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# Behaviour of cylindrical steel drums under blast loading conditions

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ABSTRACT

The Buncefield incident in the UK in 2005 involved an explosion of 240,000 m$^3$ of vapour cloud which resulted in considerable damage to properties in the surrounding area. A number of objects that can be used as overpressure indicators such as standard steel drums were located at various points around the 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 drums in order to investigate possible forensic methods to aid the incident investigation. Subsequently, a number of numerical models are developed in order to simulate the tests. Two models with varying complexity are used in the simulations: uncoupled Eulerian–Lagrangian model and coupled Eulerian–Lagrangian approaches. These models are validated against the test data from gas detonation explosion. Comparison between the numerical and experimental results suggests that both approaches tend to over-predict the deformation of drums due to identified inaccuracies from test measurements and numerical methods. However, both methods can comparatively capture the different levels of damage arising from blast loads with various intensities. These comparative levels are in general agreement with observations from test data. Parametric studies using the validated techniques are also carried out to further examine the response of steel drums. The results are summarised in the form of pressure–impulse diagrams, and typical residual shapes of drum models are selected to complement the pressure–impulse diagrams. The methods and results presented in this paper offer a very useful tool which could be employed to aid forensic investigations of future explosion incidents involving steel drums or similar field objects.

## 1. Introduction

In the last few decades, a number of major industrial accidents have occurred around the world. These include the Buncefield event in the United Kingdom (UK) back in 2005 where the explosion of 240,000 m$^3$ 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 2 m and a radius of approximately 200 m. The explosion generated much higher overpressure than would usually be expected from a typical vapour cloud explosion. As a result of the explosion and subsequent fire, large parts of the depot were destroyed. Surrounding buildings close to site suffered severe structural damage. Light damage could even be found at a distance of up to 1.5 km from the site [1].

Vapour cloud explosions (VCE) involve a cloud of combustible vapour in the atmosphere which explodes under certain conditions. The most important factors that affect the severity of the explosions are air–fuel mixture composition, ignition time and boundary conditions. In the combustible mixture, a flame could propagate through the entire cloud by two mechanisms: (1) deflagration, where the propagation of the flame is caused by heat transfer from the reacted region to the fresh mixture; (2) if the flame is driven by a shock wave which compresses and heats the mixture in front then a detonation event can be identified [2]. The characteristic shapes of the blast waves generated by the two explosion mechanisms are shown in Fig. 1.

The blast wave of detonation has a sudden rise in pressure above atmospheric conditions to a peak overpressure (free-field or side-on). The peak overpressure gradually decays to ambient pressure, followed by a small negative phase. Deflagration typically produces a blast wave with a gradual overpressure rise to peak value followed by a decay and a negative phase with similar scale 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. When a detonation blast

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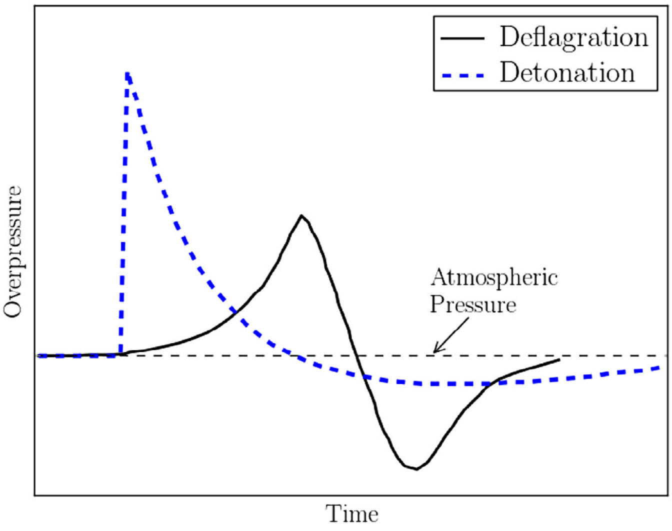

**Fig. 1.** Characteristic shapes of blast waves.

wave impinges on a surface, it is reflected. The magnitude of reflected overpressure depends on the peak incident value and angle of incidence. For deflagration, the reflected overpressure is more closely related to the parameters of incident wave and dimensions 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 [3].

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 assessment undertaken. A great deal of work has been carried out on collecting and analysing available evidence from the incident [1]. 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 standard steel drums and switch boxes distributed across the site and nearby areas. In the investigation, these field objects were used as overpressure indicators, since their final deformation can provide an indication of possible overpressure at their locations after the passage of blast waves. Fig. 2 shows damaged drums found within the vapour cloud following the Buncefield event.

Buncefield is not the first vapour cloud explosion to occur in the oil and gas industry. In 1970, at Port Hudson, Missouri, USA, a 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 [4]. Four years later in 1974, a temporary pipe failure released approximately 100 tonnes of Cyclohexnae 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 peak overpressures in the range of 1–10 bar [5].

**Fig. 2.** Typical damaged drums [1].

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 away suggesting that the overpressure exceeded 1 bar [6]. A more recent accident occurred in Texas City, in the 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 the overpressure estimated to be over 1 bar. In the initial investigation [1], the Buncefield explosion was compared with the above four previous incidents. 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 resembled Buncefield in character. However, the character and damage observed in the Flixborough and the Texas City events were not similar to that at Buncefield.

As part of the investigation work, a series of gas detonation tests [7] were recently completed under the management of the Steel Construction Institute (SCI). A number of standard steel drums similar to the ones found at Buncefield were placed around the test site and exposed to detonation blast loading with various levels of peak overpressure at different distances to the gas cloud. The overpressure–time histories at the locations of the drums were recorded by pressure transducers and the permanent deformations of the damaged drums were digitally recorded through laser sensors. Fundamental research has been already carried out previously at Imperial College London to study the response of light-weight steel structures [8] and steel switch boxes [9] which are closely related to the work presented in the current study which focuses on the response of steel drums. In the following section, an account of the tests is presented and the main results used for validation in the current work are described.

Several past studies have focused on the response of steel plates subjected to blast loading. Nurick and Martin [10] presented a comprehensive review of previous experimental and theoretical work on the deformation of thin plates subjected to impulsive loading. In Boyd's tests [11], the pressure loading was created by a spherical explosive with various masses placed, at different distances, on the central axis and normal to the plate. The resulting impulsive loading was of close-field nature. Jacinto [12] investigated the response of thin plates to far-field air blast waves with moderate intensity.

Previous research regarding the dynamic response of cylindrical shells and plates focused mainly on small explosives and elastic behaviour. In many cases, the study methods were simplified due to the large domain of the problems in addition to experimental constraints. Thompson [13] developed a simplified analytical method to estimate the response of cylindrical storage tanks to antisymmetric external blast loads. Aksogan [14] studied the dynamic buckling of an elastic cylindrical shell with variable thickness, subject to a uniform external pressure as a power function of time. Their theoretical studies focused on elastic buckling of cylindrical shells and were limited to small scale experiments. Jiang and Oslon [15] studied the transient response of cylindrical shell structures using a curved finite strip method. Similar cylindrical plates were also examined by Li and Jones [16] and Lellep and Torn [17] for small clamped shells assuming perfectly plastic materials. Pedron and Combescure [18] considered blast loading from small explosives on an immersed infinitely long stiffened shell structure. In general, research remained largely theoretical and was mainly based on scaling of small-scale experiments.