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Experimental analysis of debris distribution of masonry panels subjected to long duration blast loading

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ABSTRACT

Blast loading of structures is a complex system dependent on a vast number of parameters from both the structure and blast wave. Even for the simplest of structures, small changes to its size and shape can have a large effect on the result when subjected to blast; additionally, small changes to the pressure or duration of the blast wave can drastically alter its interaction with a specific structure. This paper, as part of a larger in-depth research study, investigates the breakage patterns and debris distribution of masonry panels subjected to blast loads with a positive phase duration typically exceeding 100 ms. Three experimental trials were conducted, in which ten masonry panels of varying geometries were subjected to blast loads with peak static overpressures of approximately 55 kPa and 110 kPa, with corresponding positive phase durations of 200 ms and 150 ms respectively. All structures underwent total structural failure, followed by significant debris distribution with the results showing structural geometry, blast overpressure and impulse to be the key parameters responsible for the breakage pattern, initial fragmentation and debris distribution respectively.

1. Introduction

Blast and its interaction with structures is a complex system. According to Needham [1], the positive phase of a blast wave is usually characterised by overpressure and is defined as the time between shock arrival and the beginning of the negative phase of the overpressure. Integrating the overpressure with the phase duration gives the impulse transmitted by the blast wave, thus a large positive phase duration or high pressure will lead to a high transmitted impulse. Long duration blast is defined here as a blast wave with a positive phase duration in excess of 100 ms, producing high impulsive loading at farther stand-off distances. Examples of such explosive events include the 1981 'Mill Race trial' [2] and the 1983 'Direct Course trial' [3] in which 544 and 600 tonnes of ANFO were detonated respectively. Whilst such explosive events are unlikely to occur in urban environments, hydrocarbon vapour cloud detonations are capable of producing similar blast conditions and can occur at chemical storage or processing plants located within urban areas. Such examples include the 2005 'Buncfield Disaster' [4] with a predicted TNT equivalence of approximately 250 tonnes, or the 2013 'West Texas Fertilizer Disaster' [5] in which a fire lead to the combustion of 30 tonnes of ammonium nitrate, amongst other combustible materials.

Damage predictions are often made using pressure impulse (*P-I*) diagrams, as displayed in Fig. 1, in which the iso-damage curves represent particular levels of damage. Whilst the multiple curves provide insight into the state of the structure and the level of damage, they offer little to no information regarding the extent of the resulting debris distribution.

Much research has been conducted investigating the effects of blast loading on masonry, with primary focus on the failure mechanisms of masonry [6–8]. Many results from such research greatly improve the predictive capability of iso-damage curves, through both numerical and experimental results [9,10]. Research investigating the flight paths, impact, bounce and roll of masonry debris has also been conducted, in which the final position of individual fragments are statistically predicted using source terms based on the initial conditions [11,12]. Almost all research conducted into masonry structures and their response subject to blast loading has focused on small to medium sized charges at relatively close ranges, or in some cases, near field detonations [13]. Such detonations produce extremely high pressure blast waves, resulting in high levels of damage; however the duration of such blast events is small, rarely exceeding 50 ms. Blast waves with high enough pressure to cause fragmentation and long positive phase durations continue to transfer large amounts of energy post-breakage, result-

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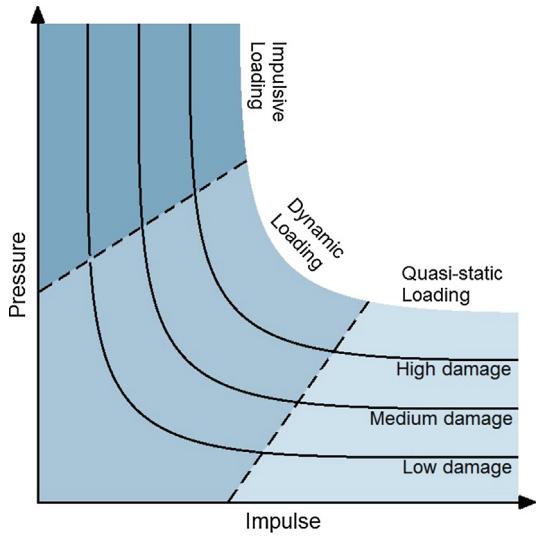

Fig. 1. Representation of a *P-I* diagram with ISO damage curves.

ing in substantial debris distributions, especially in the case of drag targets [14].

In the event of petro-chemical, or other large detonations in urban environments, the fragments from buildings constructed from brittle materials, such as concrete and masonry, produce a substantial debris distribution. This poses the threat of secondary damage to other structures, large scale infrastructure blockage and potentially lethal injuries. A long term goal of this research is to develop a fast running predictive model to assess the blockage of vital infrastructure and other potential damage caused by the effects of a long duration blast to one or more masonry structures. To achieve this, a combination of experimental and numerical data will assess the debris distribution produced by a wide variety of masonry geometries for various blast parameters. As an initial step, this paper analyses a set of key experimental trials which were conducted to assess the breakage and debris distribution of ten masonry structures when subjected to long duration blast loads.

2. Experiments

Three experimental trials, accommodating a total of ten test items, were conducted at the Air Blast Tunnel (ABT), shown in Fig. 2, which is located at MoD Shoeburyness on Foulness Island in the UK. The ABT is a large shock tube designed to replicate large explosive events, with two sections for instrumentation which are 4.9 m and 10.2 m in diameter [15]. The ABT is also fitted with a rarefaction wave eliminator (RWE) at its exhaust to reduce unwanted reflections and complex airflow interfering with the test items. Previous trials conducted at the ABT show the maximum achievable peak static overpressure in the 4.9 m and 10.2 m sections to be 100–120 kPa and 50–60 kPa respectively with corresponding positive phase durations of approximately 200 ms and 150 ms [16]. Using the Kingery and Bulmash polynomials for hemispherical surface charges [17], the TNT equivalence of the blast wave was approximately 450 Tonnes at a stand-off distance of 250 m in the 4.9 m section and 200 Tonnes at 250 m in the 10.2 m section.

With the experimental trials being the first step in a larger research project, the test items are constructed from the simplest form of masonry, single leaf running bonds. Each test item was constructed using frogged facing London bricks, with a mass of ≈2.1 kg, dimensions of 210 mm × 100 mm × 65 mm and a maximum compressive strength of approximately 4–6 N mm^{-2}. The bricks were joined by a class (ii) mortar conforming to BS:5628-1:2005 [18], with a tested compressive strength of approximately 8–10 N mm^{-2} in a 10 mm bedding. Each test item was constrained at a vertical height of 2 m corresponding to 26 layers of bricks with the base mortared to the ground; this arrangement follows the same design as previous high explosive masonry tests conducted by Keys and Clubley [19].

The primary objective of the experiments was to achieve a set of baseline results which can be used to develop damage predictions for three dimensional masonry structures. To achieve this, two categories of test items were defined; the first category employs simple geometries which represent small panels in a potential structure with the smallest panel being 1 m wide. As the simple geometries involved corner panels, boundary conditions applied to the outer edges would not necessarily be consistent between structures. Therefore, for comparative purposes, the simple geometries were implemented without boundary conditions. The second category uses half rectangular structures enclosed by a steel housing designed to reduce any infill effects of the blast wave from above. The purpose of these structures is to draw comparisons between the simple base panels in isolation and as part of a larger structure without the complication of infill before breakage. To ensure there was as little infill as possible without physically connecting the masonry to the steel roof, the top layer of masonry was covered with vinyl strips, to which a layer of expanding foam was applied. This method closed the gap between the masonry and the steel, reducing any hammer effects from the roof as well as restricting the blast in-fill. This method ensures there was as little restraint on the masonry from above as reasonably possible within the confines of the ABT.

For each structure, every 1 m panel was painted a different colour to allow comparisons between individual sections and every brick was assigned a unique number. To aid the post trial debris collection, 0.5 m × 0.5 m grids were marked on the ground in the 10.2 m section; the 4.9 m section however does not allow for two dimensional debris collection and so the pre-existing radial 1 m

Fig. 2. The Air Blast Tunnel (ABT).