ALE analyses with mapping.

Notice that the pressure measurement points, H1, V1, and D1 are located physically at the same position and one may expect the same level of pressure from all three of them. The peak pressure values recorded at the three pressure gauges, however, differ and varies 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 experimental data.

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

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

Blast Pressure Prediction Model for Urban Street Environments

Blast simulations, even with mapping approach, are an expensive computational endeavor and therefore it usually takes a long time to evaluate blast loads on structures along and across street. It is more so for problems without symmetry which occurs when an explosive detonates at an arbitrary location in a complicated urban street configuration. A quick running computational model is a necessity for the calculation of blast load due to explosion in an urban environment.

For the development of a fast running blast model we use regression analysis to estimate the relationship between an important blast simulation output variable (peak pressure) and input variables (user-specified variables to define a blast event in urban environment). These input variables include street width SW, explosive size W, explosive location $\mathbf{x}_W = (x_W, y_W)$, and type of street configuration. In our analysis, we, among several urban street configurations, only consider two representative types of street configurations: cross-road intersection and dead-end street. The figure below illustrates the input variables for each configuration, respectively.

An additional parameter that we need to consider in regression analysis is observer location $\mathbf{x}_o = (x_o, y_o)$ at which numerical value of the peak pressure is computed. In blast simulations, we created an equi-distant 10×10 grid on each wall surface along street, i.e. a total of 100 grid points, as shown below. Each grid point was used as a tracer point in LS-DYNA to track 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 blast simulation and its peak pressure value P_o is used for subsequent regression analyses. These grid points also constitute a wall mesh used for display, details of which will be discussed in the following section.

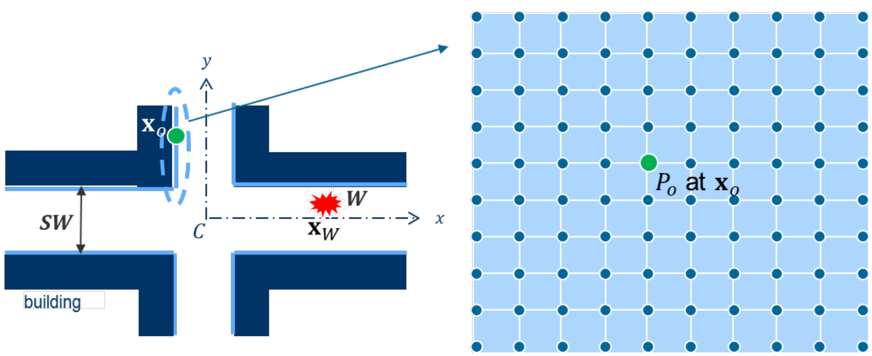


Figure 5. Grid points used for recording pressure

The aforementioned input and output variables used for regression analysis are summarized in the following flow chart. This flow chart implies that the type of urban configuration is already known.

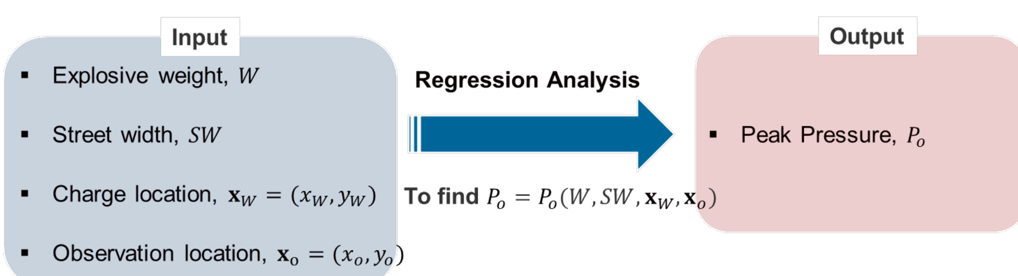


Figure 6. Input and output variables of regression analysis for blast pressure calculation

The regression analysis process yields a regression model, which contains a mathematical expression for the output variable (peak pressure) in input variables (explosive weight, street width, charge location, observation location, and type of urban configuration). This expression may be best sought using scaled distance terms as peak pressure, in case of free and surface air blast, is known to be dependent on scaled distance [6, 7]. Given W, SW, $\mathbf{x}_W$, $\mathbf{x}_\mathbf{o}$, as shown below

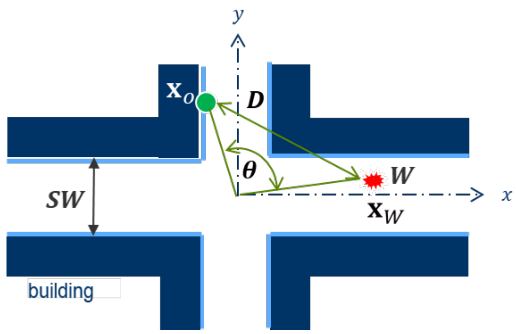


Figure 7. Input variables and their derived variables used for regression analysis

we first seek to compute:

- Scaled street width, $\frac{SW}{W^{1/3}}$
- Distance from charge to observation position, $D = |\mathbf{x}_\mathbf{o} - \mathbf{x}_\mathbf{W}|$ and then scaled distance, $\frac{D}{W^{1/3}}$
- Angle between charge and observation position, $\theta = \cos^{-1}\frac{\mathbf{x}_\mathbf{o}\cdot\mathbf{x}_\mathbf{W}}{|\mathbf{x}_\mathbf{o}||\mathbf{x}_\mathbf{W}|}$

The first two parameters, $\frac{SW}{W^{1/3}}$ and $\frac{D}{W^{1/3}}$, are used to see how explosive weight, street width, and observer location relative to explosive location affects peak pressure. The third parameter θ measures the degree to which the blast wave is concentrated in a single street wall on which the observer point lies. For the cross-road configuration shown above, 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. The parameter θ, therefore, is used to account for the fact that the blast wave energy is not equally conveyed in all four streets.
These input parameters are used to find a regression model that gives the least 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 wall nodes and P_s^i and P_p^i are pressure values at wall node i obtained from simulation and predicted using regression analysis, respectively.

Validation of Blast Pressure Prediction Model

Regression analysis results are compared with actual simulation results at wall display nodes. As mentioned in the previous section each wall consists of equally spaced 10 by 10 grid points, as shown in Figure 5. Each wall is modelled as a 50m by 50m square domain made up of 9 by 9 cells, each cell comprising four grid points (or display wall nodes). A distribution of peak pressure over a wall is obtained by assigning appropriate pressure value to every nodal point as shown below.

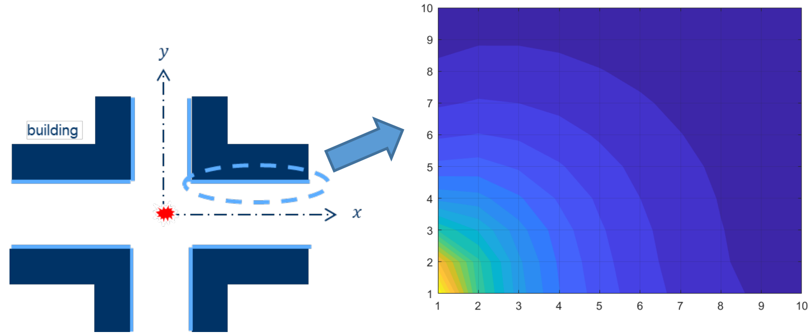
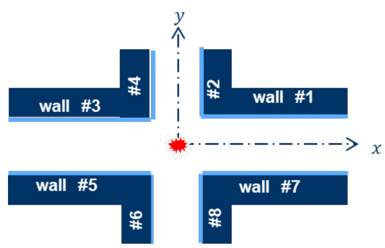


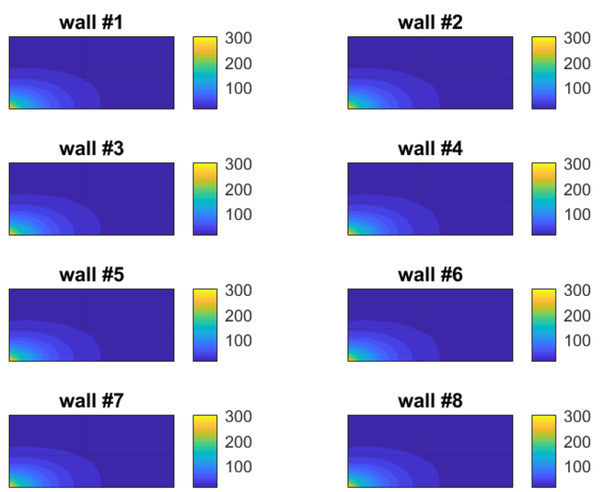
Figure 8. Contour plot of peak pressure distribution over a wall when an explosive detonates at the center

In order to show relative difference in peak pressure between simulation and regression model RMS difference, which is defined in Equation (1), is computed at each grid point and is averaged to calculate a numeric measure of the difference. Three disparate cases, all in cross-road configurations, are considered for the comparison between LS-DYNA simulation results and regression model prediction. One is the case where an explosive is located at the center of cross-road, another is with explosion at the middle of street, and the other is explosion at an off-center location. Street width, explosive size, and explosive location for each of the three blast cases are given in the figures below. Wall indices and contour plots of pressure distribution over walls are also shown in the figures. Averaged RMS differences have been computed for all three cases and they result in 0.0057, 0.0074, and 0.0076, respectively.

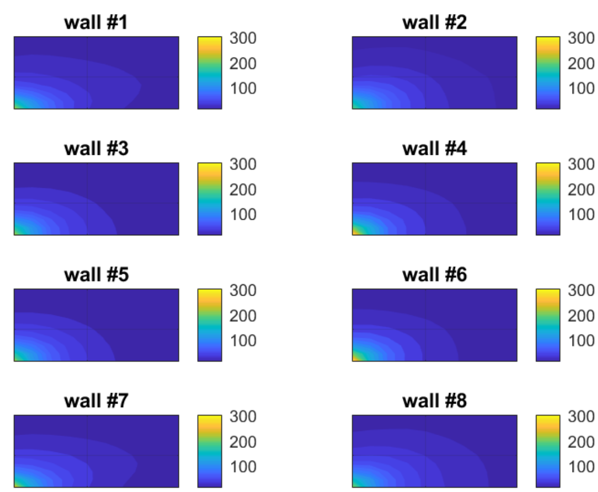


W = 1650 kg, SW = 15 m, x = 0 m, y = 0 m

(a) Input parameters

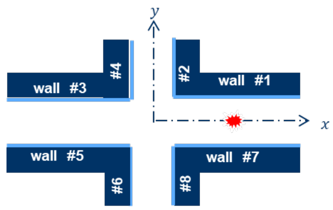


(b) Pressure (psi) obtained from simulation



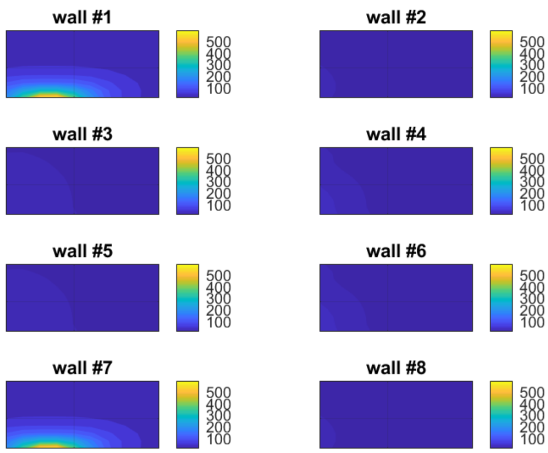
(c) Pressure (psi) predicted using regression model

Figure 9. Explosion at the center of cross-road

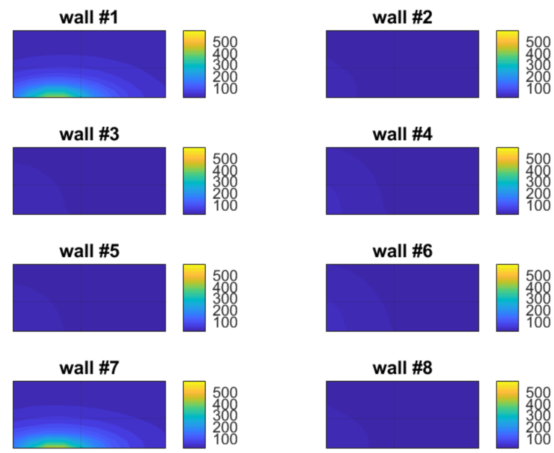


W = 1500 kg, SW = 20 m,
x = 25 m, y = 0 m

(a) Input parameters

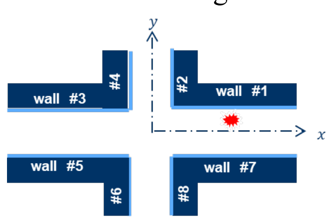


(b) Pressure (psi) obtained from simulation



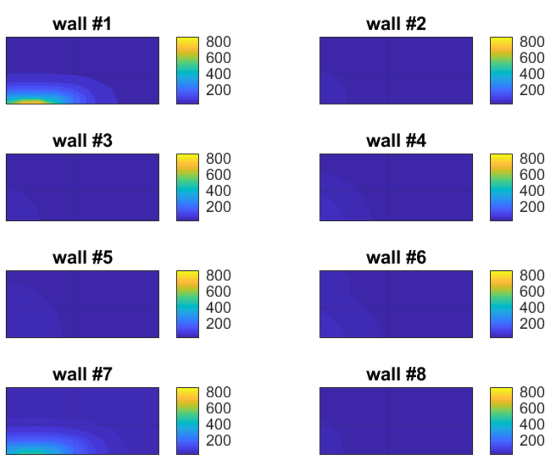
(c) Pressure (psi) predicted using regression model

Figure 10. Explosion in the middle of street

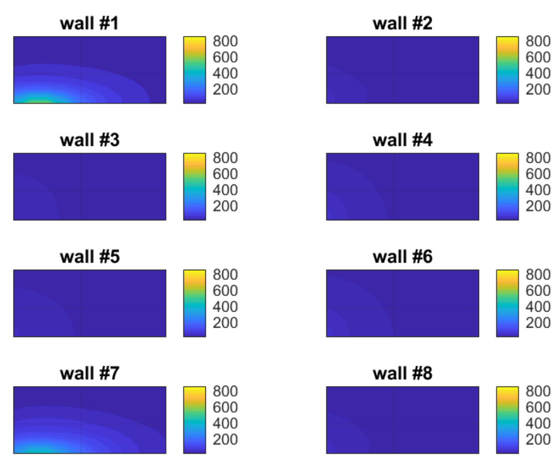


W = 2000 kg, SW = 20 m,
x = 20 m, y = 1.127 m

(a) Input parameters



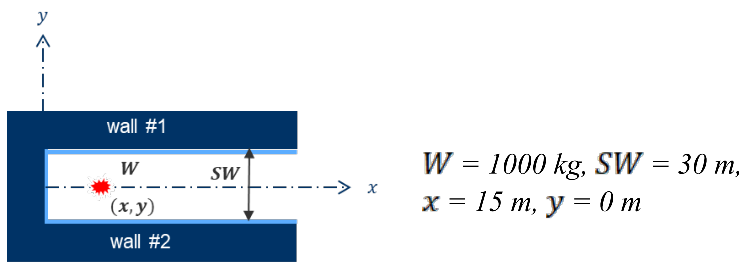
(b) Pressure (psi) obtained from simulation



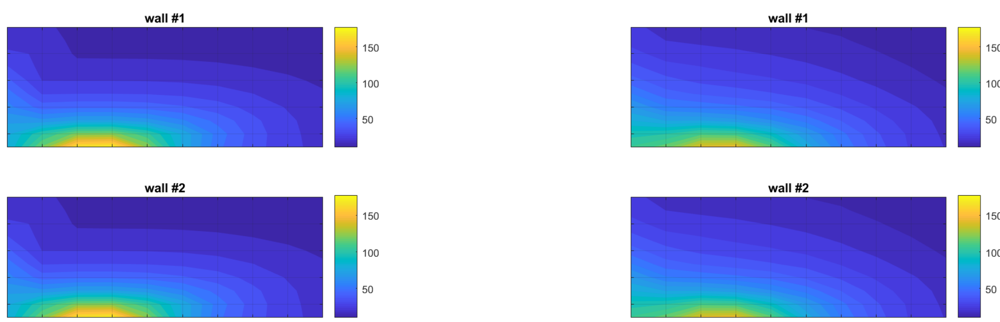
(c) Pressure (psi) predicted using regression model

Figure 11. Explosion at an off-center location

For dead-end configurations LS-DYNA blast simulations have been carried out using every combination of five discrete street width (10m, 15m, 20m, 25m, and 30m) and five different sizes of TNT charge (1000kg, 1500kg, 2000kg, 2500kg, and 3000kg), with explosive location changing discretely along and across street. For each combination of street width and charge size, blast simulations considered about 4-5 different charge locations along the center line of street and the same number of off-center charge locations. It should be also noted that all blast simulations used multi-material ALE models and followed the mapping process explained in previous sections. Pressure output data obtained from all the simulations have been used for regression analysis to create the regression model implemented in the blast app. The validity of the regression model for dead-end configurations is determined through comparison between LS-DYNA simulation results and regression model prediction at some new explosive locations.
Two new explosive locations are considered for the verification study. The first case is when 1000 kg TNT is located at 15m away from the dead-end and the explosive is at the center line of street, making the problem symmetric, as shown below. Averaged RMS difference was computed for the case, which resulted in 0.016.



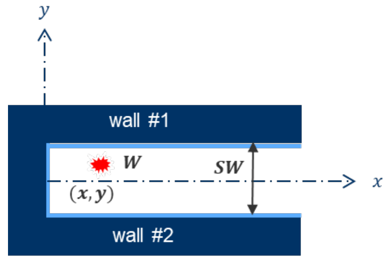
(a) Input parameters



(b) Pressure (psi) obtained from simulation (left) and using regression model (right)

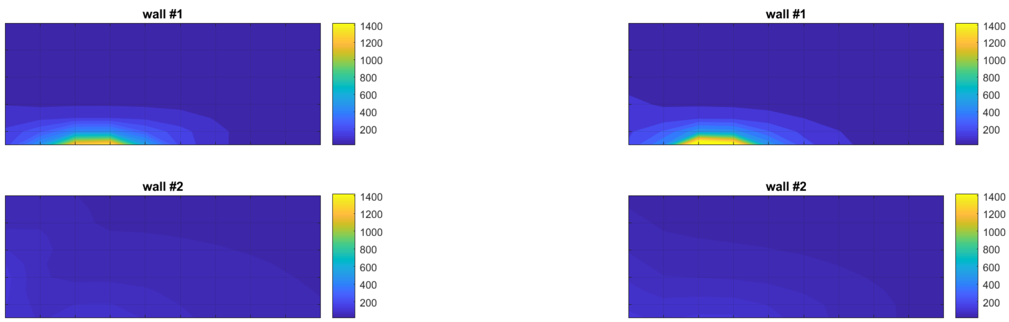
Figure 12. Explosion in the middle of dead-end street configuration

The second problem considered for the verification study is illustrated in the figure below. As can be seen, 1500kg TNT is 15m away from the dead-end and is close to wall so that the problem is not symmetric. Pressure distribution over the walls is compared between LS-DYNA simulation and regression model. Averaged RMS difference was 0.026 for this case.



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

(a) Input parameters



(b) Pressure (psi) obtained from simulation (left) and using regression model (right)

Figure 13. Explosion at an off-center location in dead-end street configuration

Conclusions

In summary, it has been demonstrated that vehicle bomb explosion in urban street configurations can be modeled in LS-DYNA using the MM-ALE formulation with mapping of solutions from 1D to 2D and then from 2D to 3D. This blast modeling and analysis approach has been shown to achieve accuracy in estimating peak blast pressure, with reasonable amount of computational efforts. The ALE mapping approach was validated by comparing its simulation results to experimental data from literature. For the development of a fast running blast model we used regression analysis to estimate the relationship between an important blast simulation output variable (peak pressure) and input variables including street width, explosive size, explosive location, and type of street configuration. The regression-based formula between peak blast pressure and blast parameters was also validated by comparing regression analysis results with actual simulation results.

Acknowledgement

This research was supported by the Department of Homeland Security Science and Technology Directorate, contract No. 70-RSAT-19-C-00000046.

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