PREDICTION OF BLAST OVERPRESSURE AND BLAST LEAKAGE OF CONFINED EXPLOSIONS

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ABSTRACT

A blast test is to be conducted to study the impact of confined explosions inside an enclosed structure with a door opening. The main challenges in the design of this blast test are that the structure must be able to withstand the blast overpressures from confined explosions as well as to ensure the safety of the personnel standing outside the structure. This paper presents the predictions of the blast overpressures inside the structure and blast leakage pressures through the door using engineering code calculations and advanced simulation software package.

Key words: Confined explosions, Blast overpressure, Blast leakage pressure

INTRODUCTION

Designing buildings to withstand blast explosions is of great interests nowadays. There are many established methodologies to predict the blast loads acting on the buildings due to an explosion outside of the building. On the other hand, explosions that happened in a confined space is relatively difficult to model and predict due mainly to the complex and interactive nature of the pressure waves reflecting from within the enclosure. Explosion within a structure produces two loading phases: the confinement provided by the structure generates reflected blast overpressure in the first phase while the accumulation of high temperatures and gaseous products cause a build-up of quasi-static pressure or gas pressure in the second phase. Leakages through the vents add on to the complexity of modelling and prediction of such explosion.

Literature Review

Research on enclosed explosions usually focused mainly on the impact of explosion on small confinement with the ignitions simulated using shock tubes. Such scale of experiment provides excellent opportunity to study the characteristics and the behaviours of the shock waves in great details. However, explosions in a confined space of a large scale are usually more difficult to study in details due to the constraints imposed on the resources, costs, logistics, and other considerations. Pritchard [1] had earlier proposed developing an explosion model to predict accurately and quickly the explosion pressures produced by an ignition of gases or vapours in confined spaces as early as in the mid 90's. Such explosion model would be very useful to industries in designing of enclosures and vessels to minimize and contain the effects of explosions. Nishimura [2] also mentioned that pressure behaviour calculated analytically assuming laminar flame propagation tends to underestimate when compared with experimental data. Nishimura proposed to model the flame front as a fractal structure instead of laminar in order to predict the pressure behaviour.

Recently, many researchers had proposed using Computational Fluid Dynamic (CFD) models to simulate and study such complex phenomenon. Gavelli [3] used a modern CFD tool developed specifically for the simulation of gas dispersion and vapour cloud explosions.

Gaveli demonstrated that for indoor releases of flammable gases, minor differences in the characteristics of the releases (direction of the jet, momentum of the release, etc) can have significant impact of the growth of the cloud and consequently, on the location of viable ignition sources as well as on the intensity of the resulting overpressures. Di Sarli [4] portrayed the central role of using Large Eddy Simulation as the adequate tool for capturing the inherently unsteady interplay of flame propagation, flow field and geometry associated to explosion phenomena. Di Sarli described the complexity of modelling gas explosions especially relating the need of modelling phenomena such as flammable gas becoming non-uniform and the interactions between flame and pressure waves becoming important at large scales. However, the computation cost increases exponentially with the scale of the models which strongly limits the application of LES to large scale explosions. Woolley [5] discussed in details on developing a mathematical model to simulate the explosions of methane-hydrogen mixture in a confined, vented vessels. Using a Reynolds stress turbulence model applied to the prediction of large-scale vented explosions and coupled to the turbulent pre-mixed combustion model, Woolley predicted the overpressures and flame velocities with good degree of accuracies. Dobashi [6] pointed out that even though explosion phenomena can be simulated by CFD techniques, CFD simulations are usually not suitable for risk assessment because CFD needs much time, cost and detailed information about the explosion conditions. Instead, Dobashi proposed a new prediction method for blast wave intensity from gas deflagrations considering the effects of flame instabilities to provide consequence analyses of accidental gas explosions to assess the risk of chemical plants, hazardous-materials sites and new energy systems.

Objective

It is of great opportune for us that a blast test is to be conducted in a structure to measure the pressures acting inside due to a small explosion. The structure is designed with four walls, a roof, and a door opening at the front wall for ventilation. Pressures will be picked up by the respective pressure transducers placed at selected locations within the structure. Our structure will be similar to the set-up conducted in the study by Edri [7] and Yankelevsky [8] but with minor changes in terms of structural dimensions and venting opening locations. The study by Edri aimed at understanding some characteristics of an interior explosion within a room with limited venting. In that study, the dependence between the charge weight and the volume of the structural enclosure and gas pressure were obtained and compared with analytic results. Yankelevsky studied the characteristics of an interior explosion using experimental and theoretical investigations and described the gas pressures using an analytical model. Yankelevsky also developed effective simplified models to describe the detonation products outflows from the room through the venting openings.

Our key objective in this paper is to present our predictions of the overpressure acting on the walls when a small explosion occurred inside this enclosed structure. To use a commercial CFD code to model and simulate such a case would capture the fluid interactions accurately and give better prediction of the overpressure acting on the walls. However, CFD simulations are usually not suitable as much time, cost and detailed information about the explosion conditions are required.

For this test, we employed design methodologies based on semi-empirical equations leveraging on extensive experimental data as well as an advanced finite element method software for our predictions.

METHODOLOGY

The intended structure for this blast test is a rectangular room with a roof. There is a door opening at the front wall to allow for ventilation during explosion. The structure is constructed using reinforced concrete walls protected with steel plates. A small explosion is allowed to be ignited inside the structure a short distance away from the door opening and the pressures acting on the walls will be measured using pressure transducers.

Predictions of the pressures acting on the walls were made using four different methodologies: Unified Facilities Criteria for Structures to resist the Effects of Accidental Explosion (UFC) which is based on empirical methods derived from many tests conducted; SHOCK & FRANG, computer analysis program which derived from a series of tests conducted; ProSAir, a compressible Computational Fluid Dynamics (CFD) package; and, LS-DYNA, which is a commercially available advanced finite element program.

UFC

UFC 3-340-02 [9] presents methods of design for protective construction used in facilities for development, testing, production, storage, maintenance, modification, inspection, demilitarization, and disposal of explosive materials. In so doing, it establishes design procedures and construction techniques whereby propagation of explosion (from one structure or part of a structure to another) or mass detonation can be prevented and personnel and valuable equipment can be protected.

The primary objectives of UFC are to establish design procedures and construction techniques whereby propagation of explosion (from one structure or part of a structure to another) or mass detonation can be prevented and to provide protection for personnel and valuable equipment. In addition, this manual also establishes blast load parameters required for design of protective structures and provides methods for calculating the dynamic response of structural elements.

SHOCK & FRANG

SHOCK is a blast load analysis program which calculates the impulse and pressure on either all or part of the blast surface from the incident blast wave and from the waves bounded by one to four reflecting surfaces. Using SHOCK, maximum average pressure on the blast surface from each incident and reflected wave, total average impulse from the sum of all the waves and the impulse duration on the blast surface can be obtained.

FRANG is a semi-empirical numerical analysis program used to predict the total quasi-static gas pressure impulse. The program referenced by the tri-service design manual “Structures to Resist the Effects of Accidental Explosions” (Navy NAVFAC P-397, Army TM5-1300, and AirForce AFM 88-22). FRANG is widely used in calculating the internal gas pressure loads from a confined explosion. The shock loads calculated from SHOCK are applied as an impulse at time = 0.

PROSAIR

ProSAir (Propagation Of Shocks in AIR) is a compressible fluid dynamics solver developed by Cranfield University for assessing blast loading. ProSAir is an improved graphical user interface and in due course will feature improved algorithms and the ability to model a wider range of blast-related phenomena. In general, ProSAir is used to model air-blasts in and around structures and estimating the resultant structural loading.

LS-DYNA

LS-DYNA is a general purpose advanced finite element program used by the automobile, aerospace, defence, construction and other industries. The code's origins lie in highly nonlinear, transient dynamic finite element analysis using explicit time integration. It is now available commercially and is widely used for both research and industrial purposes to solve complex problems.

This is the first attempt we are leveraging on LS-DYNA to simulate an indoor explosion. This indoor explosion was simulated using the Arbitrary Lagrangian Eulerian (ALE) module within the fluid analysis capabilities of LS-DYNA. The explosive was simulated using the 'mine' option inside ALE module while the enclosed room was modelled as steel walls with a door opening. It was not our intent to model and simulate the fluid interactions and behaviours inside the room during such explosion event, which can be better served by using a commercial CFD code. In which case, the computing resources required would be much more intensive to capture the unsteady flow behaviours interacting inside the room during and after the explosion. Instead, LS-DYNA was used to simplify the problem and hence reduces the computing resources demand to simulate such a test case. The trade-off being that accuracies of the pressure predictions would deteriorate as the room size gets larger and when the fluid interactions become more intense.

LS-DYNA model of the structure

A mine is placed near the door opening of the enclosed room modelled as a rectangular steel box. The steel structure was modelled using material *MAT_PIECEWISE_LINEAR_PLASTICITY. Figure 1 shown below is a single component, modelled with shell elements. Leveraging on the symmetry of the room, only half of the room was modelled.

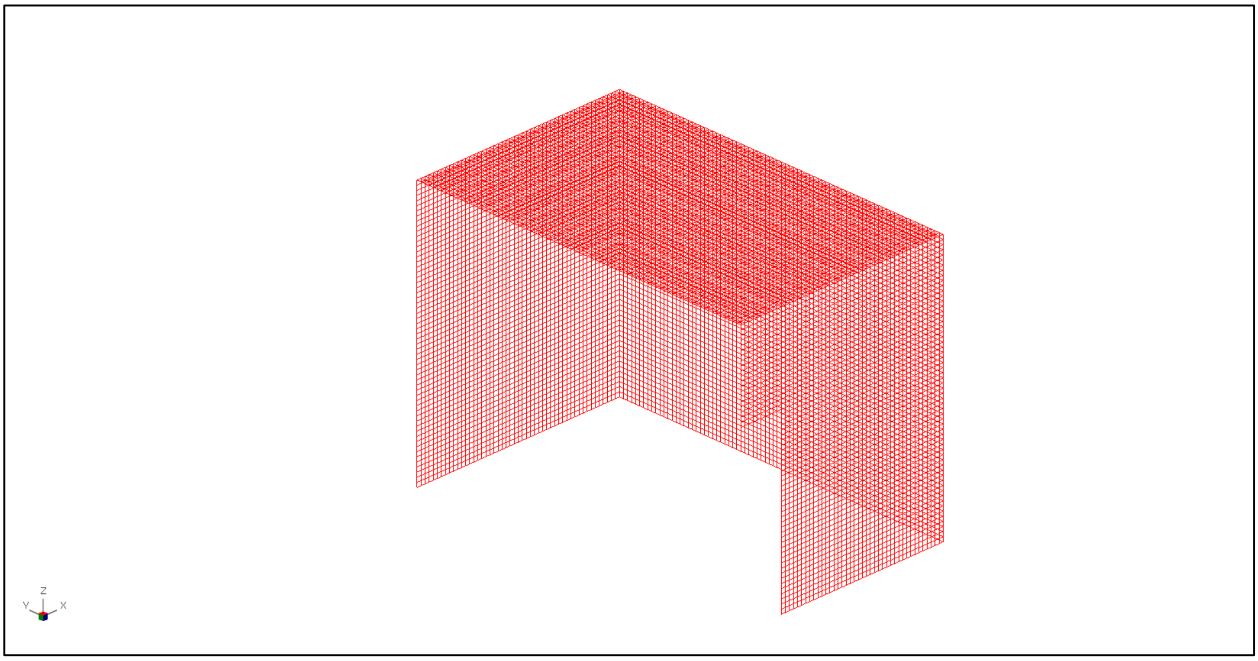

Figure 1: FE mesh of steel box model in ISO view in LS-DYNA

The mine, surrounding air and soil are modelled with ALE elements and connected to the Lagrange elements with *CONSTRAINED_LAGRANGE_IN_SOLID card. The mine is modelled with material model *MAT_HIGH_EXPLOSIVE_BURN. The material data used in LS-DYNA is consistent with those used by Zahra [10] and other LS-DYNA users.

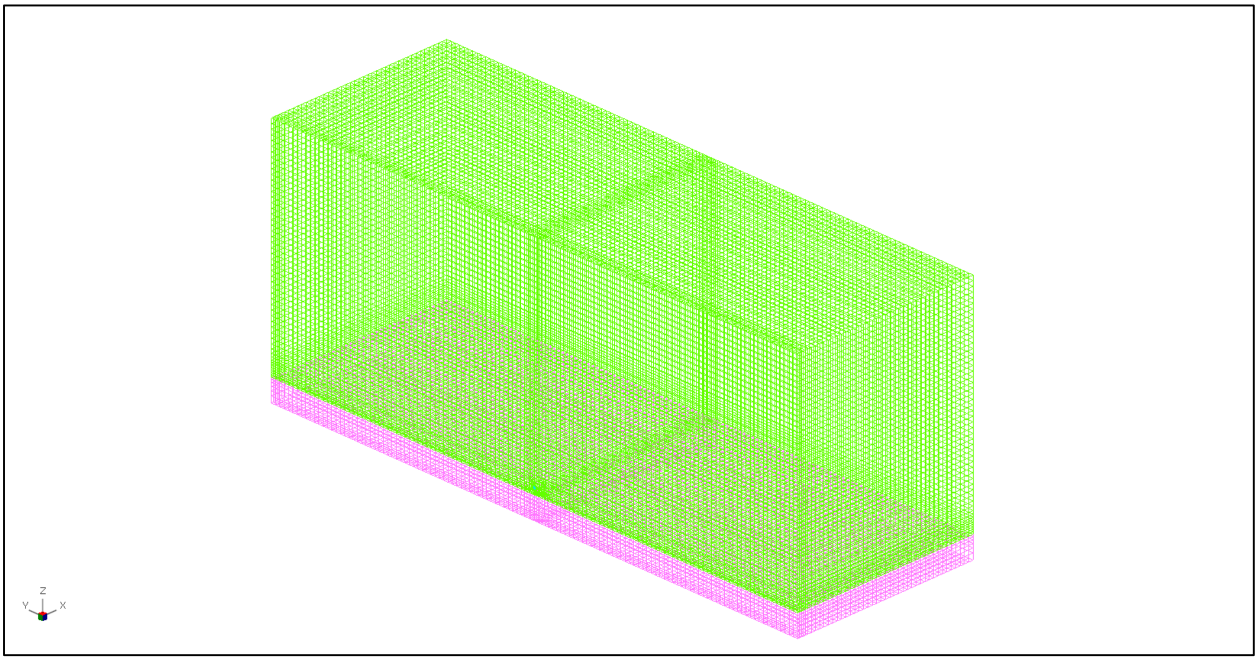

Figure 2: FE mesh of ALE model in ISO view in LS-DYNA

Several pressure sensors were located at the walls to measure pressures over time. The LS-DYNA structure model and the locations of the pressure sensors are shown in Figure 3.

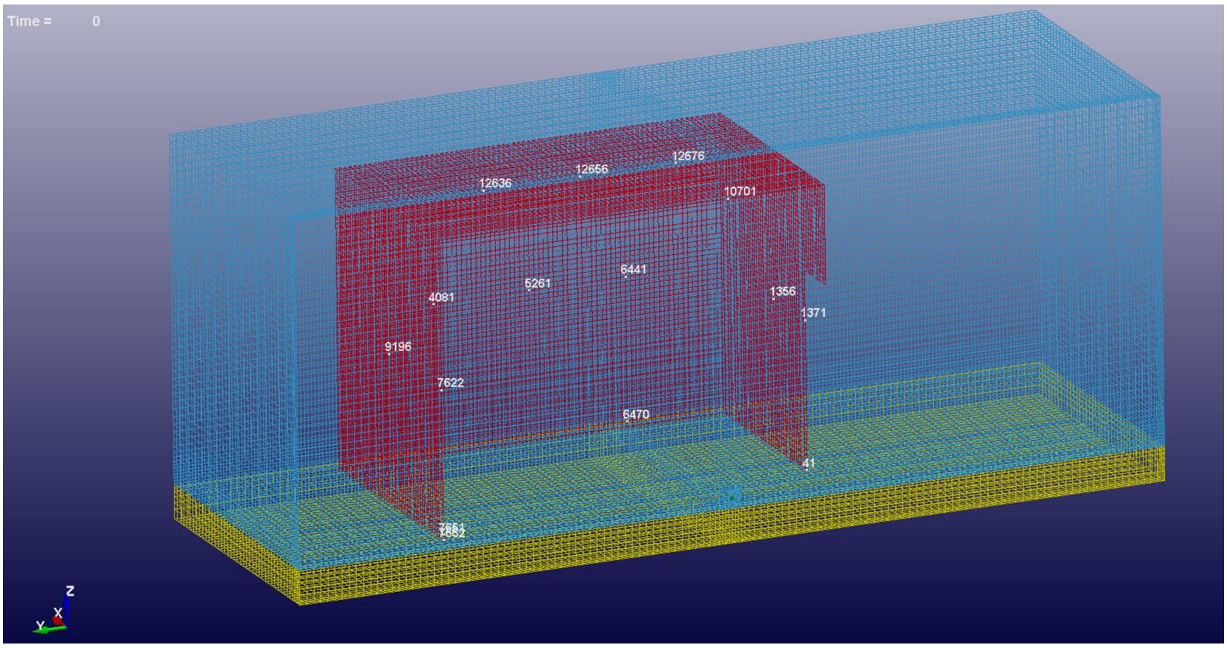

Figure 3: The structure model and locations of the pressure sensors in LS-DYNA

RESULTS

UFC describes the pressures inside a vented chamber when an explosion occurs as the shock pressures escape to the outside along with venting of the gas pressures. Trailing shocks overrun and coalesce with the lead shock at some distance to form a single diverging shock wave. Close to the structure, the blast pressures are affected by the structure itself as the shock pressures spill around edges of the structure and form highly turbulent vortices. At further distances, this effect is no longer present and the shock pressure decreases with increasing distances. However, UFC is unable to estimate the reflected pressure at the walls as well as the gas pressure accurately, due to limiting values given in the charts. Because of the limitations in the range of the test data and the limited number of values of the parameters calculated, the values of the average shock loads will be approximately equal to those corresponding to the limiting values.

The leakage pressures are enhanced in the direction of venting (front) and reduced to the side and rear. The enhancement of pressures in the front and reduction of pressures to the side and rear are less extreme as the distance away from the structure is increased. Reasonable estimation of the pressures produced in the front, side and back directions could be obtained based on the methodologies described in UFC. The pressures produced are a function of scaled distance and the vent area divided by the volume to the two-thirds power ($A/V^{2/3}$).

SHOCK & FRANG are used to calculate the internal shock loads on the blast surface and gas pressure. The detonation of a condensed high explosive inside a confined structure produces two loading phases, which consist of shock pressures and gas pressures.

ProSAir is used to model air-blasts in and around structures and estimating the resultant structural loading. The overpressure and impulse can be plotted after post-processing the ProSAir output files. Figure 4-9 shows overpressure contour plot captured at various time in ProSAir.

In the case of LS-DYNA, we modelled the indoor explosion using the ALE-FSI module available in LS-DYNA. A half model of the steel room with an opening representing the door was modelled with an explosive inside the structure. Figure 10 shows a typical pressure contour.

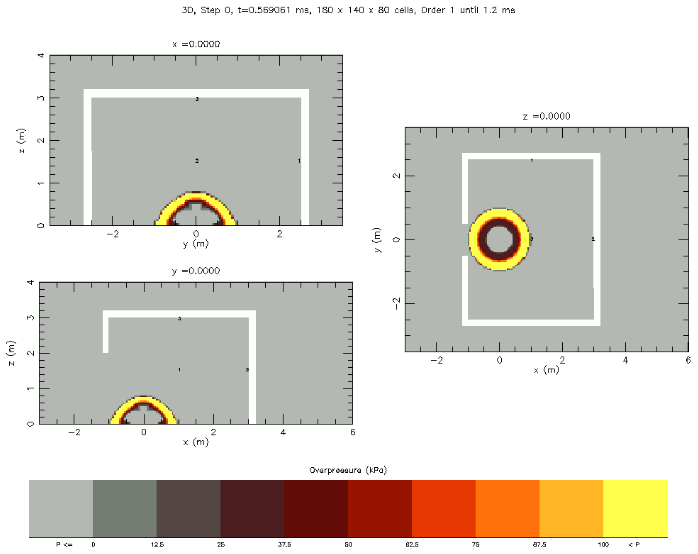

Figure 4: Overpressure contour plot at 0.57ms in ProSAir

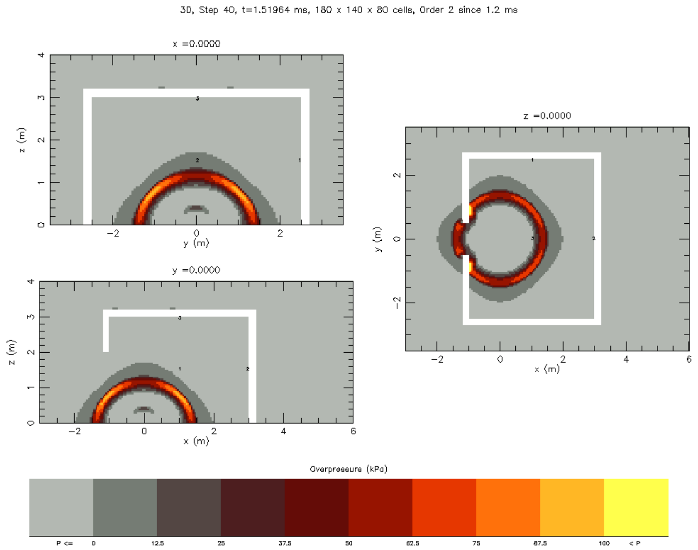

Figure 5: Overpressure contour plot at 1.52 ms in ProSAir

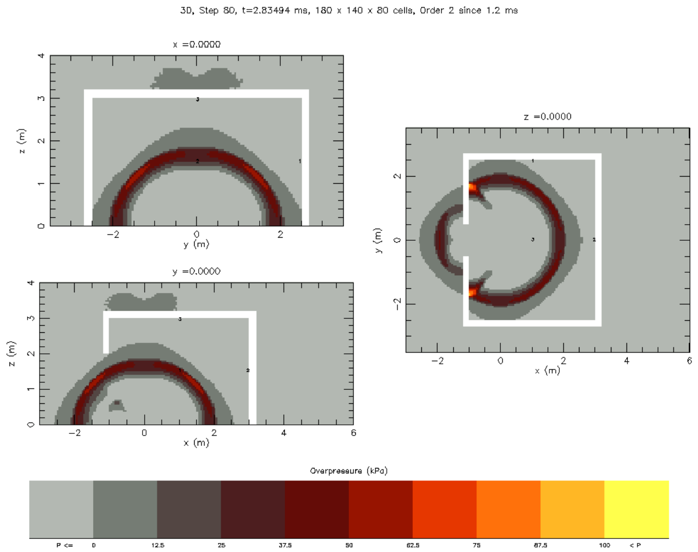

Figure 6: Overpressure contour plot at 2.83 ms in ProSAir

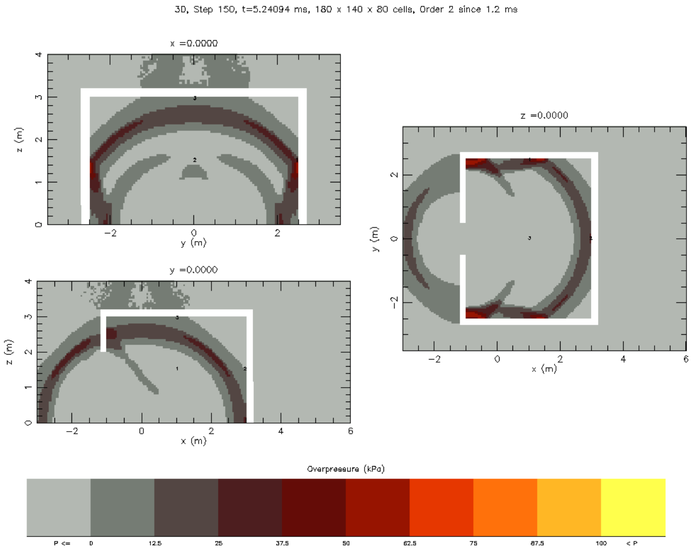

Figure 7: Overpressure contour plot at 5.25 ms in ProSAir

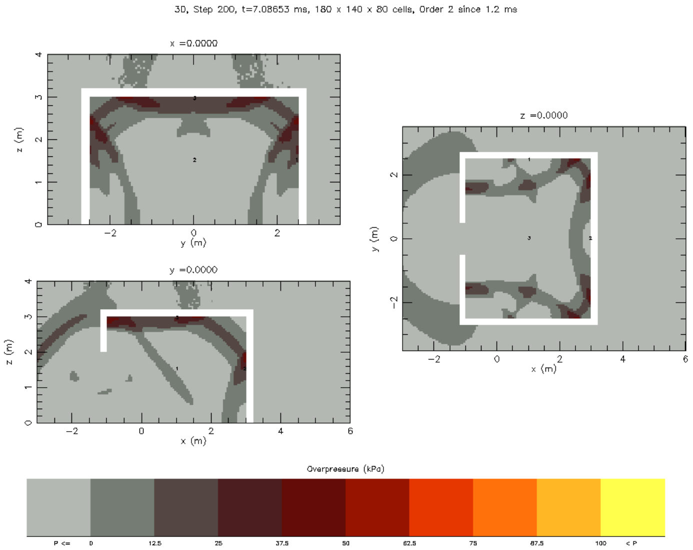

Figure 8: Overpressure contour plot at 7.09 ms in ProSAir

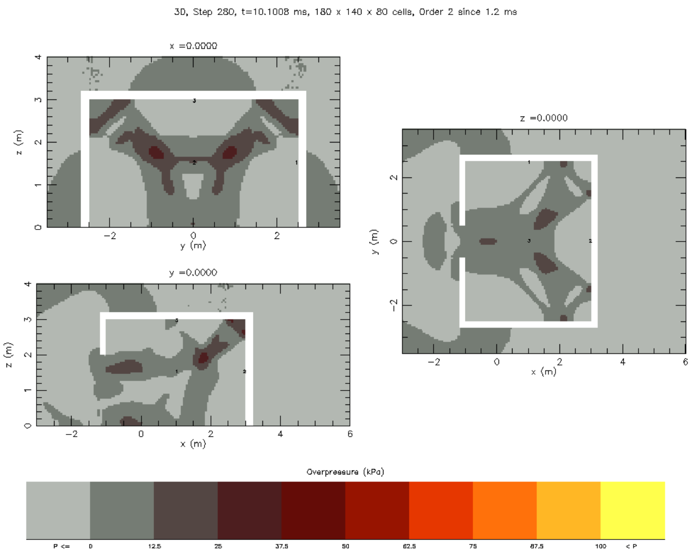

Figure 9: Overpressure contour plot at 10.10 ms in ProSAir

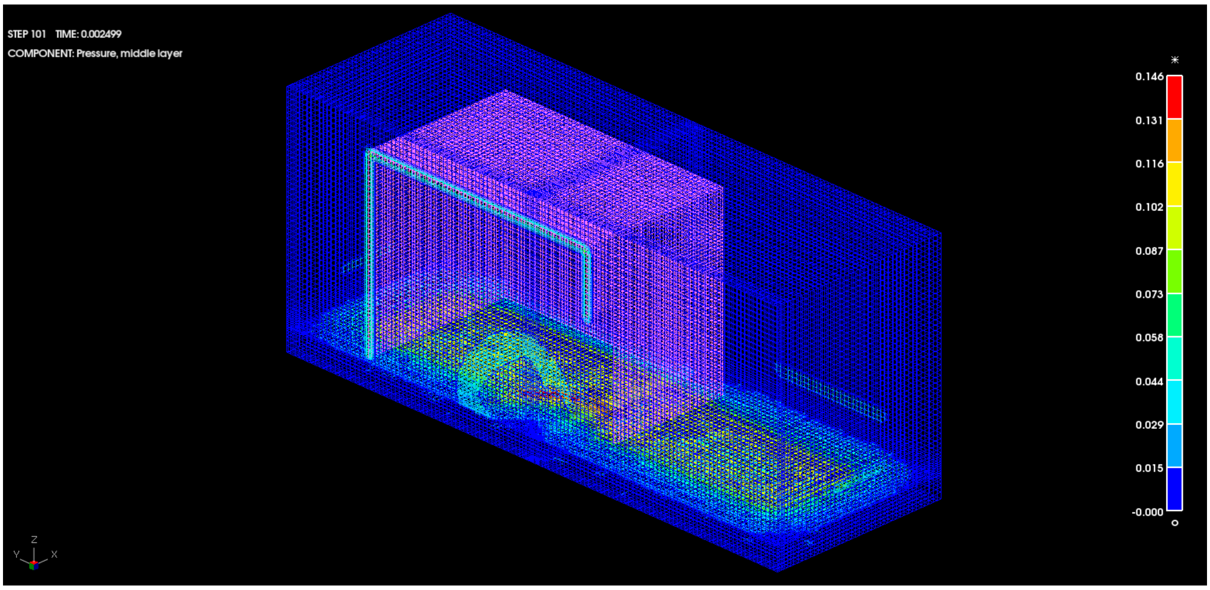

Figure 10: Pressure contour on the walls in LS-DYNA

Using the described methodologies, the overpressures inside the structure at various locations were determined. It is noted that UFC predicted lower peak pressures when compared to the other methods used. One reason could be that UFC was not able to capture the interactions between the reflected shock waves and the walls accurately. In addition, the gas pressure was also not accounted for. SHOCK & FRANG gave higher peak pressure predictions and also provided a prediction of the gas pressure. The results from ProSAir is closed to the results from SHOCK. Our LS-DYNA model was able to capture the peak pressures and provided time histories of the pressures acting on the walls inside the structure.

The leakage pressure outside the structure was also predicted using UFC and ProSAir. Attempts were made to predict the blast leakage pressure using LS-DYNA but our LS-DYNA model appeared to predict much higher blast leakage pressures when compared to UFC predictions. This could be that blast leakage pressure is highly dependent on the fluid interactions during and after explosions, which are complex phenomena involving shock wave reflecting inside the structure while propagating towards outside the structure through the opening. Such complex phenomena could be better captured using a CFD code instead.

All these predicted blast overpressure inside the structure as well as the blast leakage pressures outside the structure will be compared with our actual test measurements when a blast test is conducted later this year.

CONCLUSION

Prediction of the overpressures acting on the walls of an enclosed structure due to an indoor explosion was carried out. Our LS-DYNA model was able to provide reasonable prediction of the overpressures acting on the walls but seemed unsuitable to predict the blast leakage pressures outside the structure. Further investigations will be conducted by a blast test with pressure measurements later this year to compare with these predicted results.

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