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BLAST RESPONSE OF FIELD OBJECTS

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Abstract. *During the last few decades, several major industry accidents occurred across the world. These include the Buncefield event in the United Kingdom (UK) back in 2005. There were a number of steel switch boxes in the site located within the area covered by the vapour cloud. The present work reports numerical studies on the steel boxes covering both detonation and deflagration scenarios and assessing the response of those boxes in order to aid the investigation of the explosion. New Eulerian capabilites in ABAQUS has are together with existing Lagrangian formulations to create three numerical models with increasing complexity: (1) Pure Lagrangian model; (2) Uncoupled Eulerian – Lagrangian model; (3) Coupled Eulerian – Lagrangian model. Results from different modelling approaches are discussed and parametric studies are carried out based on Pure Lagrangian models to investigate the response of the switch box to a series of combination of pressures and impulses. Findings from the parametric study are summarised in the form of pressure – impulse diagrams and residual deformation of selected boxes are presented. The results confirmed the estiamted minimum overpressure level of 200kPa and it can also be concluded that the overpressure wave inside the cloud is most likely to be of a deflgrative form. The forensic study described in this paper has gives a good insight into the likely loading scenarios. The study presents a systematic approach for analysing the response of small objects to various blast loadings and the results have shown sthat the forensic studies can be undertaken by using the pressure – impulse diagrams in conjunction with damaged residual deformations.*

1 INTRODUCTION

During the last few decades, a number of major industrial accidents have occurred around the world. These include the Buncefield event in the United Kingdom back in 2005 where the explosion of 240000 m3 of vapour cloud resulted in considerable damage to business and residential properties in the surrounding area [1]. The explosion generated much higher overpressure than would usually be expected from a typical vapour cloud explosion. The severity of the explosion would not have been anticipated in any major hazardous assessment of oil storage depots before the incident.

A cloud of combustible vapour in the atmosphere can explode under certain conditions, which is usually referred to as a vapour cloud explosion (VCE). In the combustible-air mixture a flame could propagate through the entire cloud by two different mechanisms: (i) deflagration, where the propagation of the flame is caused by heat transfer from the reacted region to the fresh mixture. Deflagration is easy to initiate, but only generates relatively low peak overpressures in an unconfined, uncongested area. (ii) If the flame is coupled with a shock wave which compresses and heats the mixture in front then a detonation event can be identified. Detonation in a vapour cloud could be very destructive but difficult to initiate. It produces a shock wave of high overpressure.

For the purpose of assessing the overpressure history across the incident site, evidence relating to overpressure is important as part of the forensic studies. It was found that there were many small objects such as steel switch boxes distributed across the site and nearby areas. These field objects could be used as overpressure indicators, as the final deformation of these objects can provide an indication of possible overpressure at their location after the passage of blast waves. Figure 1 shows three damaged steel switch boxes found within the vapour cloud. One of the main objectives of the work presented in this paper is to carry out numerical analyses covering both detonation and deflagration scenarios with a range of overpressures and impulses, in order to examine more realistically the possible blast characteristics experienced at Buncefield.

Figure 1 Damaged steel switch boxes in the vapour cloud (Courtesy of HSE)

A recent release of the advanced finite element program ABAQUS [13] provides an Eulerian modelling capability and a contact algorithm for interaction between Lagrangian and Eulerian formulations. The validity of the Eulerian capabilities in ABAQUS has been recently examined in detail by Mougeotte and Carlucci [3, 4]. The present work uses the numerical approaches provided by ABAQUS to analyse the response of steel switch boxes to a range of explosions leading to the generation of Pressure-Impulse diagrams. These diagrams provide an insight into the relationship between blast characteristics and structural damage, and could be used for forensic assessments as well as design considerations.

2 NUMERICAL APPROACHES

Most blast problems usually involve the following phases: (i) the explosion phase where the source produces higher pressure and high temperature gases that propagate outwards and generates pressure waves in the medium (air), (ii) the propagation phase where the pressure waves travel in the surrounding medium (air) towards the target, (iii) the interacting phase between the travelling pressure waves and the target, (iv) the final phase where the target responses to the impinging pressure waves.

In general, the propagation of pressure waves and structural responses are treated separately. The pressure waves can be determined simply by using of empirical charts in manuals such as those included in UFC – 3 – 340 – 02 [8]. Alternatively it can be generated by an Eulerian model such as that in ABAQUS [3, 4] if the target is of complex geometry. Regarding the structural response, a simple system is often reduced into a single degree of freedom (SDOF) model based on Bigg's method [10]. There are also improved models which take into account the catenary actions [11]. For a more complex system the SDOF is not applicable hence a Lagrangian finite element model can be used to calculate the response to blast loadings. In reality, the movement of a structure is often directly coupled with the surrounding fluid due to the interaction between the response and fluid motion. Therefore, in ABAQUS the Eulerian model of blast can be coupled with as Lagrangian model of the structure to capture such interaction. This numerical technique is referred as coupled Eulerian – Lagrangian modelling.

A typical switch box shown in Figure 1 has dimensions of 300mm×300mm×150mm, with wall thickness of 1mm. There are two supporting methods: one is supported vertically along the edges of the box back panel, and the other is supported at the box bottom. The box is modelled by S4R reduced integration shell elements in ABAQUS, and two hinge type connectors were used to represent the actual steel hinge. Several coupon tests were carried out to determine the material properties of the box, and a yield stress of 300 MPa was found to be representative of the material. A Johnson – Cook plasticity and stain – rate model was employed for the modelling, such that:

$$\sigma_Y = \left[A + B\left(\varepsilon_{eff}^{p}\right)^{N}\right]\left[1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right] \qquad (1)$$

where in the strain hardening part: the nominal yield stress A = 300 MPa, the strain hardening constant B = 200Mpa and the hardening exponential constant N=0.228. For the strain rate dependence: the rate constant C=0.017 and the reference strain rate $\dot{\varepsilon}_0$=1/s. The two variables are the effective plastic strain ε_{eff}^{p} and strain rate $\dot{\varepsilon}$.

The combination of Eulerian and Lagrangian capabilities in ABAQUS provides three possible modelling approaches:

Lagrangian analysis (LC and LI)

This approach only has a Lagrangian finite element model of the switch box. Blast waves are implemented as pressure loadings on the surfaces of the box, incident or reflected where appropriate. Two methods were used to determine the load – time histories: one is from the CONWEP data base built in ABAQUS (referred to as model LC) and the other is from analytical calculation (which is an idealised pressure profile referred to as model LI). The difference is that the idealised pressure profile takes into account the pressure relief effect for a finite dimension target for calculating the reflected pressure where CONWEP does not give a reflected pressure from an infinite surface.

Uncoupled Eulerian – Lagrangian analysis (UEL)

The UEL approach involves three steps. The first step is a one dimensional Eulerian modelling to produce the required pressure waves by specifying a triangular particle velocity inflow boundary condition. The Eulerian model is grade meshed to maximise the computing efficiency. Figure 2 (a) shows a schematic of the one dimensional Eulerian model.

Once the applied particle velocity triangle can generate the required pressure waves, this velocity profile is used in the second step and applied on a three dimensional Eulerian model with an empty volume, as shown in Figure 2 (b). The empty volume is the space occupied by the box and in this second step the pressure wave interacts with the box volume and the pressure loading on each surface is recorded. Pressure waves from the three dimensional Eulerian model can be seen in Figure 2 (c), and for comparison corresponding pressure waves predicted by CONWEP and analytical method (idealised) are also included.

The last step in this approach is the Lagrangian modelling. The pressure loadings recorded in the second step are now applied on the Lagrangian model of the box as surface pressure loads where appropriate.

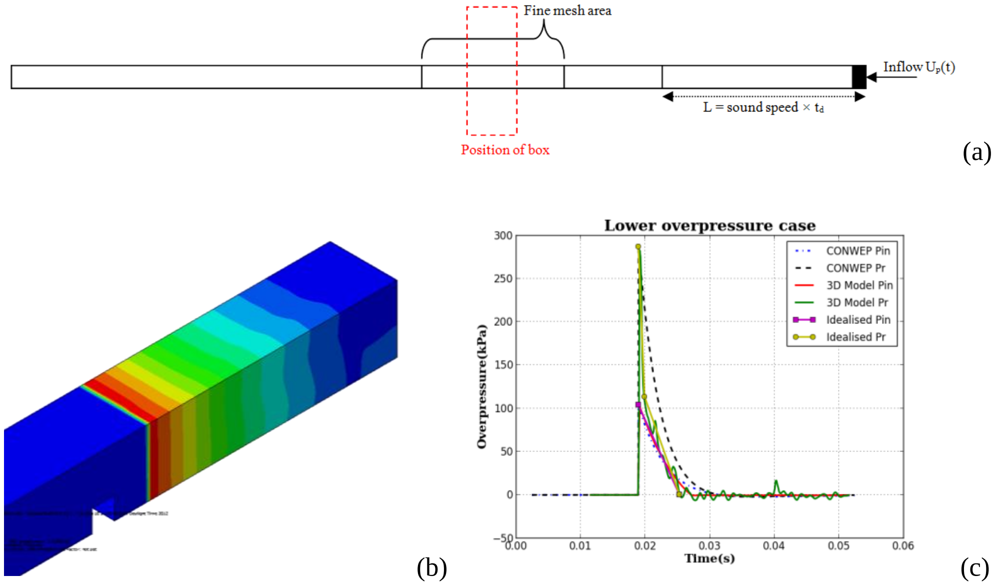


Figure 2 (a) schematic of one dimensional Eulerian model (b) numerical Eulerian model with pressure waves (reflected value) and box volume (c) pressure waves predicted by different tools

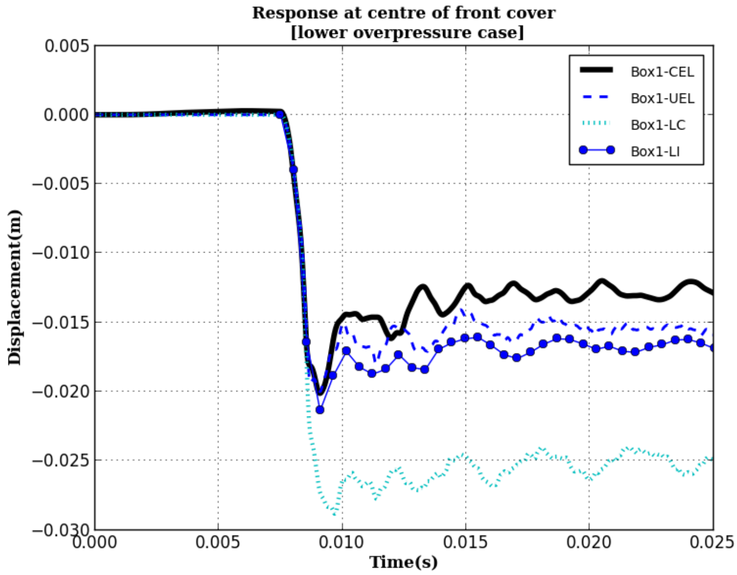
Coupled Eulerian – Lagrangian analysis (CEL)

The coupled method uses the determined particle velocity profile in the first step of the uncoupled approach. The inflow particle velocity is applied at the inlet Eulerian boundary. The explicit general contact definition automatically implements the interaction between the Eulerian and the Lagrangian parts.

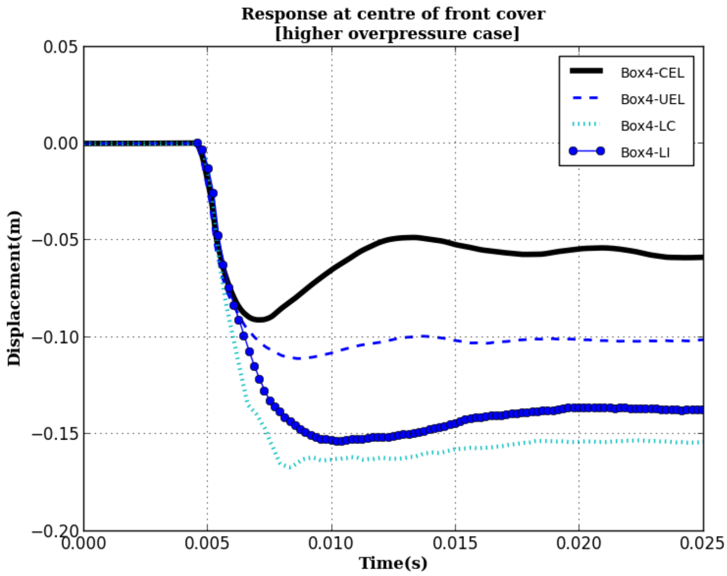
In the previous paragraphs we introduced various numerical simulation approaches were introduced above. To compare these afore mentioned approaches for the purpose of performing parametric studies, the explosion scenarios need to be specified and subsequently the response of the boxes can be studied. Limited experimental data is available in the report produced by HSE [1], and based on those data, two explosion scenarios are specified: the first one is a relatively low overpressure detonation with incident overpressure of 100 kPa (reflected 274 kPa) and duration of 8ms. The second is a relatively high overpressure detonation with incident overpressure of 400 kPa (reflected 1665) and duration of 4ms. Figure 2 (c) shows the reflected pressure – time profile predicted by different tools for the lower overpressure case.

Comparative assessments

Having defined the explosion scenarios, the responses of the box can now be studied. The study is mainly focused on the deflection at the centre of the box front panel. For the lower overpressure case, the maximum deflection predicted by the Lagrangian model with idealised pressure profile model (LI) is in good agreement with the UEL and CEL models, as shown in Figure 3(a), although the discrepancy is larger at the residual deformation. However, in the case of relatively high overpressure, the maximum deflections predicted by LI and UEL models are apparently different to the results from the CEL model, as shown in Figure 3(b). In both cases, the model LC produces the largest maximum deflections.



(a)



(b)

Figure 3 Displacement – time histories of the centre of the box front surface

It is important to note that in Figure 3, the order of the maximum deflection of the box front panel predicted by the different models is generally as following: LC > LI > UEL > CEL. Results of CEL models are discussed in the next paragraph while the order between LC, LI and UEL can be explained by referring to Figure 2(c), in which the peak reflected pressures are the same for all three types of loads: CONWEP (for LC model), 3D Eulerian (for UEL model) and Idealised (for LI model). However, the reflected impulses from those pressure loadings are different with CONWEP producing the largest impulse and the 3D Eulerian producing the least. With the same pressure levels, the pressure loading with the largest impulse produces the greatest deflection response. This explains why the Lagrangian model with CONWEP load (LC) predicted much larger deflection than UEL and LI models.

In Figure 4(b), the results of the Lagrangian model with idealised pressure (LI) deviated significantly from the CEL model compared with other boxes. Since the pressure relief effect is inherent in the CEL model, the discrepancy could be explained by the impulse reduction due to the movement of the target surface. The reflected pressures of the idealised profile and UEL were determined based on a rigid surface which was stationary throughout the loading duration. However, in the CEL model, the reflected pressure was affected by the movement of the front surface of the box model. For the CEL models, the average velocities at the centre of the front surface up to maximum dynamic deflection were determined as: 14.9 m/s for low pressure case and 41.8 m/s for high pressure case. The differences in peak deflection between the Lagrangian model with idealised pressure (LI) and the CEL models were determined as: 10% for low pressure case and 68% for high pressure case. The higher velocity of movement of the front surface resulted in a higher discrepancy and thus more impulse reduction. Similar observations were made by Borvik [5] on the movement of the reaction surface where more impulse has been reduced at the reaction wall with higher velocities.

The results indicate that the accuracy of the Lagrangian (LI) model appears to reduce at incident pressures above 400 kPa. Further consideration showed that the velocity at the deflected surface played an important role. The velocity of the deflected surface of Box 4 in CEL model was high enough to reduce significantly the impulse imparted on it. The combination of pressure and impulse determined the response of the surface including the average velocity to maximum deflection. At the same level of damage, a combination of high pressure with low impulse would result in a higher velocity of response than a combination of low pressure with high impulse. Accordingly, the Pressure-Impulse studies presented below were limited to a maximum incident pressure of 400 kPa (reflected pressure of 1665 kPa for an ideal blast wave) in order to keep the response velocity low and hence ensure the validity of the Lagrangian model. The HSE report [2] has briefly reviewed 9 previous significant vapour cloud explosion incidents for which detailed data is available. The work indicates that most of the major incidents experienced overpressure of 100 kPa or less within the cloud. The exception is the Flixborough incident in which the overpressure was estimated to be 1000 kPa. Therefore, this limiting pressure level of 400 kPa is notably higher than the lower bounds suggested from the Buncefield investigation and also adequate for most of the incidents.

As a result of the study of the response of boxes to two different explosion scenarios, it has been decided that the following parametric studies is best performed based on the Lagrangian model with idealised pressure loading profiles and a maximum incident overpressure of 400kPa (reflected value of 1665 kPa).

3 PRESSURE – IMPULSE DIAGRAMS

In order to study the possible overpressure experienced at the Buncefield event, it is necessary to examine a wide range of overpressure and impulses. In all P – I diagram studies in the present work, the overpressure and impulse ranged from 10 – 400 kPa (reflected pressure: roughly 20 kPa – 1665 kPa) and 10 – 10000 Pa.s respectively. The positive duration of overpressure ranged from 2ms to 2000ms at incident pressure of 10 kpa and from 0.05ms to 50ms at incident pressure of 400 kPa. Three shapes of blast waves were also used in the parametric studies.

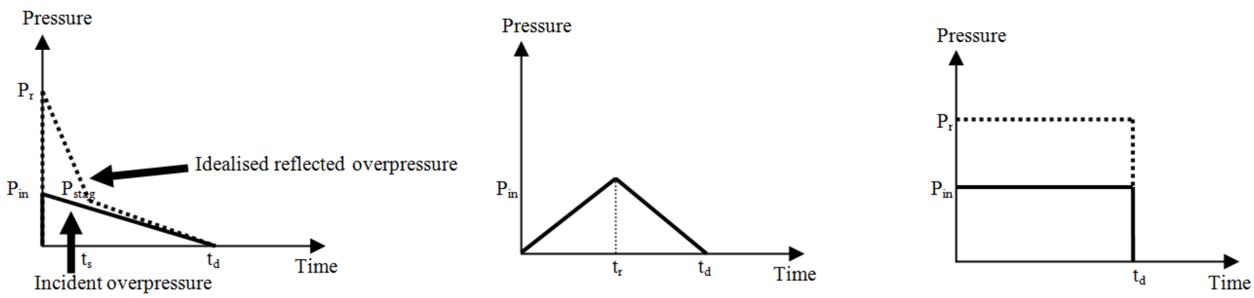


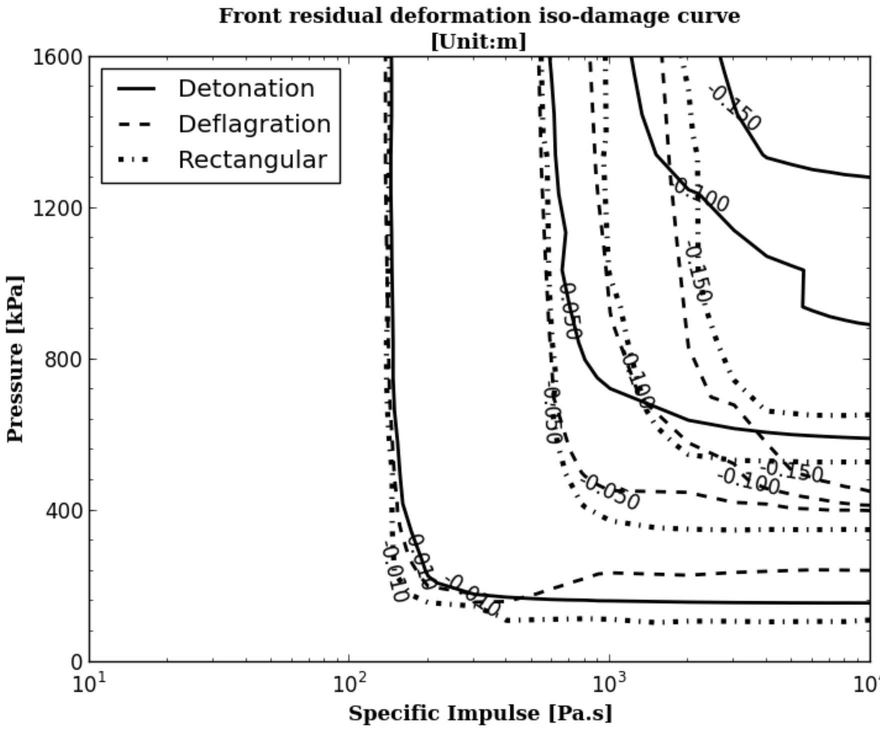
Figure 4 Pressure load types: left – detonation; middle – deflagration; right – rectangular

The three types of pressure loadings are: detonation, deflagration and rectangular, as depicted in Figure 5. For detonation and rectangular types of loads, the front surface of the box will be subjected to reflected pressures (Pr) and the other surfaces were subjected to incident pressures (Pin). It is important to note that for detonation pressure loadings, the reflected pressure is the idealised reflected pressure which takes into account the pressure relief effect of a finite dimension target.

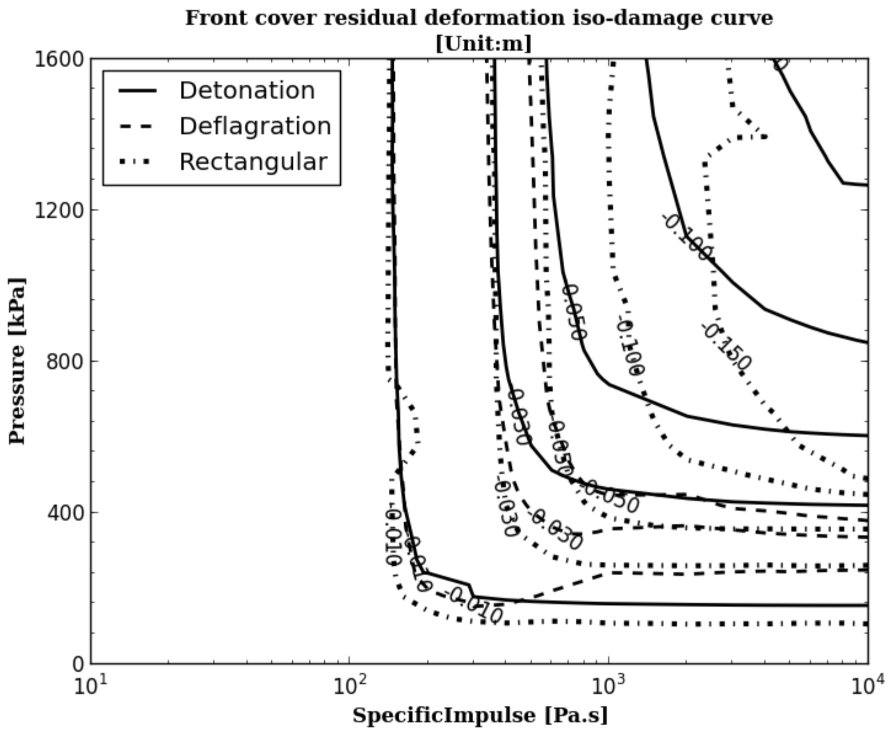
For the deflagration type of loading, only one type of pressure loading was used and applied on all the surfaces of the box model. This is due to the consideration that for a deflagration blast wave, the Rankine – Hugonoit relationship is no longer applicable, so the reflected pressure cannot be readily calculated. The rise of overpressure for deflagration takes a finite time, the pressure relief may start before the peak is reached, and the stagnation pressure would also have a finite rise time. The loading form the non-ideal blast wave is strongly related to the dimension of the target and the blast parameters. As a result, the reflection enhancement of a deflagration will be significantly reduced compared with an ideal blast wave of the same overpressure level [6]. Therefore no effect is made to distinguish the reflected pressure from incident in the case of a deflagration pressure wave. Although when interpreting the results and if we recognise the pressure on the front surface to be a reflected value, the results will become conservative as other surfaces are subjected to the reflected pressures as well.

Structural response

The structural responses of the box model are presented in terms of two pressures – impulse diagrams in Figure 5. In order to have direct visual assessment of the response of boxes, a group of selected residual shapes in the quasi – static regions are presented in Figure 6. In Figure 5, the iso – damage curves were plotted based on residual deflection at the centre of the front surface. Responses for three different types of loads are superimposed.



(a)



(b)

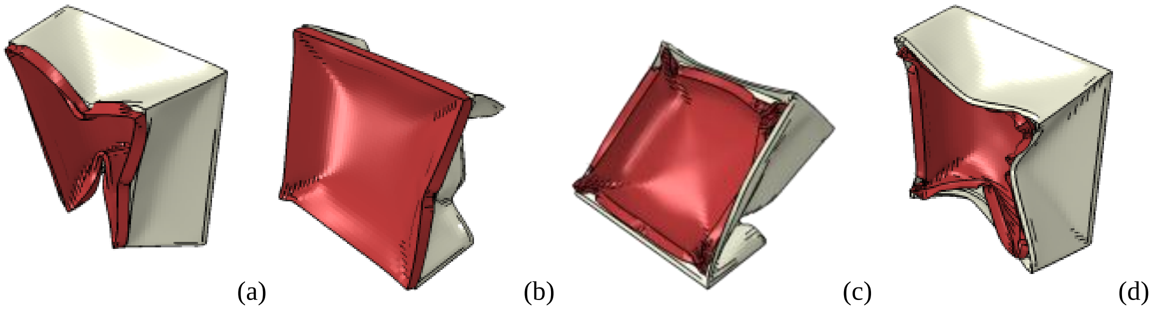
Figure 5 Pressure – impulse diagrams (a) box model constrained vertically at back (b) box model constrained at bottom

Damage levels are shown together with the iso – damage curves and it is worthy of noting that at lower damage level such as -0.01m the curves are approximately the same for boxes of two different supporting conditions. However at higher damage level the curves are quite different and this is mainly due to the supporting boundaries which results in a different response at higher damage levels. It can be observed from the -0.01m damage curves of Figure 5 (a) that the quasi – static asymptote ranges from approximately 100 kPa to 240 kPa for all load types, which is a relatively wide range. The impulse asymptote ranges from 137 Pa.s to 144 Pa.s, which is a relatively small range. It can be concluded that damage level of -0.01m is sensitive to the impulse and relatively insensitive to peak applied pressure. This observation holds true for other damage levels as well but overall the sensitivity is reduced with increased damage. The iso – damage curves for all three load cases tend to converge in the impulsive region as expected as the shape of the load is not important in this region.

It should be noted that in the dynamic and quasi – static region of the -0.01m damage curve for deflagration load case is of a different shape than for the other load forms. The quasi – static asymptote of the damage curve is shifted upward slightly when compared to other load cases. This is a well understood phenomenon and is due to the finite rise time at the beginning of the deflagration load curve. In Figure 5 (a), in the dynamic and quasi – static region, rectangular loads produce more damage than the other two as for a fixed impulse it requires lower peak pressure to produce the same level of deformation at the centre of the front panel. Beyond damage level of -0.05m, deflagration produces the worst damage to the front panel as at given peak pressure and impulse it produces the most damage to the front surface. The buckling of the top side of the box (as shown in Figure 6 (a)) significantly promotes the deformation in the centre of the front panel. It is the reason that the iso – damage curves of deflagration load is positioned very closely in the quasi – static region while curves for the other two load cases are relatively evenly spread over the diagram.

The general features of plots (b) in Figure 5 are very similar to plot (a) discussed above. Responses of front surfaces are sensitive to peak applied pressures in the quasi – static region for deflagration, due to the buckling of the side wall promoting deformation in the front panel as shown in Figure 6 (b). Moreover, the buckling of side wall near the bottom (shown in Figure 6 (c)) occurs for rectangular load cases in the quasi – static region. This has a significant effect on the deformation of front surfaces and leads to the damage curves of -0.1m and -0.15m approaching each other.

Three residual deformation levels for the box model subject to deflagration and rectangular types of loading are presented in Figure 6. They are selected in the quasi – static region with specified impulse of 10000 Pa.s. This is to examine the residual shape of the box under pressure loadings of long durations. In each of the three deformed shapes, buckling of the box occurred at different positions. However, the overpressure level at which the buckling occurred was similar. For deflagration case in Figure 6 (a) and (b) of different supporting conditions, the overpressures are 440 and 420 kPa. It has been assumed that no reflection is considered for deflagration load cases to calculate the responses, as the reflection enhancement of deflagration is significantly reduced. With the due consideration of the reduced reflection when interpreting the results we should recognise the overpressure on the front surface to be the reflected one. Hence roughly with an assumed reflection factor of 2 for a non-ideal blast wave the incident overpressures of deflagration to cause buckling on the walls are approximately to be 220 and 210 kPa. And Figure 6 (c) and (d) show that buckling of the box occurred at incident overpressure of 160 kPa for rectangular and 280kPa for detonation. The supporting conditions in Figure 6 are: (a) supported at back, (b) supported at bottom, (c) supported at bottom and (d) supported at back.



(a) (b) (c) (d)

Figure 6 Residual shape of box in quasi – static region I=10000 Pa.s (a) deflagration – 440 kPa (b) deflagration – 420 kPa (c) rectangular – 497(incident 160) kPa (d) detonation – 1035(incident 280 kPa)

The damage is mostly focused on the front covers of the boxes when subjected to detonation and rectangular load, while when the buckling of wall occurs near the bottom, the body of the box seems to be bent around the fixed bottom. Due to the reduced reflection enhancement, deflagration loads produce more symmetric deformed shape than detonation and rectangular load types. The residual shapes of boxes from the quasi – static series predicted by applying deflagration loads (Figure 6 (b)) compare more favorably with Figure 1. These observations suggest that within the vapour cloud the overpressure wave is most likely to be of a deflagrative form. Studies of the buckling features of the boxes suggest the level of overpressure should be at least 200 kPa. This is in agreement with the conclusion of the incident investigation carried out by HSE. Without the measurements of the damage boxes in the incident, the actual level of overpressure is difficult to determine accurately. Nevertheless, the forensic study described above gives an insight into the likely loading scenarios.

4 CONCLUSION

In this study three numerical approaches have been used to analysing the response of a switch junction box to various blast loadings, namely: (a) Pure Lagrangian, (b) Uncoupled Lagrangian – Eulerian, and (c) Coupled Eulerian – Lagrangian. The deformation responses from uncoupled and coupled Eulerian – Lagrangian approaches were found to be less pronounced compared to a pure Lagrangian simulation with pressure load calculated by the CONWEP function in ABAQUS. However, the pure Lagrangian model with idealised pressure load profile can produce acceptable results compared to the coupled Eulerian – Lagrangian approach. With consideration of both accuracy and computational efficiency, a pure Lagrangian model with idealised load has been adopted in a parametric study of the response of the box to combinations of pressures and impulses. In the parametric study, the maximum incident pressure was limited to 400 kPa (reflected pressure of 1665kPa) in order to minimise the impulse reduction on the front face of the box hence to ensure the validity of the Lagrangian model. The present work demonstrated a systematic approach for analysing the response of a small object to various blast loading scenarios. Studies of small objects other than steel switch boxes examined in this study could be based on Lagrangian approaches. However, as shown in this investigation, the possible reduction in impulse would need to be taken into consideration to ensure the accuracy of numerical models.

Results of the parametric studies carried out on the Lagrangian model were summarised in the form of pressure – impulse diagrams. Iso – damage curves were plotted based on the deflection of the front surface of the box. Residual deformations of representative models in quasi – static regions in the pressure – impulse diagrams were also presented in this paper. Through the studies on the switch boxes, it was found that the minimum require pressure level to cause the damage observed at Buncefield Incident is about 200 kPa. This is based on comparing the buckling deformation of the wall of the box models to the damage pattern of the boxes recovered on site. From a qualitative point of view, by comparing the residual shapes of the numerical models with the damaged boxes it can be concluded that the blast within the vapour cloud in the Buncefield Incident was deflagration. Exact estimation of the overpressure level is difficult since the deformation measurements of the damaged junction boxes are not available, therefore a meaningful quantitative comparison cannot be conducted.

This study has shown that forensic studies of the response of the junction box can be undertaken by using the pressure – impulse diagrams in conjunction with residual shapes. With the measurements of the damaged box, the pressure – impulse diagrams can be used to determine the blast parameters which caused the observed level of damage. While measurements are not readily available, the presented residual shapes can be used to identify similar deformation features such as buckling of the wall and then determine the pressure levels required to initiate such damage. This methodology can be used for future forensic studies on other similar objects and structures damaged in explosion accidents.

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