

TOWARDS UNDERSTANDING THE BUNCEFIELD EXPLOSION THROUGH ADVANCED NUMERICAL ANALYSIS AND EXPERIMENTAL INVESTIGATIONS

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The paper reports on two series of studies carried out to understand the Buncefield explosions (Explosion Mechanism Advisory Group, 2007; HSE, 2009). The first series of studies were carried out to aid understanding of the severe damages which indicated the possibility of explosion overpressures well above those in an open turbulent deflagration. These involved numerically simulating the detonation of pancake shaped clouds using similar settings and configurations as those experimentally tested by Fishburn (1981). Reasonably good agreement is achieved on the predicted overpressure and drag impulse for the three monitoring points in the tests. Further analysis of the predictions have illustrated important salient features of such pancake cloud detonations which are in line with some forensic evidence of the incident. The second series of studies involve experimental and finite element (FE) analysis of lightweight metal boxes, similar to the lightweight steel junction boxes on the site located within the area covered by the gas cloud at Buncefield. These boxes were tested under a range of different loading conditions using hydrostatic pressure, gas explosions and high explosive charges during the Phase I research. Measurements were conducted for the residual plastic deformations of these boxes. A FE modelling approach was developed and validated with these measurements and the recorded pressure-time history during the tests. The results have been used to produce iso-deformation lines which can be used to aid accident investigations by back tracking the blast loading from structure deformation.

KEYWORDS: Detonation; Blast loading; Dynamic response; FE modelling; Steel boxes

INTRODUCTION

The Buncefield depot explosion on 11 December 2005 resulted in the largest fire in Europe since World War II. The severity of the explosions challenges our current understanding of such large scale explosion accidents and uncovers design implications which warrant timely consideration by industry (Explosion Mechanism Advisory Group, 2007). Following the initial investigation, the Explosion Mechanism Group Phase I preliminary research was initiated which concluded that the most likely scenario at Buncefield was a deflagration outside the emergency pump house that changed into a detonation due to flame acceleration in the undergrowth and trees along Three Cherry Trees Lane. The detonation extended to a significant part of the remaining vapour cloud (HSE, 2009). CCTV images suggested that the cloud was pancake shaped with an average depth of 2 m. Based on inventory information, the chemical composition of the cloud is similar to butane or propane in terms of reactivity (HSE, 2009; Atkinson, 2008). It was identified that little was known about the pressure fields caused by detonation of low-lying vapour clouds in the open or when they impinged on buildings (HSE, 2009) while it is known that this configuration effectively maximises the blast damage for a given amount of explosion energy by keeping the energy release near the ground. Sichel and Foster (1979) carried out an analysis of planar detonation and found that the pressure behind the detonation front decreases quite rapidly and the positive phase duration near the centre of the cloud is extremely long even though the pressure is relatively low. Fishburn et al. (1981) conducted theoretical and experimental studies of the blast effect from a pancake shaped fuel drop-air cloud detonation. The HEMO hydrocarcode was used to simulate centrally initiated detonation in a cloud. Numerical simulations were conducted for a pancake-cylindrical case with 128 m diameter and 4.57 m height in 2-D while the experiment was conducted with an irregular shaped cloud of approximately 70 m diameter and 5.8 m thick detonated from two corners near the cloud edge. The theoretical results compared satisfactorily with pressure data obtained from detonation of a large (~70 m nominal diameter) hydrocarbon fuel-air cloud. The authors have mentioned that the pressure profile does not depend on the radius, except for the outer edges. However, the HEMO code, like other hydrocodes used in some ongoing industrial investigations, is based on the simplified CJ-volume burn method which assumes that the flow is one dimensional and the front of the detonation is a jump discontinuity with infinite reaction rate (Giroux, 1971). Such approach misses out important characteristics of the fully three-dimensional detonation, and will not be able to capture the deviation of detonation pressure and velocity in complex geometries and in the presence of obstacles where the reflected shocks need to be taken into consideration.

Heidari et al. (2010a, 2010b) developed a modelling strategy for consequence analysis of medium and large

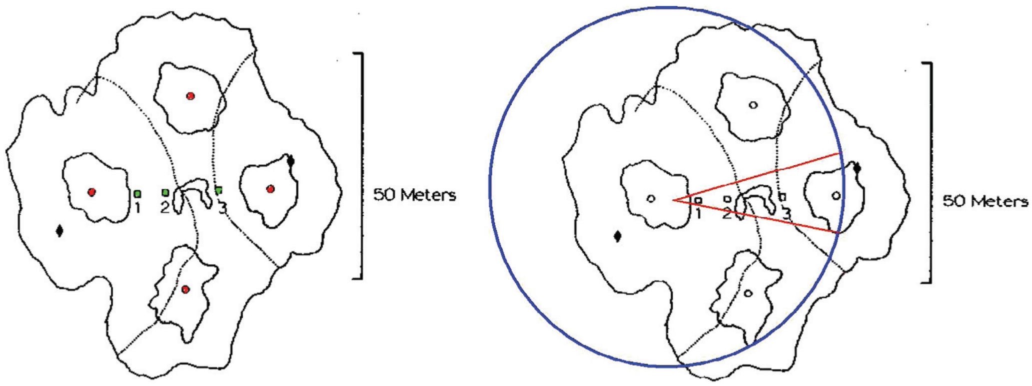

Figure 1. Overhead view of experimental cloud (reproduced from Fishburn et al. 1981) and the wedge shaped computational domain

scale gaseous detonation. The model is based on the solution of Euler equations with one step chemistry. Predictions were firstly conducted for smaller domains of various sizes in both one and two dimensional studies to find suitable pre-exponential factor and activation energy which will predict the correct CJ parameters with the chosen grid resolutions while supplying the right energy into the system. They studied hydrogen-air and propane-air planar cloud using a one step reaction model. The predictions demonstrated sharp fall of overpressure at the edge of the cloud. In contrary to common belief that the impulse of all explosions will push objects away from the epicentre, the predictions have revealed the existence of high negative drag impulse within the detonated cloud. Such impulse was also found to vary with heights. The findings from the analysis were in line with the forensic evidence on damages in some historic accidents and challenges previous analysis of the Ufa train disaster which led to liquefied petroleum gas explosion killed 575 and wounded 623 (Wikipedia, 2010). The forensic evidence suggested localised detonation but was considered as the consequence of fire storms by the investigation team (Makhviladze, 2002). While it is acknowledged that there is some difference between a pancake shaped and planar cloud. The first part of the present study will simulate the pancake shaped cloud experimentally tested by Fishburn et al. (Fishburn, 1981).

There were a number of objects (e.g. switch boxes, oil drums, cars) distributed across the site and immediate surrounding areas. The condition of these objects after the explosion provided an indication of the overpressure magnitude at the location of these objects. During the Buncefield Explosion Mechanism Phase 1 research (HSE, 2009), the lightweight steel junction boxes on the site located within the area covered by the gas cloud were compared with similar boxes tested under a range of different loading conditions using hydrostatic pressure, gas explosions and High Explosive charges (HE). Measurements were conducted for the residual plastic deformations for these boxes. In the second part of the paper, we report on the finite element (FE) study of these boxes under prescribed blast loading applied in the experiment and compare the predictions with the measurements. The objective was to demonstrate that validated FE modelling can be used to derive iso-deformation lines for a range of objects to aid accident investigations by back tracking the blast loading from structure deformation.

NUMERICAL SIMULATIONS OF PANCAKE SHAPED CLOUD

Computations were set up using the experimental configurations of Fishburn et al. (1981). As shown in Figure 1, the experimental domain was a non-uniform cloud, being nominally 70 m in diameter and 5.8 m thick, created from fuel vaporisation from the 4 points which are marked in green. Ignition was started from the two points at two opposite corners of the cloud and the resulting detonation started to move inwards. Computations were carried out for a cylindrical-pancake cloud shape of 80 m diameter with one ignition in the centre of the cloud. In order to save computational time, the cloud is assumed to be axi-symmetric and wedge boundary conditions are used.

Measurements were available for pressure and impulse at the 3 monitoring points shown in Figures 1 and 2. Comparison is made between the predicted and measured impulses at these points and shows reasonably good agreement.

The predicted pressure-time history at 13 monitoring locations of which 7 are within the cloud, are plotted in Figure 3. It can be seen that there is a sharp drop in overpressure from the edge of the cloud where the aftershock expansion starts. Such sharp fall of overpressure at the cloud edge is thought to be possibly relevant to some forensic evidence at Buncefield. As shown in Figure 4, among the lines of the crushed cars, the rest of them were much more significantly damaged than the one in the front. This is thought to be possible indication that there was a shape fall in the blast wave pressure between the location of front car and the one behind.

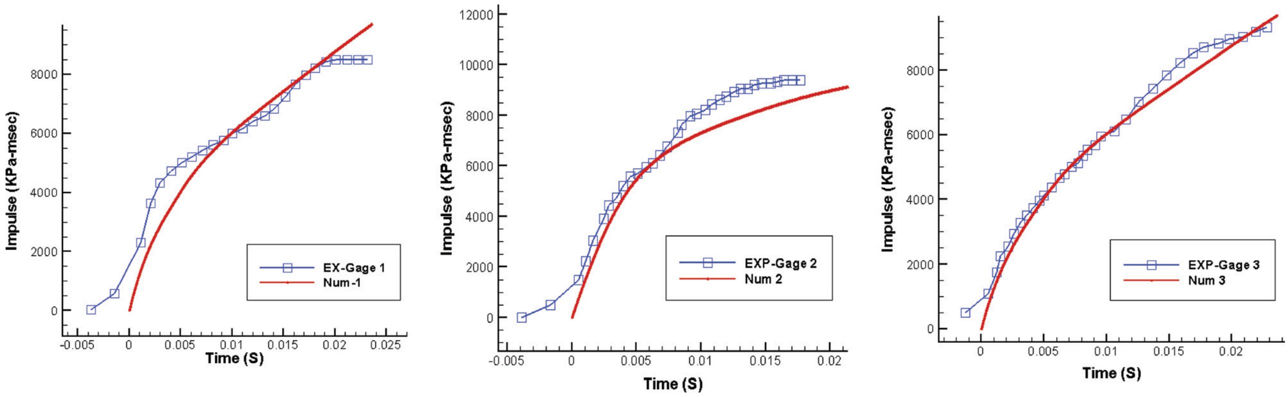

Figure 2. Comparison of the predicted and measured drag impulse for the three monitoring points

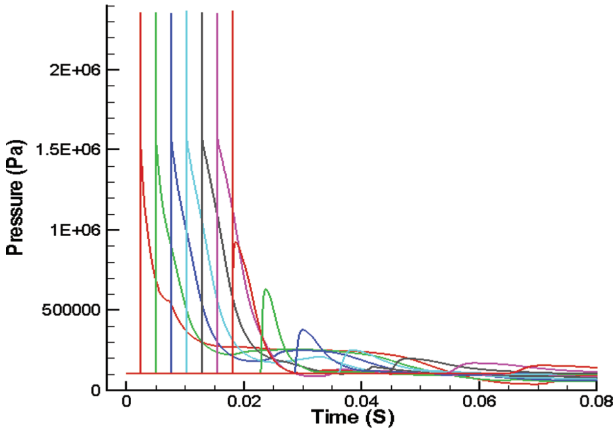

Figure 3. The predicted overpressure at the monitoring points

Figure 4. Lines of crashed cars at Buncefield site (reproduced from Explosion Mechanism Advisory Group report, 2007)

Comparison is made between the measured and predicted pressure-time history in Figure 5. Both show very similar trends and give the same maximum close to the CJ value. There are, however, some discrepancies which might be partly caused by the assumption of uniform fuel concentration in the numerical simulations while the actual fuel concentration in the cloud was non-inform in the experiment. In the measured pressure-time history for

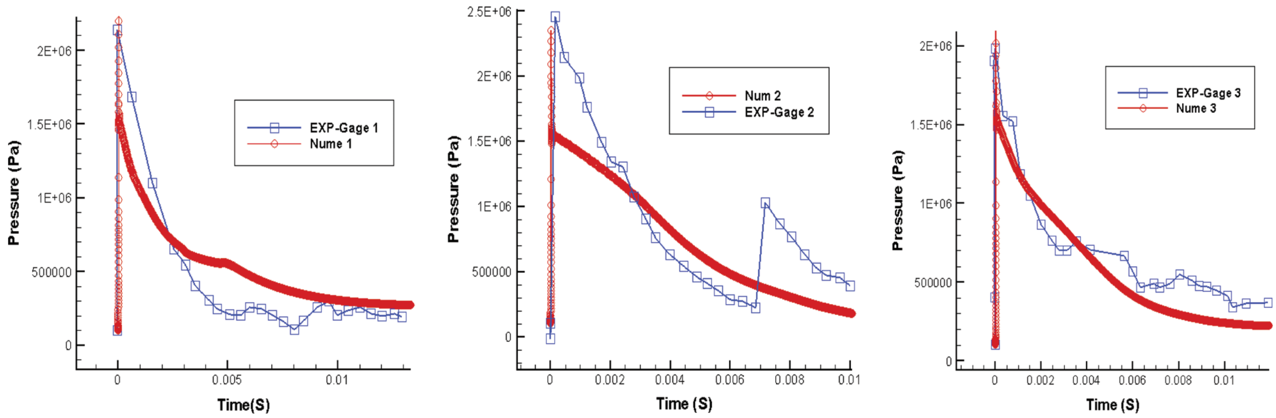

Figure 5. Comparison of the predicted and measured overpressures at three monitoring points

the 2nd monitoring point, we see a second pressure peak which are significantly lower than the first peak. As mentioned earlier, there were two ignition points on the two corners of the cloud, this is thought to be possibly the result of the blast wave generated by the second detonation wave coming from opposite direction moving towards the 2nd monitoring point. As the wave reached this location, the local fuel was already consumed by the first detonation wave and what was recorded was just the blast wave propagating through the burnt products. However since we are modelling a uniform cloud with one ignition point in the centre, this second peak does not exist in our simulations. A full 3-dimensional simulation with corner ignitions might be necessary to capture such fine details of this particular experiment.

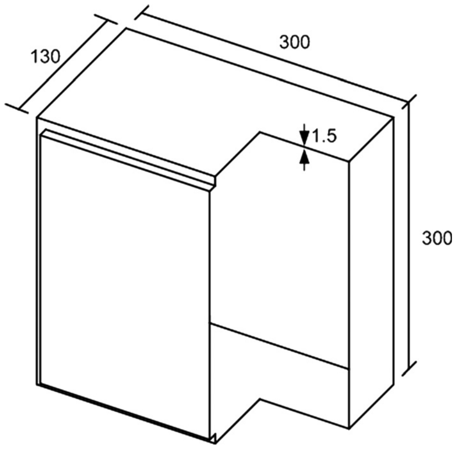

Figure 6. Scheme of the switch box (all dimensions in mm)

FINITE ELEMENT MODELLING (FEM) OF THE SWITCH BOX

In order to model the switch boxes, the pressure-time recorded in the experimental studies was applied to the structure. A pure Lagrangian formulation was adopted for the explicit simulation. The box was modelled with thin-shell elements specific for explicit dynamic analysis with a thickness of 1.5 mm. The dimensions are presented in Figure 6 for the small box (for the big box the design is similar but with 600 mm × 600 mm × 230 mm dimensions) which is of the same size as those crashed switch boxes at Buncefield as shown in Figure 7. The FE model used Belytschko-Lin-Tsay quadrilateral shell elements which are based on a combined co-rotational and velocity strain.

The steel was modelled using MATERIAL_PIECEWISE_LINEAR_PLASTICITY, pertaining to the von Mises yield condition with isotropic strain hardening, and strain rate-dependent dynamic yield stress based on the Cowper and Symonds model. According to the expected strain rate for this kind of action in previous investigations and following the work presented in [3], the mechanical properties applied to the material model were a Young's modulus of 210 GPa, a yield stress of 1000 MPa and a Poisson's ratio 0.28. For the side facing the blast, the reflected pressure was applied and for all the other faces the incident pressure was applied. All applied pressures are inwards.

The first step of this study was to calibrate a geometric and material model. This was achieved by comparing the results obtained in both experimental and numerical studies. The numerical studies replicated the experimental conditions by applying the experimentally measured load profiles in all the four scenarios including small box hit on the side (SBS), small box hit on the front (SBF) and the same for the big box (BBS and BBF).

Figure 8 shows the predicted deformed shape evolution in time for the big box with the front face facing the blast. All the faces are subjected to inwards pressure. However, in some cases, the relatively higher values of the reflected pressure cause the side faces to deform in the opposite direction of the loading.

Figure 9 shows the predictions for the small box hit on the side. The predicted deformed shape after 20 ms is seen to resemble well the deformation in experimentally tested box.

A summary of the comparison between the numerical predictions and experimental measurements can be seen in Table 1. As can be seen there were some situations where comparison had to be made in a face other than the one directly facing the blast. In some cases, it was not possible to make comparison due to severe damage of the boxes. The comparison shows discrepancies ranging from 3.8% to 32.7% between the predictions and measurements. As expected the higher deformations occurred in the test with the highest pressures. Under the same loading condition,

Figure 7. Crachsed switch box at Buncefield (reproduced from Explosion Mechanism Advisory Group report, 2007)

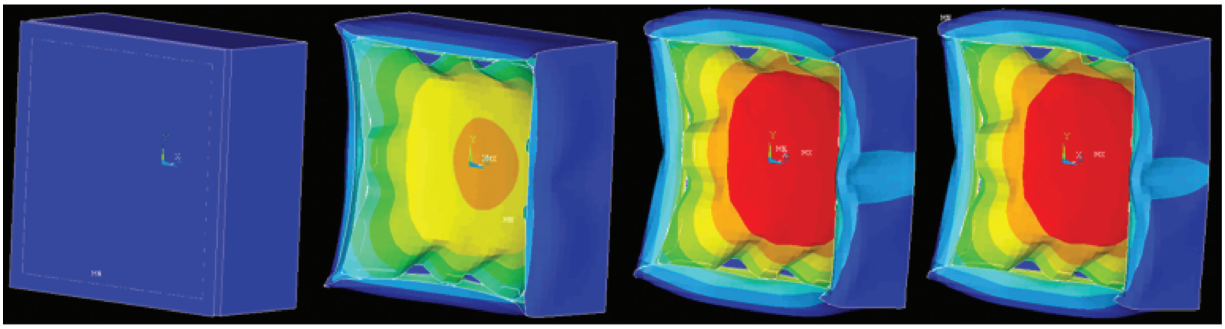

Figure 8. Deformed shape of the FE model for the big box hit on the front

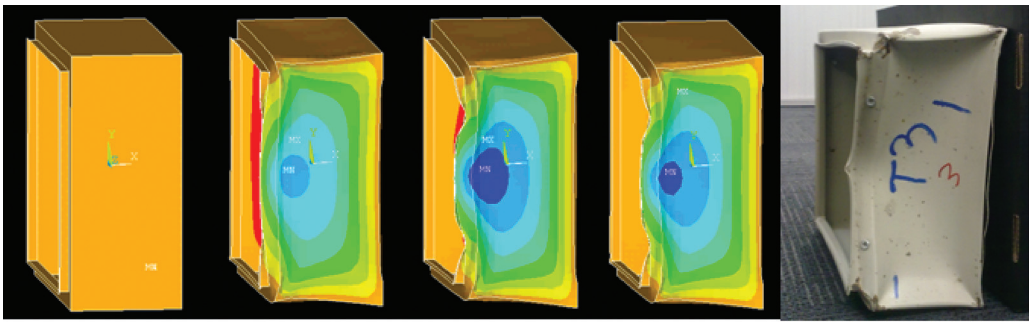

Figure 9. Comparison of the FE model with the relevant experimentally tested box (small box hit on the side)

Table 1. Summary of the comparison between the numerical and experimental analyses

Test		Residual deformation (mm) Exp.	Residual deformation (mm) Num.	Difference (mm) [%]	Comments
T2 ($I_r = 2.6$ kN.s)	SBF	15.7	19.0	3.3 (17.1%)	Deformation measured in the side facing the blast
	BBS	20.0	23.9	3.9 (16.4%)	Deformation measured in the front face
	BBF	94.1	126.5	32.4 (25.6%)	Deformation measured in the side facing the blast
T1 ($I_r = 4.7$ kN.s)	SBF	1.6	1.4	0.2 (10.4%)	Deformation measured in the side face
	BBS	25.5	17.2	8.3 (32.7%)	Deformation measured in the side face
	BBF	32.9	30.2	2.7 (8.2%)	Deformation measured in the side face
T3 ($I_r = 13.8$ kN.s)	SBS	56.0	53.9	2.1 (3.8%)	Deformation measured in the side facing the blast
	SBF	7.4	6.6	0.8 (11.7%)	Deformation measured in the back face
	BBS	124.9	142.4	17.5 (12.3%)	Deformation measured in the side facing the blast
T4 ($I_r = 20.8$ kN.s)	SBS	16.4	13.2	3.2 (19.6%)	Deformation measured in the side face
	SBF	29.8	40.2	10.4 (25.9%)	Deformation measured in the side face
	BBF	27.1	30.2	3.1 (10.1%)	Deformation measured in the back face

the worst deformation was found to occur for the big box hit on the front. In most cases, the predicted deformations are higher than the experimental measurements.

Following the above comparison, a series of numerical simulations were carried out by systematically varying the reflected pressure and positive duration of the load

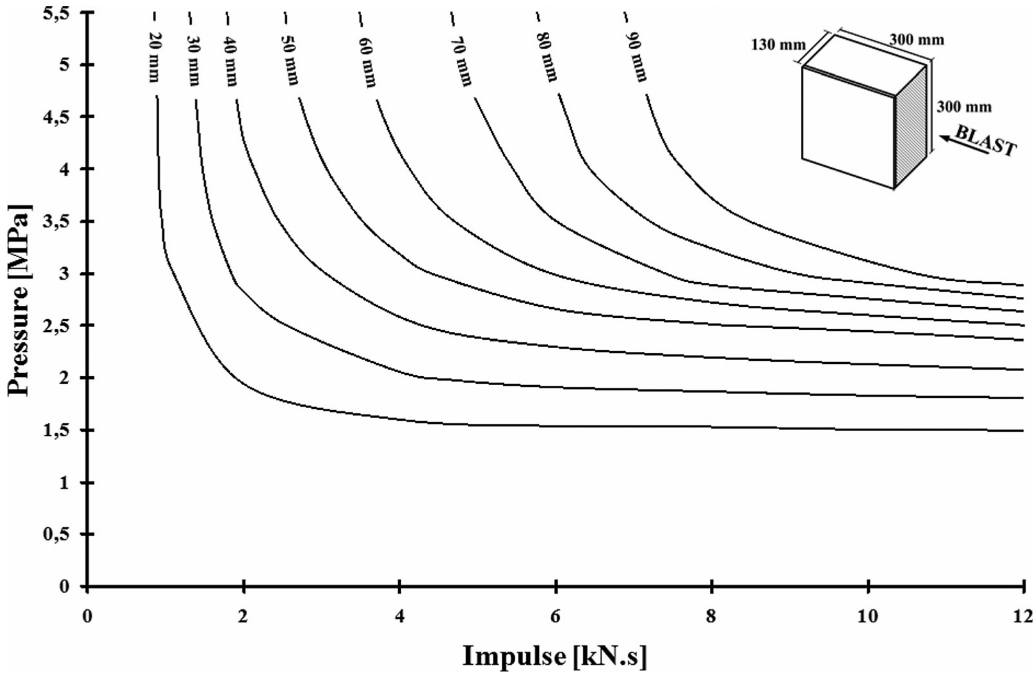

Figure 10. Iso-deformation lines for the small box hit on the side face. Deformation represented: 20, 30, 40, 50, 60, 70, 80 and 90 mm.

(reflected impulse). The results were used to generate iso-deformation lines with each line representing one specific value of deformation. From these iso-deformation lines, one can identify all possible combinations of pressure and impulse (for the selected range) that can cause permanent deformation. Figures 10–13 show the results of this analysis for all four situations (SBS, SBF, BBS, and BBF). It can be seen that the big box shows a higher deformation than the small box and the situation hit on the front leads to a higher deformation too.

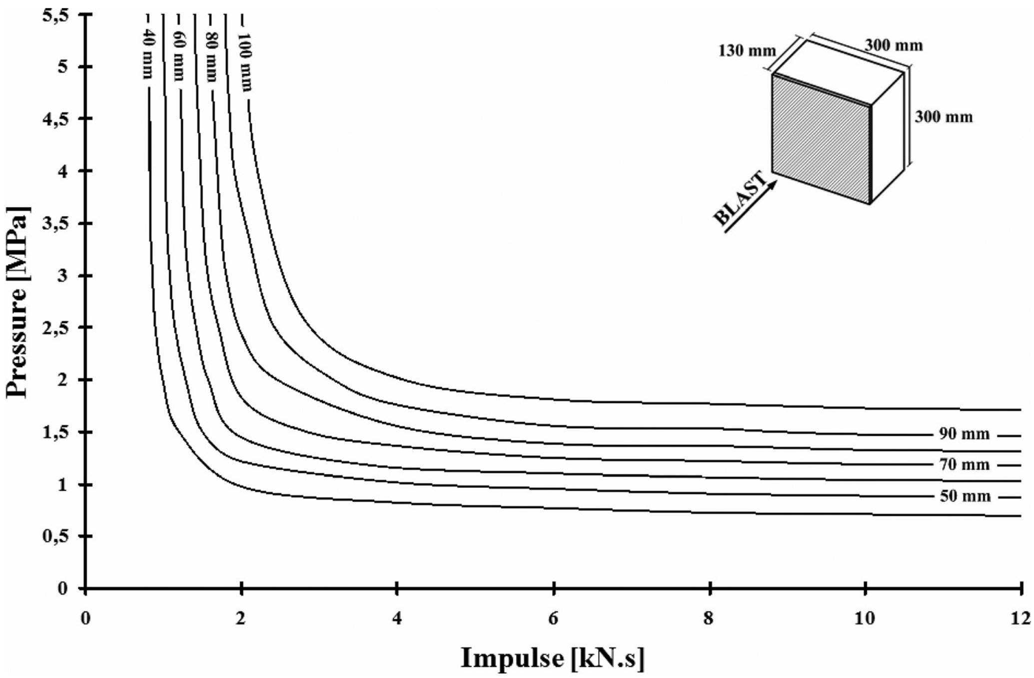

Figure 11. Iso-deformation lines for the small box hit on the front face. Deformation represented: 40, 50, 60, 70, 80, 90 and 100 mm

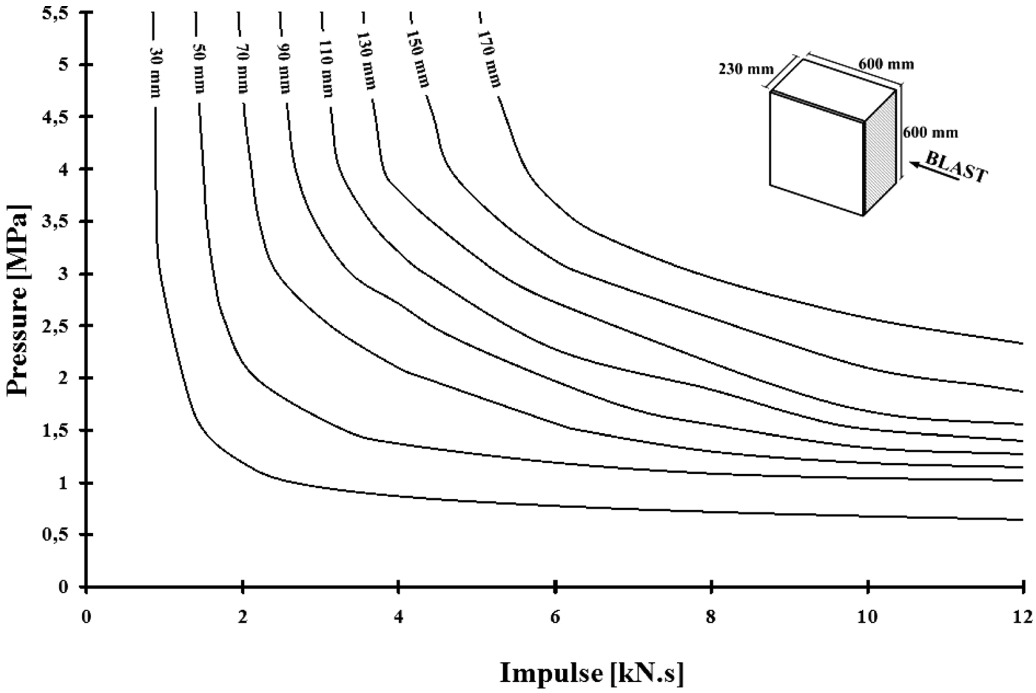

Figure 12. Iso-deformation lines for the big box hit on the side face. Deformation represented: 30, 50, 70, 90, 110, 130, 150 and 170 mm

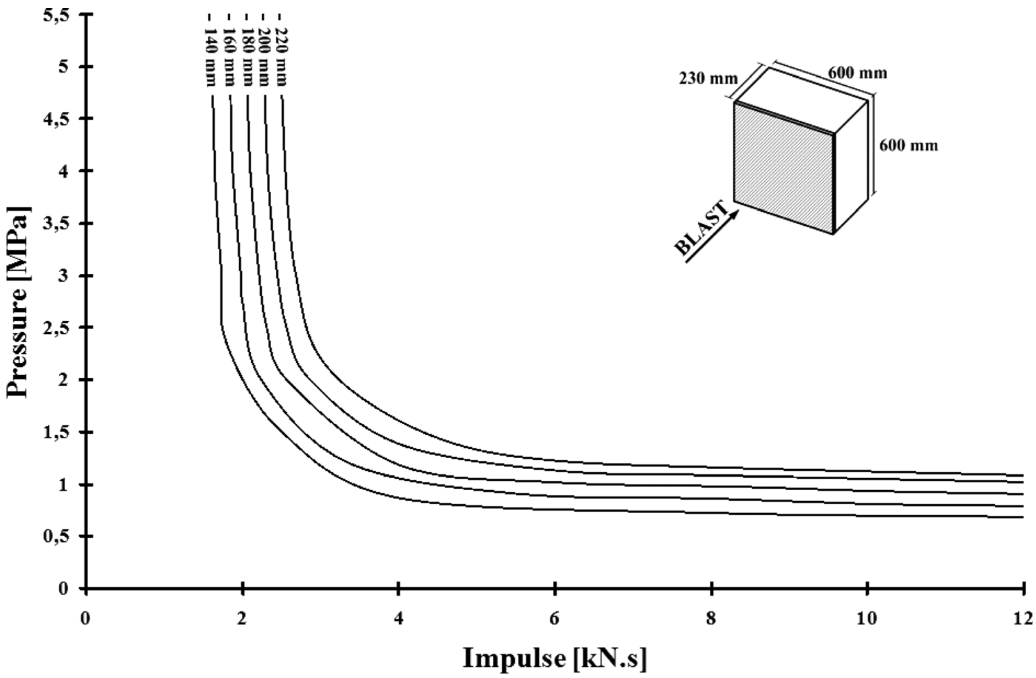

Figure 13. Iso-deformation lines for the big box hit on the front face. Deformation represented: 140, 160, 180, 200 and 220 mm

CONCLUSIONS

Numerical simulations of the pancake shaped cloud detonation were carried out and compared with the measurements of Fishburn et al. (1981). Reasonably good agreement is achieved on the predicted overpressure and drag impulse for the three monitoring points in the tests. The results have also shown that there is a sharp fall of overpressure at the edge of the cloud.

While the model is fully three dimensional, the present simulations were conducted in two-dimensional axi-symmetric set to save computational time. This has resulted in discrepancies on some salient features such as the 2nd peak on the pressure-time history. In order to characterise the pressure profiles associated with non-symmetric detonations and their effect on the surroundings (building structures and other objects), further work is underway to model the pancake cloud in three dimensions.

Finite element analysis of the lightweight metal boxes, similar to the steel junction boxes on the site located within the area covered by the gas cloud in the Buncefield explosion have been carried out. Static analysis was firstly conducted and the predictions were found to be in reasonably good agreement with the measurements conducted under a range of different loading conditions using hydrostatic pressure. Further FE analysis was then conducted to produce iso-deformation lines for these specific boxes under different dynamic loading conditions. Such iso-deformation lines can be used in accident investigations to back track the overpressure, fuel type and quantity from the observed structure deformations.

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