Validation of LS-DYNA® MMALE with Blast Experiments

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Abstract

The general multi-material arbitrary Lagrangian-Eulerian (MMALE) solver is available in the finite element analysis software LS-DYNA®. In the context of blast simulation, this solution approach involves explicit modeling of the explosive, the blast transmission media and the structure subjected to the blast within the MMALE solver.

This paper presents a validation study of the LS-DYNA MMALE approach with existing experimental studies of blast wave clearing and blast in an urban environment, as well as numerical results from the finite volume method software Air3d. The overpressure histories, peak overpressures and impulses are compared. It is demonstrated that the results from LS-DYNA produce excellent correlation with experimental and Air3d simulation results. Whilst this is a validation with prior knowledge of the experimental results, it suggests that the LS-DYNA simulation capability is accurate for the cases studied.

Introduction

The state-of-the-practice for computing air blast effects due to detonations of chemical explosives ranges from the use of the empirical design databases developed by different parties to numerical evaluation using computational fluid dynamics (CFD) simulations.

There are several codes for calculating fluid loadings on structures. Some of them are stand-alone CFD software such as ANSYS CFX, ANSYS FLUENT, OPENFOAM, and STAR. Others are embedded in general purpose finite element software such as LS-DYNA® (LSTC, 2012) and ANSYS AUTODYN. Among the stand-alone CFD codes, it is worth mentioning that Air3d (Rose, 2006) was developed specifically for air blast calculation with finite volume method. Air3d uses an advection upstream splitting method together with the MUSCL(monotone upstream-centered scheme for conservative laws)-Hancock time integrator.

The general multi-material arbitrary Lagrangian-Eulerian (MMALE) solver is available in the finite element analysis software LS-DYNA. In the context of blast simulation, this solution approach involves explicit modeling of the explosive, the blast transmission media and the structure subjected to the blast within the MMALE solver. Sophisticated equations of state (EOS) control the behavior of blast transmission media and explosives, additionally burn models control the explosive detonation. The structure is generally treated as Lagrangian and fluid-structure interaction (FSI) is used for coupling with the MMALE domain.

The following sections present a validation study of the LS-DYNA MMALE approach with existing experimental studies of blast wave clearing and blast in an urban environment, as well as numerical results from Air3d. Three-dimensional analyses were conducted, followed by comparisons of overpressure histories, peak overpressures and impulses.

Blast Wave Clearing

When a blast wave strikes a structural surface, the reflected pressure and impulse produced on the surface may be influenced by the propagation of a rarefaction or clearing wave from the free edges. This is referred to as blast wave clearing or diffraction loading.

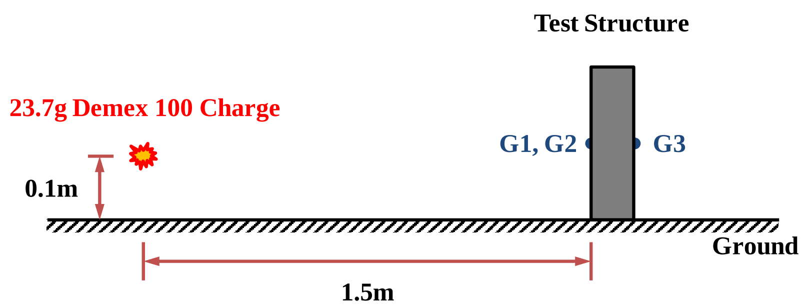

Figure 1: Schematic of the test configuration

The experiment for a comparison against numerical results of Air3d and LS-DYNA was taken from a series of 1/10-scale experiments for a blast wave clearing investigation (Rose and Smith, 1995; Rose 2001). The test configuration is showed in Figure 1. The height of the charge above the smooth and flat surface is 0.1 m. The stand-off distance of the charge from the test structure is 1.5m. The charge used in the experiments was 23.7g Demex 100 explosive initiated by an electric detonator. Rose and Smith (1995) derived from the side-on overpressure records that the maximum pressure TNT equivalence ranges from 0.6 to 2.2 (median 1.32) and the positive phase impulse TNT equivalence ranges from 0.8 to 2.4 (median 1.04). A TNT equivalence of 1.15 for Demex 100 was assumed in Smith *et al.* (1999) and Rose (2001), and was adopted in this study. The charge weight used in the analysis is 27.26g TNT, providing a scaled range of 4.964 m/kg$^{1/3}$.

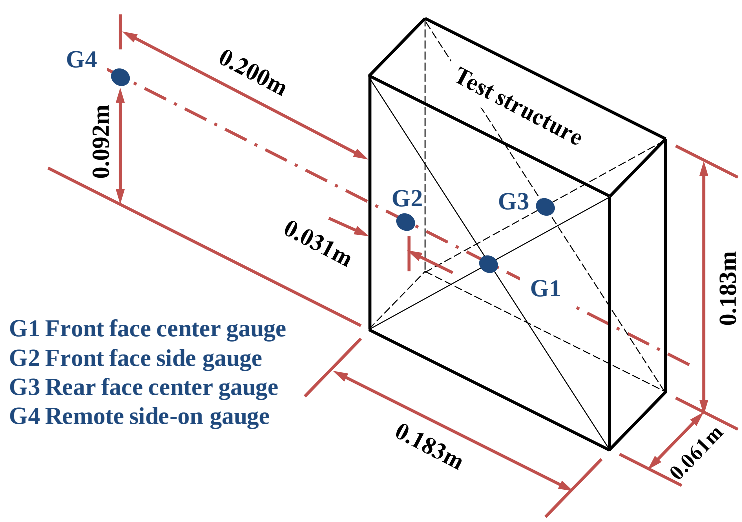

Figure 2: Details of test structure and pressure gauges

The test structure was made from 10mm steel plate with gauges (G1 to G3) mounted flush on the front and rear surfaces. A side-on pressure gauge G4 was installed at the same radial distance from the charge as gauge G1. The structure and the locations of the pressure gauges are shown in

Figure 2. The ambient pressure measured on the first and second day of testing was 100.55kPa and 101.12kPa.

A schematic of LS-DYNA the model is shown in Figure 3. Only half of the problem is simulated because of symmetry. The half domain is 2.4m in the charge-target direction and 2.0m in the transverse directions. The structure is modeled as rigid. The explosive and air domain are modeled with the MMALE approach, using a first order donor-cell (piecewise constant) and half-index-shift advection algorithm, conserving total energy over each advection step.

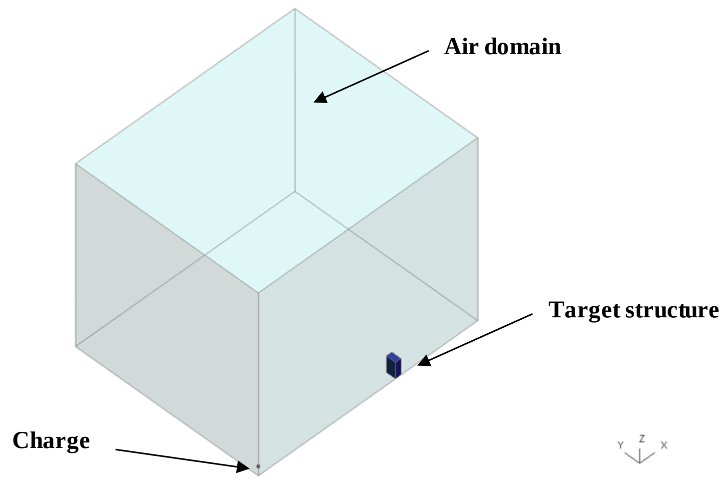

Figure 3: LS-DYNA half model for blast wave clearing test

The air is modeled as perfect gas with zero shear strength. Material model MAT_NULL and EOS model EOS_LINEAR_POLYNOMIAL were used. The reference density of air is assumed ρ_0 = 1.2g/m^3. The equation of state is assumed linear in internal energy as given by

$$P = (C_4 + C_5\,\mu)\,e_{ipv0} = (\gamma - 1)\,(\rho/\rho_0)\,e_{ipv0}$$

where $C_4 = C_5 = \gamma - 1 = 0.4$, γ is ratio of the heat capacity at constant pressure C_P to heat capacity at constant volume C_V, μ is the volumetric parameter $\mu = \rho/\rho_0 - 1$, ρ is the current density, e_{ipv0} is the initial internal energy per reference volume $e_{ipv0} = P_0 v_0/(\gamma - 1)$. Initial pressure was specified P_0 = 101kPa and initial relative volume was specified v_0 = 1.0.

The explosive is modeled with Jones-Wilkins-Lee high explosive EOS. Material model MAT_HIGH_EXPLOSIVE_BURN and EOS model EOS_JWL were used. The reference density was specified ρ_0 = 1.6kg/m^3. The detonation velocity was specified D = 6930m/s. The Chapman-Jouget pressure was specified P_{CJ} = 21GPa. The JWL EOS parameters were specified as A = 3.7, B = 0.032, R_1 = 4.2, R_2 = 1.0, ω = 0.3. The initial internal energy per reference volume was specified e_{ipv0} = 7.3GPa such that the initial internal energy per mass is 4.6MJ/kg. The initial relative volume was specified v_0 = 1.0.

For the balance between accuracy and computational expense, a finer axisymmetric mesh was used for smaller region adjacent to the charge, and a coarser three-dimensional mesh for the whole domain. An initial axisymmetric MMALE analysis was conducted with a termination time of t = 1.0ms, which is earlier than when the pressure wave reaches the test structure. The uniform rectangular element size was 2.0mm. The charge was center detonated. These axisymmetric results were then mapped to the three-dimensional half model (Figure 3) using the mapping algorithm developed by Aquelet and Souli (2008).

Mesh sensitivity of the three-dimensional results were assessed. Four meshes, with element sizes of 10mm, 20mm, 30mm, and 40mm, were used for the three-dimensional analyses. The comparisons of overpressure and impulse histories for gauge G1 are plotted in Figures 4 and 5, respectively. Reasonable convergence in both overpressure and impulse were observed for G1 and all other gauges (not shown).

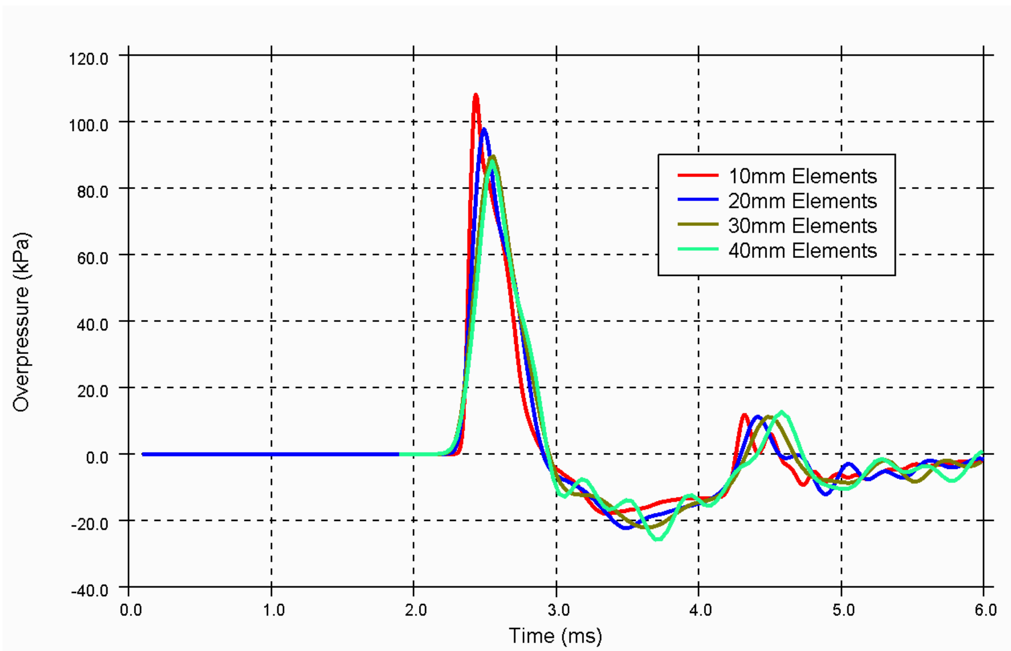

Figure 4: Comparison of overpressure history for different mesh sizes (Gauge G1)

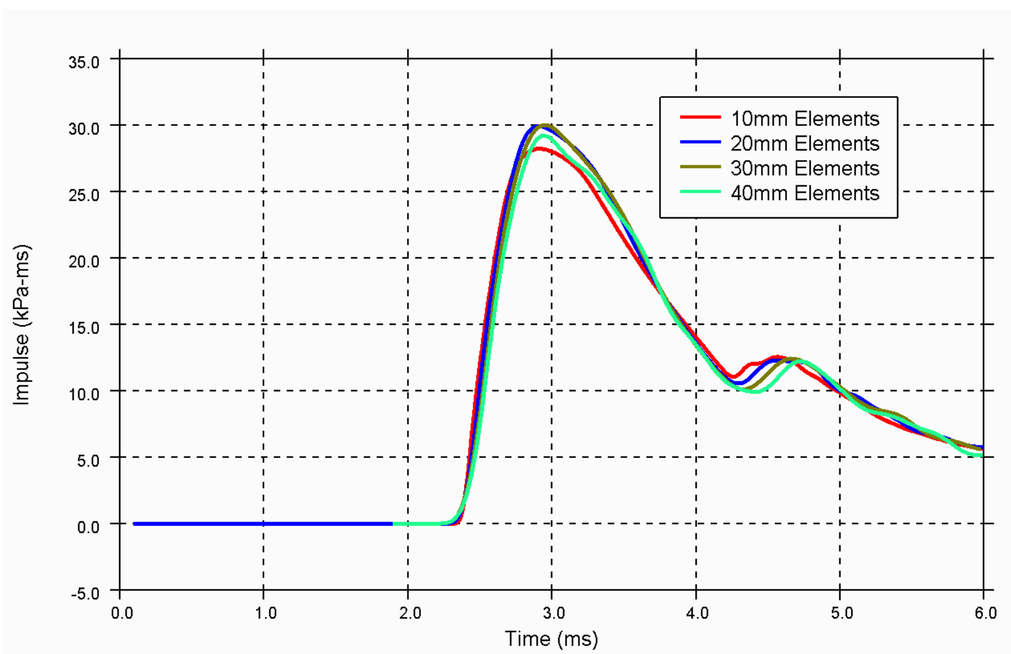

Figure 5: Comparison of impulse history for different mesh sizes (Gauge G1)

The overpressure contour simulated by LS-DYNA with the 10mm element size at time t = 3.050ms at the symmetry section is shown in Figure 6. The overpressure was calculated as the total pressure less the ambient pressure P_0 = 101kPa. The reflected and diffracted wave are observed in the figure, corresponding to the two major peaks in pressure-time histories at gauges G1 and G3 shown in Figure 7. The blue dots on Figure 6 indicate the locations of gauges G1 and G3 on the front and rear surfaces, respectively, of the structure.

An Air3d analysis was also conducted using the procedure documented in Rose (2001, 2006). Cell size of 5.0mm was used in the axisymmetric analysis. A similar half model was used in the three-dimensional analysis. The half domain was 2.5m in the charge-target direction and 0.5m in the transverse directions. The cell size was 10.0mm, and the CFL number was specified as C = 0.5 (The time step is calculated from the Courant-Friedrichs-Lewy condition, $\Delta t = Ch / (c + v_{max})$, where h is the cell size, c is the sound speed and v_{max} is the maximum material velocity).

Pressure histories at gauges G1 to G4 from the experiment, Air3d and LS-DYNA are compared in Figure 7. The agreement between the simulations and the experiments for the first shock wave peak are excellent. The timing and shape of the overpressure peaks at G1 and G2 were captured accurately by the simulations. The second peaks at G1 and G2 occur earlier in the experiment than predicted by the simulations. The second pressure peak at G3 is not captured in the simulations. The side-on pressure at G4 also suggest excellent agreement between the experiment and the simulations. Impulses were generally overestimated by the simulations. The errors of LS-DYNA impulses relative to the experiments at gauges G1 to G4 are 8%, 14%, -8% and 4%, respectively. The overall accuracy of the simulations is satisfactory.

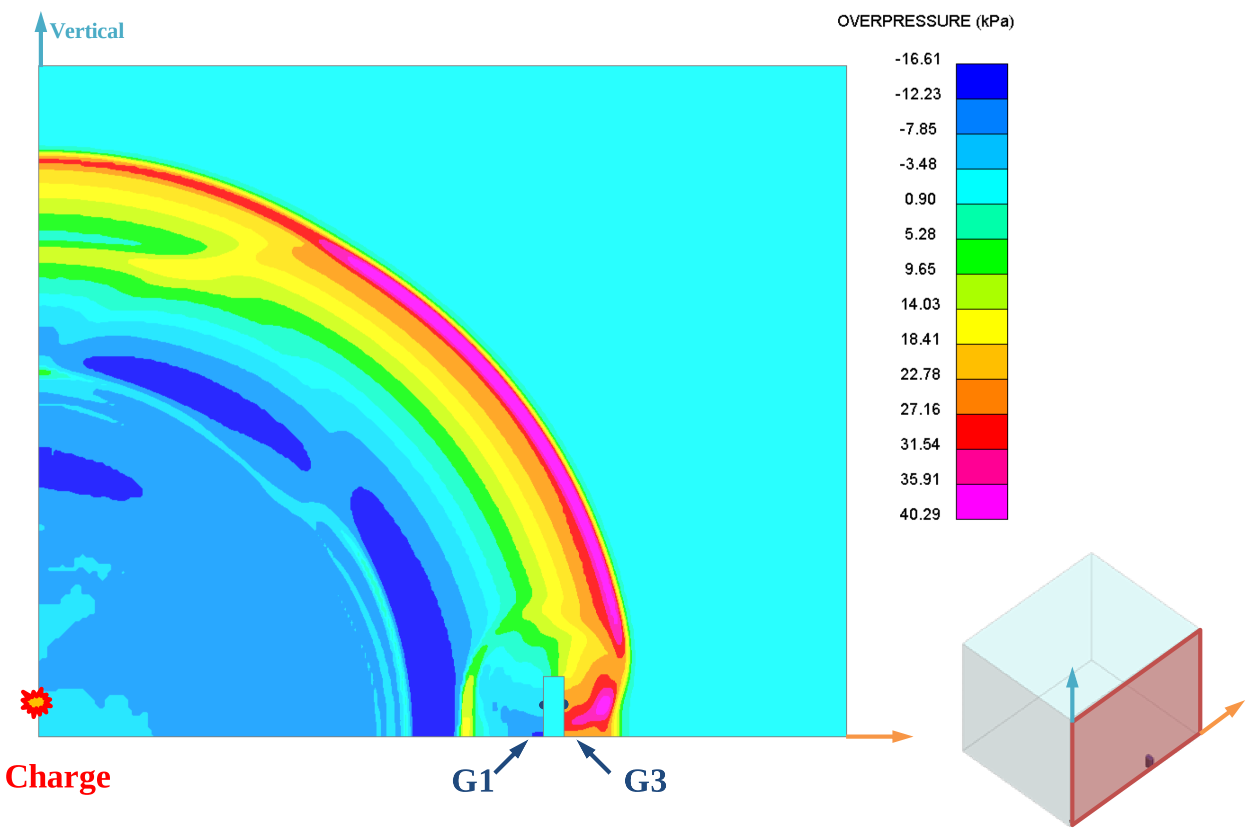

Figure 6: Overpressure contour showing reflected and diffracted waves (t = 3.050ms)
The red hatched surface indicates the section where the contour is plotted.

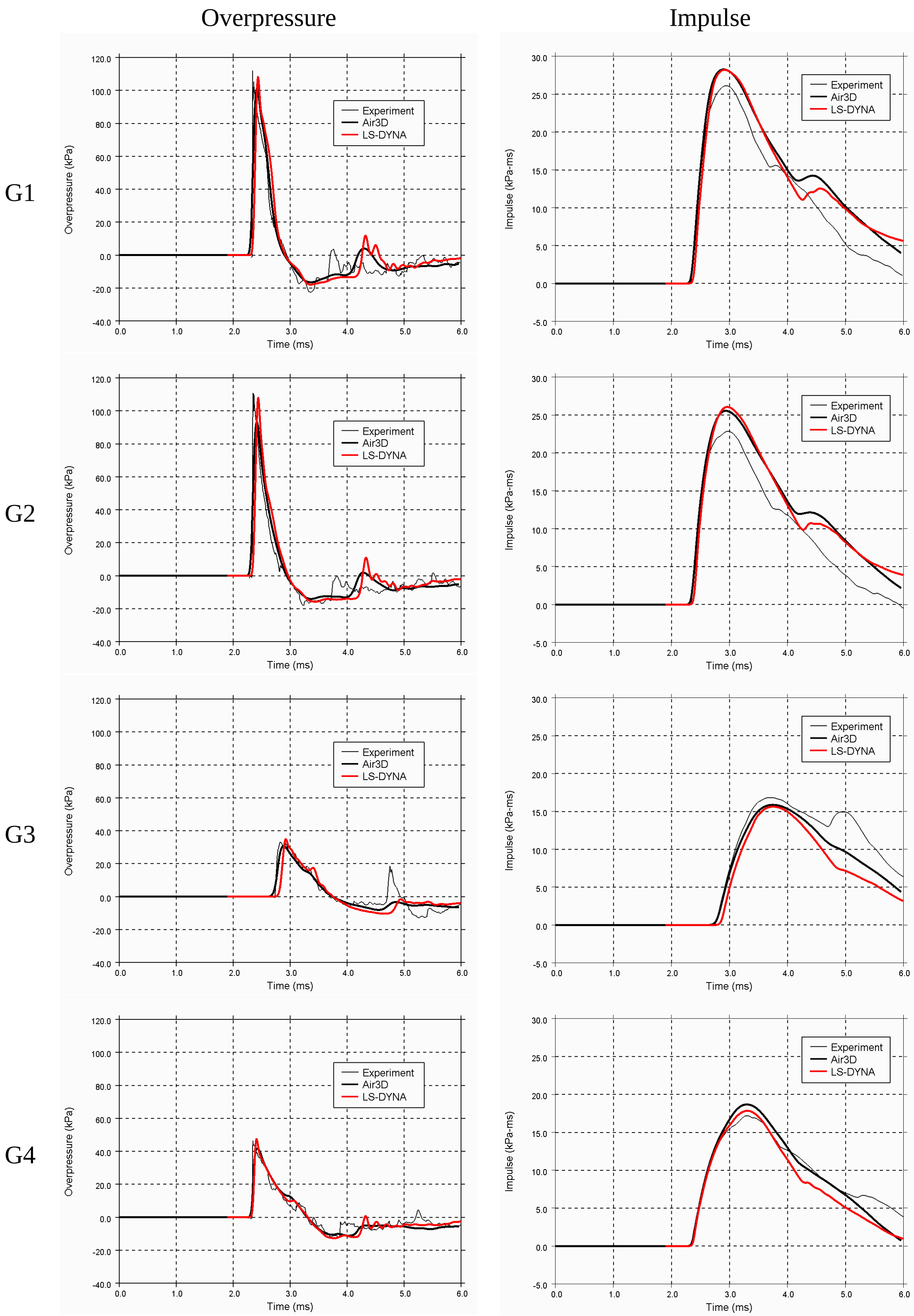

Figure 7: Result comparison of experiments, Air3d and LS-DYNA analyses

Blast in an Urban Environment

The use of large vehicle bombs by terrorists to attack city centers gives rise to the problem of blast in an urban environment. The confinement and channeling effect of urban geometry on blast loadings adds complexity. The use of standard spherical and hemispherical air blast databases is unable to give a complete and accurate picture of the resultant overpressure and impulse. There are many investigations that have led to a better understanding on this subject. The series of experiments reported by Whalen (1998) and Smith *et al.* (2001) are good examples of these investigations. Five simple generic street configurations, with constant street width and building height, were studied. The plan views are shown in Figure 8, where the locations of explosive charge and the pressure gauge arrays are indicated.

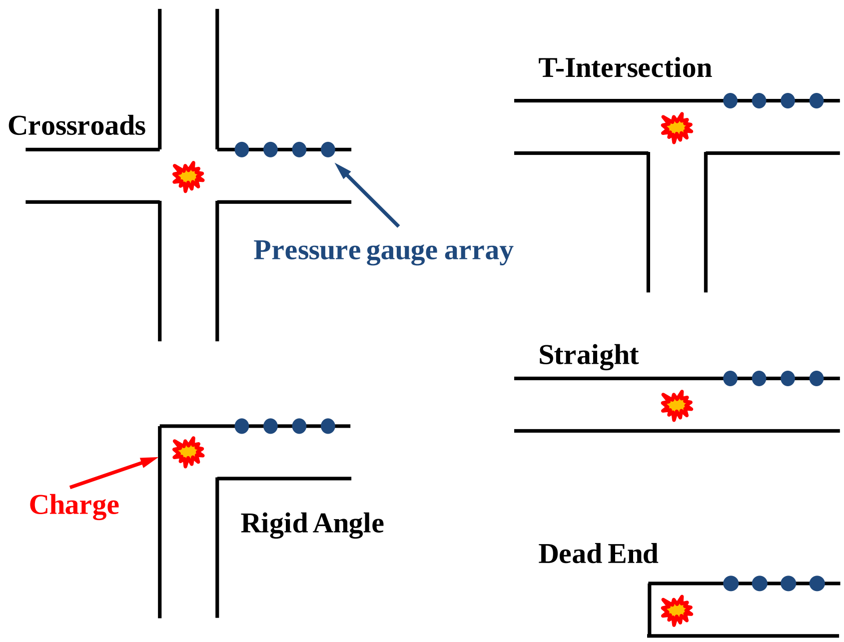

Figure 8: Plan views of generic street configurations

The 1/50-scale model intersections were made from 6 mm thick steel plates. In this model, the street was 0.3m wide, and the height of the building along the street was 1.0m. The explosive charge was 11.13g of plastic explosive SX2 which, together with a 1g detonator, gave a total charge equivalent to 12g TNT. By detonating at 25mm above the ground, a vehicle bomb of approximately 1625kg TNT at full scale was simulated. To damp out any vibrational response, the vertical steel plates representing the buildings (which were sited on a 6 mm thick horizontal steel plate representing the ground) were backed with sand to a height extending above all the gauges.

The validation consists of comparisons of experimental and numerical pressure histories for the dead end intersection configuration, which is an interesting geometry because it has the most confinement from the buildings and a strong reflected shock is expected from the closed end. The pressure gauges were fixed flush to the surface at the locations shown in Figure 9. Locations H1, V1 and D1 are coincident.

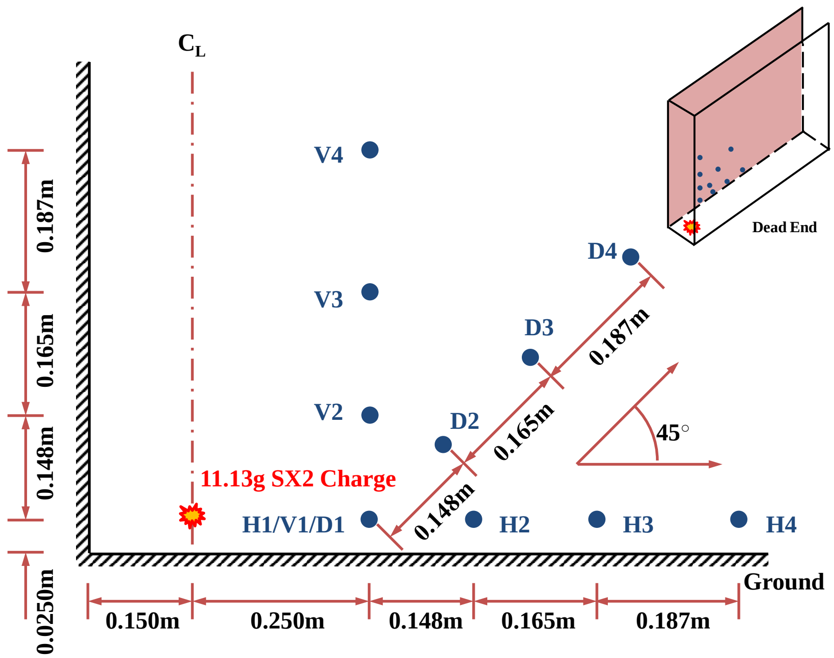

Figure 9: Locations of pressure gauges (red hatched surface indicates the plan of the gauges)

For the dead end intersection configuration, three experimental detonations were carried out for each of the three arrays of gauges, i.e., 4 horizontal (H1 to H4), 4 vertical (V1 to V4) and 4 on a line at 45 degrees (D1 to D4), making a total of 9 firings and a grand total of 36 pressure-time histories (Smith *et al.*, 2001). The presented experimental and Air3d simulation results are reproduced from Rose (2001). A schematic of the LS-DYNA model is shown in Figure 10. Only half the three-dimensional geometry is simulated because of symmetry. The simulation was conducted using a similar approach as discussed in the previous section and using the same material parameters with a uniform element size of 10.0mm.

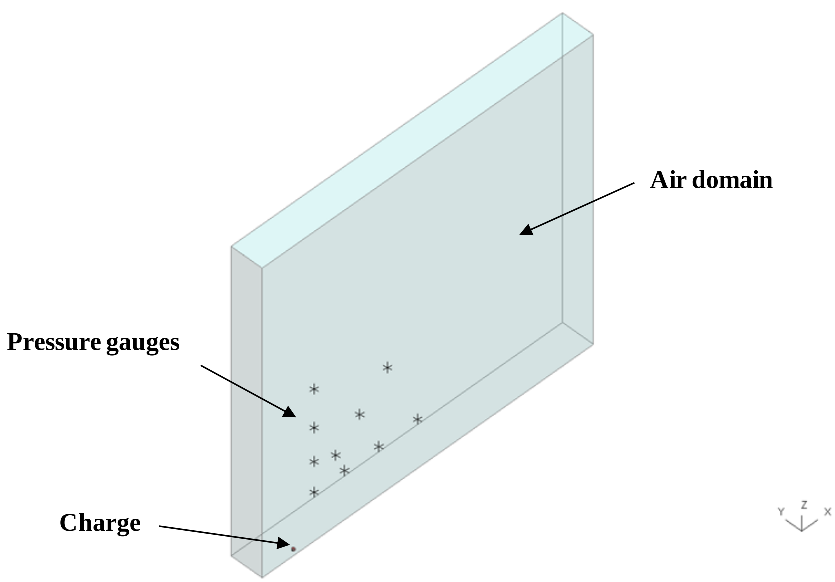

Figure 10: LS-DYNA half model for the dead end intersection configuration

Comparison of the peak overpressure and maximum impulse for the experiment with the Air3d and LS-DYNA simulation results is summarized in Table 1, and visualized in Figure 11.

Pressure histories at the gauges are compared in Figure 12. No wave forms were provided by Rose (2001) for gauges V1 and D1, presumably because they were similar to the wave form provided for gauge H1. The comparisons suggest that the simulations generally underestimate the peak pressures for larger stand-off distances and overestimate the maximum impulse for smaller stand-off distances. The agreement between the simulations and the experiments for the first pressure peak is generally better than for the successive peaks. The use of TNT equivalency is a likely cause for the disagreement between simulations (Air3d and LS-DYNA) and experiments, especially at locations close to the charge where the detonation products dominate and are different for different types of explosives. The overall accuracy and ability to capture salient features of a confined urban blast by these simulations are satisfactory.

Concluding Remarks

The comparisons in this paper demonstrates that the results from LS-DYNA produce excellent correlation with experimental and Air3d simulation results. Whilst this is a validation with prior knowledge of the experimental results, it suggests that the LS-DYNA simulation capability is adequate for the cases studied. However, further development of simulation accuracy and more validation against experimental data are suggested.

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Table 1: Comparison for blast loadings in an urban environment with dead end configuration

Plane	Loc.	Overpressure (kPa)					Impulse (kPa-ms)				
		Exp*	Air3d		LS-DYNA		Exp*	Air3d		LS-DYNA	
			Val	Err %	Val	Err %		Val	Err %	Val	Err %
H	1	3210	2739	-15	2590	-19	130	210	62	188	45
	2	1352	1016	-25	925	-32	132	153	16	131	-1
	3	570	412	-28	350	-39	110	120	9	105	-5
	4	363	262	-28	185	-49	92	93	1	85	-8
V	1	3476	2739	-21	2590	-25	123	210	71	188	53
	2	1672	1473	-12	1334	-20	107	154	44	130	21
	3	679	573	-16	544	-20	92	116	26	99	8
	4	760	452	-41	364	-52	90	92	2	86	-4
D	1	2612	2739	5	2590	-1	139	210	51	188	35
	2	1297	1044	-20	938	-28	117	147	26	122	4
	3	468	459	-2	406	-13	93	114	23	98	5
	4	398	421	6	254	-36	81	96	19	86	6

* Experimental results are averages of multiple firings (Rose, 2001)

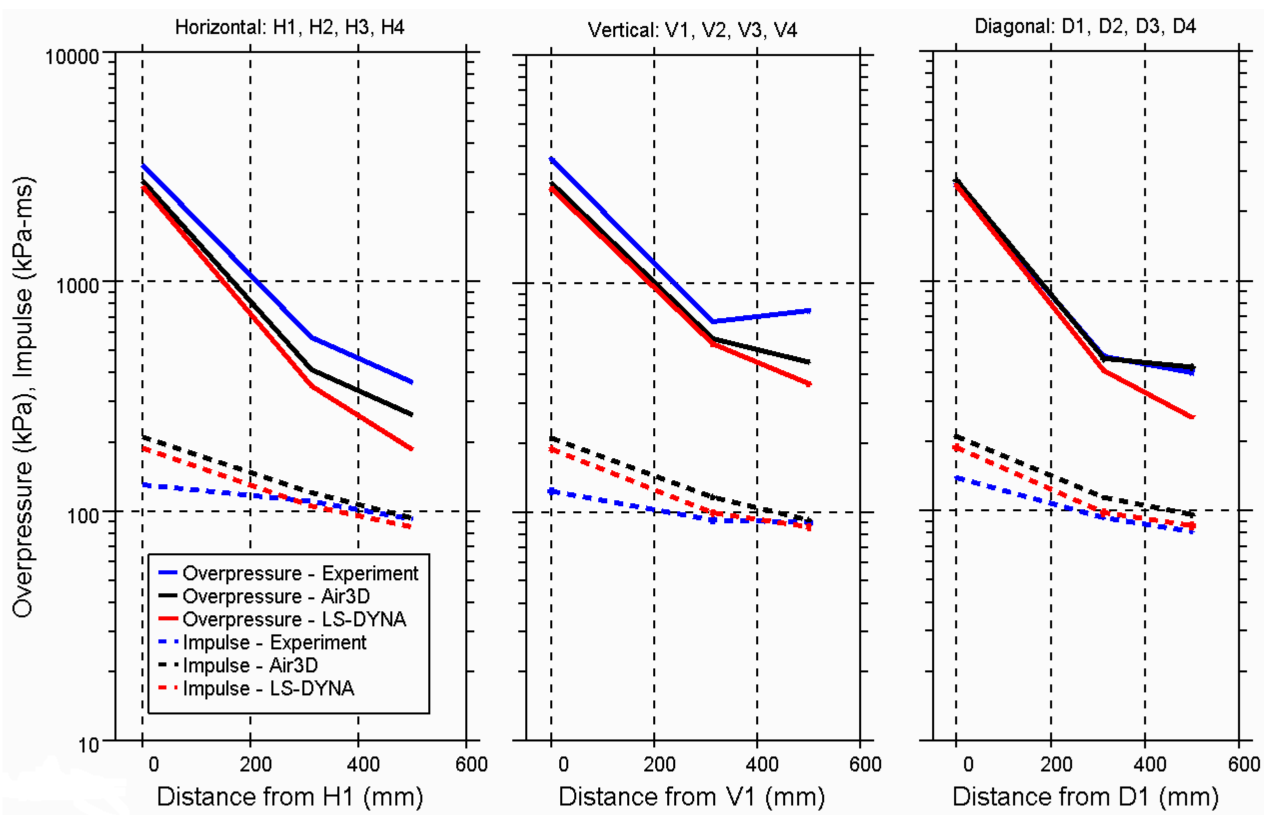
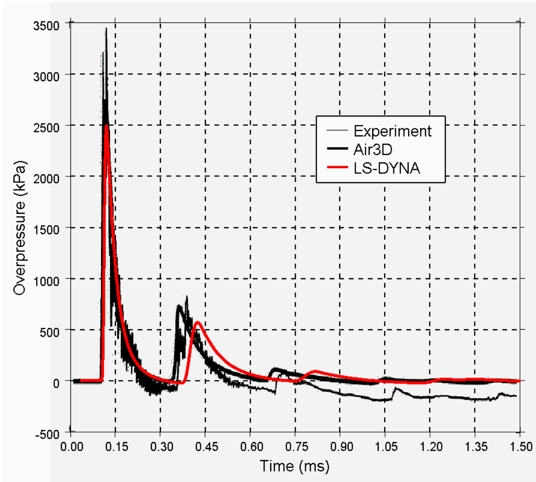
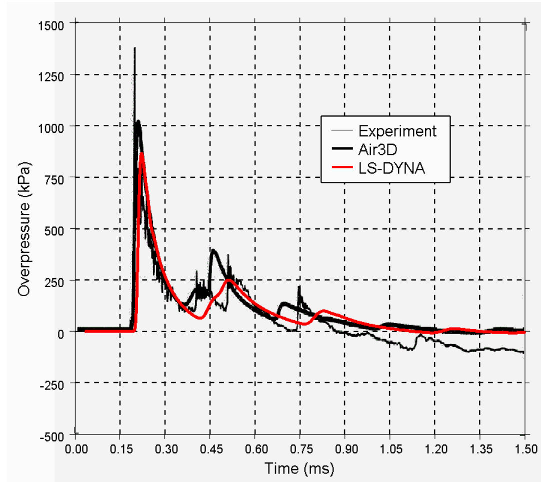


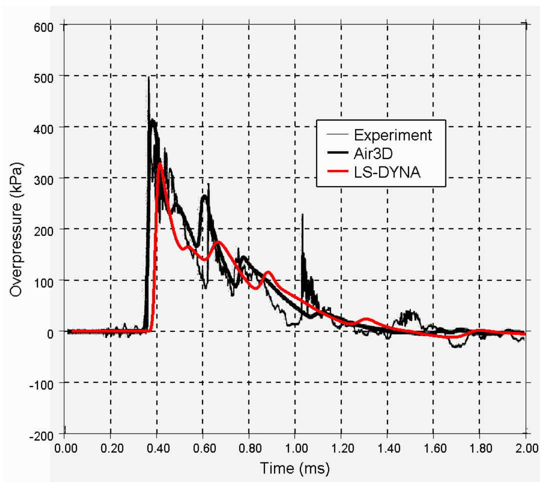
Figure 11: Comparison for blast loadings in an urban environment with dead end configuration



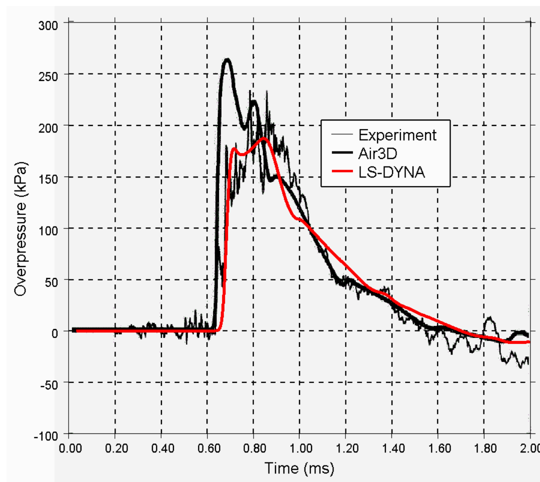
H1



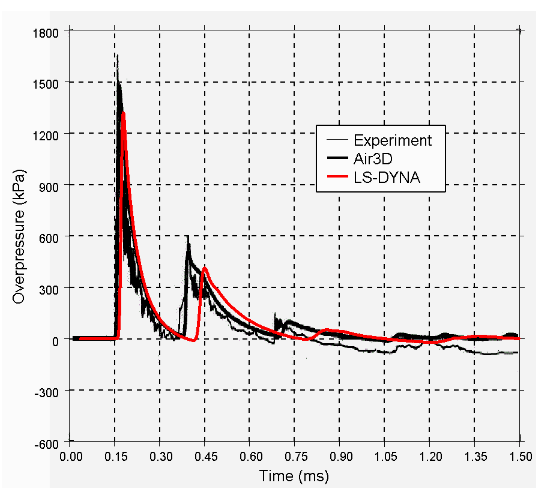
H2



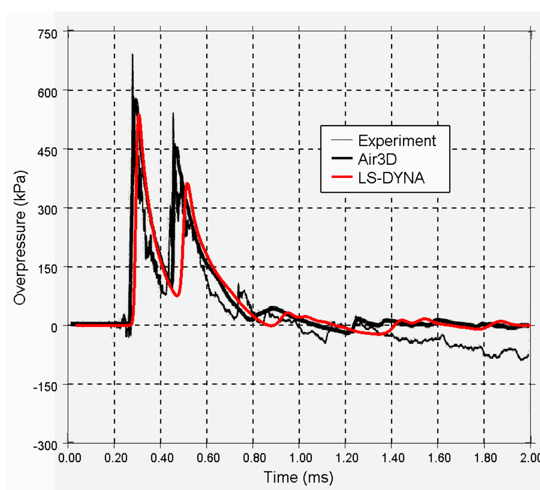
H3



H4

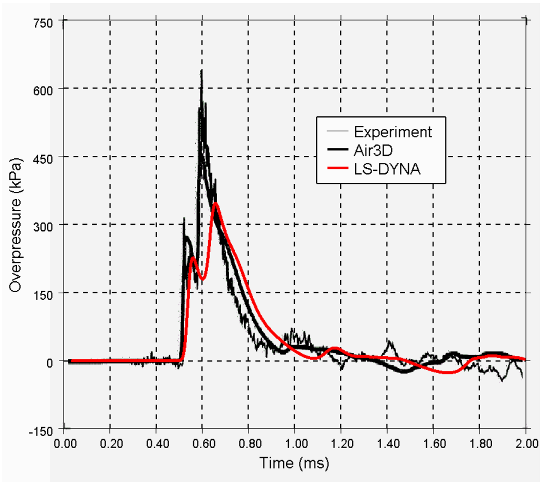


V2

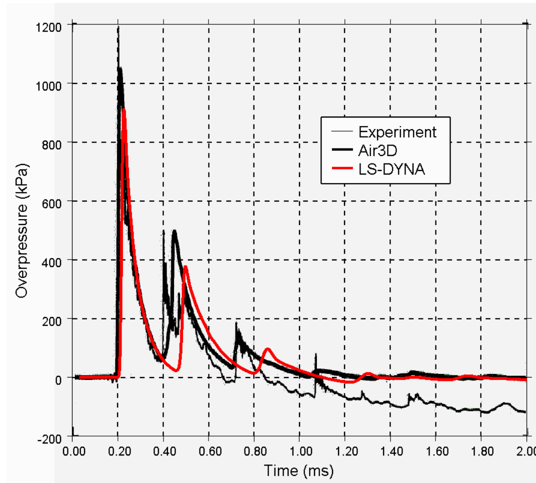


V3

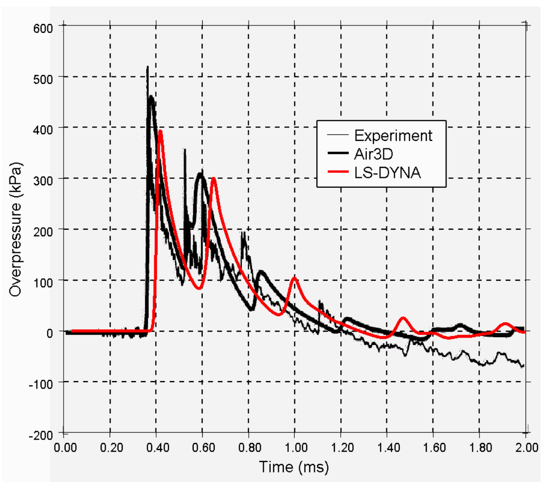
Figure 12: Result comparison of experiments, Air3d and LS-DYNA analyses



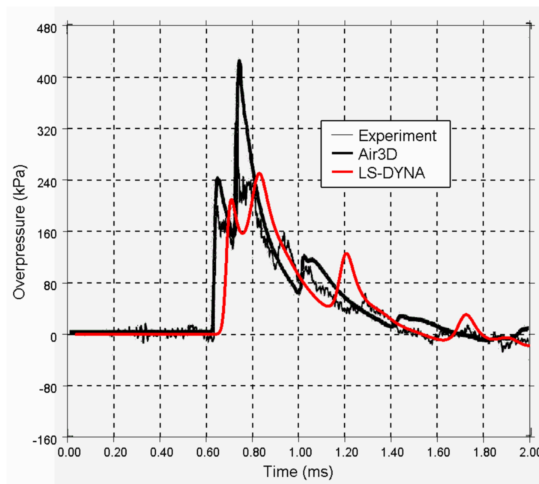
V4



D2



D3



D4

Figure 12: Result comparison of experiments, Air3d and LS-DYNA analyses (continued)