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Blast assessment of steel switch boxes under detonation loading scenarios

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ABSTRACT

A number of major industry incidents have occurred globally in recent years involving the ignition of a vapour cloud which resulted in loss of life and considerable damage. One such case was the Buncefield incident which occurred in 2005 and involved an explosion of two hundred and forty thousand cubic meters of vapour cloud which resulted in considerable damage to business and residential properties in the surrounding area. A number of overpressure indicators such as steel switch boxes were located at various points around this site. These were found deformed to different levels after the explosion. These overpressure sensitive objects were used to assess the overpressure level at the locations of the objects during the incident. This study describes full scale validation tests and numerical simulations of far-field air blast loading acting on deformable steel boxes in order to investigate possible forensic methods to aid the incident investigation. Subsequently, a number of numerical models with varying complexity are developed in order to simulate the tests. These consist of Lagrangian, uncoupled Eulerian–Lagrangian and coupled Eulerian–Lagrangian models. The models are validated against the test results from a gas detonation explosion. Comparison between the numerical and experimental results suggests that the coupled Eulerian–Lagrangian approach is able to accurately predict the deformation of the box under blast loading, but requires a prohibitive computational resource. On the other hand, the Lagrangian model tends to over-predict the results but with significantly lower computational cost. The present work shows that advanced finite element methods can be used for problems involving air blast loading and reliable results can be obtained. The validated finite element models of steel switch boxes could be a useful tool for forensic studies in explosion incidents to estimate the overpressure levels at the site.

1. Introduction

A number of major industrial accidents have occurred around the world in the last few decades. These include the Buncefield event in the United Kingdom (UK) back in 2005 where the explosion of two hundred and forty thousand cubic meters of vapour cloud resulted in considerable damage to business and residential properties in the surrounding area [1]. The incident occurred as a result of fuel spilling from an over-filled storage tank, resulting in a vapour cloud with a depth of two metres and a radius of approximately 200 m. The explosion generated much higher overpressures than would usually be expected from a typical vapour cloud explosion. As a result of the explosion and the subsequent fire, large parts of the depot were destroyed. Surrounding buildings close to the site suffered severe structural damage. Light damage could even be found at a distance of up to 1.5 km from the site [1].

A cloud of combustible vapour in the atmosphere can explode under certain conditions, which is usually referred to as a vapour cloud explosion (VCE). The severity of the explosion depends on the composition of the fuel-air mixture, ignition time and its boundary conditions, among other factors. In the combustible-air mixture a flame could propagate through the entire cloud by two mechanisms: (i) deflagration, where the propagation of the flame is caused by heat transfer from the reacted region to the fresh mixture. (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. The characteristic shapes of the blast waves generated by the two explosion mechanisms are presented in Fig. 1.

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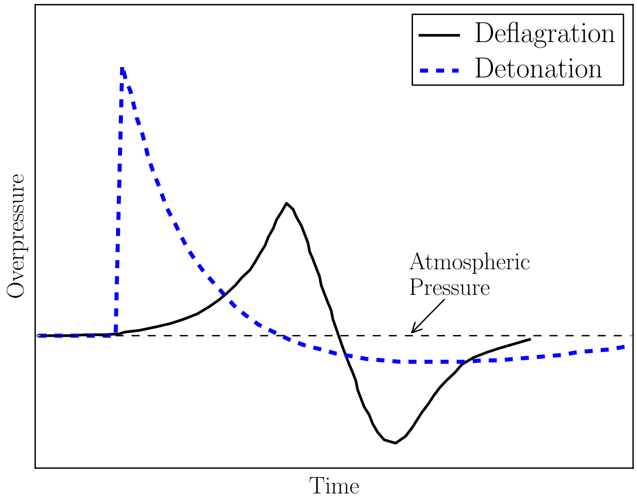

Fig. 1. Characteristic shapes of blast waves.

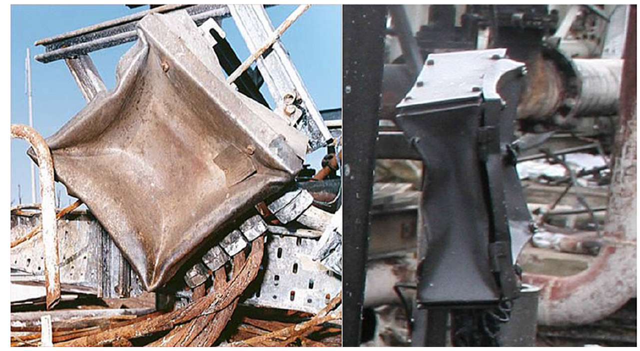

Fig. 2. Two typical damaged boxes (Courtesy of the Health and Safety Laboratory).

The blast wave from a detonation has a sudden rise in pressure above atmospheric condition to a peak free-field (side on or incident) overpressure. The peak incident overpressure gradually decays to atmospheric pressure, followed by a negative phase with pressure less than ambient, the magnitude of which is dependent on the explosive, stand-off distance and weight of the charge. Deflagration produces a blast wave with a gradual pressure rise to the peak side-on overpressure followed by a gradual decay and a negative phase with a similar magnitude to the incident positive phase. Generally, detonation produces a blast wave with higher peak overpressure but shorter positive duration than in a deflagration case. Deflagration is able to transform into detonation within a highly congested region. Finally, when the detonation blast wave impinges on a surface, it will be reflected. The magnitude of the reflected pressure depends on the peak of the incident wave and the angle of incidence. For deflagration, the reflected overpressure is more closely dependent on the parameters of the incident wave and the dimension of the target. It does not have a significant enhancement as normally expected from a detonation blast wave at the same level of peak incident overpressure [2].

In response to the incident, the Buncefield Major Incident Investigation Board (MIIB) invited a group of experts from academia and industry to advise on the assessments undertaken. A great deal of work has been carried out on collecting and analysing available evidence from the incident. For the purpose of assessing the blast overpressure history across the incident site, evidence relating to overpressure is important as part of the investigation. It was found that there were many small objects such as steel switch boxes distributed across the site and nearby areas. In the investigation, these field objects were 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. Fig. 2 shows two damaged steel switch boxes found within the vapour cloud.

Buncefield is not the first vapour cloud explosion to occur in the oil and gas industry. In 1970, at Port Hudson, Missouri, U.S, pipeline failure released a large amount of propane and resulted in an explosion causing significant damage to buildings within the cloud where the estimated overpressure was over 1 bar [3]. Four years later in 1974, a temporary pipe failure released approximately 100 tonnes of Cyclohexane at the Flixborough Nypro plant, UK. The subsequent explosion was severe and also caused considerable damage to the buildings on site. The explosion mechanism included a transition from deflagration to detonation and was estimated to have overpressures between 1 and 10 bar [4].

Another incident involving pipe failure occurred near the city of Ufa, Russia, in 1989. The released petroleum gas was ignited by sparks created between two passenger trains passing each other nearby. A large area of trees on the ground had been blown over suggesting that the overpressures exceeded 1 bar [5]. A more recent accident occurred at Texas city, USA in 2005. A total of 28,700 L of hydrocarbons were released into the atmosphere and mixed with air which subsequently ignited. The damage was focused in a congested area of site with overpressures again estimated to be over 1 bar.

In the initial investigation [1], the Buncefield incident was compared with the above four previous explosions. The available evidence suggested that in terms of explosion characteristics, fuel type, terrain, cloud size and release duration, both Port Hudson and Ufa accidents strongly resemble Buncefield in character. However the character and damage evidence of Flixborough and the Texas City explosion definitely do not resemble that at Buncefield.

As part of the investigation work, a recent series of gas detonation tests [6] were completed under management of the Steel Construction Institute (SCI). A number of steel switch boxes similar to the ones found at Buncefield were placed around the test site and exposed to blast waves with various levels of overpressure at different distances to the edge of the gas cloud. The free-field incident overpressure time histories at the locations of the boxes were recorded by pressure transducers and the residual deformation of the damaged boxes were digitally recorded through a laser scanner. In the following section, an account of the tests is presented and the main results used for validation in the current work are described.

The most widely used method to study the structural response to blast loadings is the Biggs' simple degree of freedom method [7]. Based on Biggs' simple model, SCI [8] developed an improved model which includes the catenary action and incorporates the effects of support stiffness. Approximate techniques were also used by Schleyer and Hsu [9] to predict the response of structural members to pulse loading. Energy methods were used to formulate the governing equations and the response was divided into different stages according to the deformation state of the structure.

The steel switch boxes on the Buncefield site are made of thin rectangular plates. Nurick and Martin [10] presented a comprehensive review of previous experimental and theoretical work on the deformation of thin plates subjected to impulsive loading. Predictions included bending and membrane effects which compared favourably with test results for small deflections. Using approximate methods based on mode shapes, the accuracy of predictions improved at much higher deformation levels. Most of the research focused on near-field impulsive loadings. In Boyd's