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Experimental studies on the deformation and damage of steel cylindrical shells subjected to double-explosion loadings

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ABSTRACT

Metal cylindrical shells with different wall thicknesses were subjected to double explosion detonated at varying stand-off distances. For comparison, single-explosion tests were conducted under the same conditions as those in the second explosion of the double- explosion tests. Five different types of failure modes were observed. Here, the energy distribution of the different failure modes is discussed. The effects of the double-explosion impact, the stand-off distance, and the wall thickness of the cylindrical shell on the deformation and damage of the metal cylindrical shells were investigated. The results indicated that the deformed cylindrical shells which were impacted by the first blast absorbed more energy under a given explosion load than the undamaged shells under the same explosion load according to the energy absorption theory. Vickers hardness tests presented a noticeable increase in the hardness of the cylindrical shell at the plastic hinge region and the central region with the number of witnessed blast loads increased. The stand-off distance and the wall thickness significantly influenced the failure mode and the energy absorption and distribution of the cylindrical shells under double-explosion loadings. The severity of the damage observed in the cylindrical shell increased with a decreasing stand-off distance. Moreover, when the cylindrical shell further deformed from local plastic deformation to crack, the local plastic deformation zone was decreased abruptly. The ability of the cylindrical shell to resist double explosions was enhanced by increasing the wall thickness because thicker shells have more energy absorption capacity and higher threshold for damage than thinner shells. Under the same explosive load, of which the energy has not reached the damage threshold of the cylindrical shell, the energy absorption of the cylindrical shell and the magnitude of the energy reduction both decreased when the wall thickness of the cylindrical shell increased in equal increments. Under the presented experimental conditions, the cylindrical shell first cracked along the radial direction.

1. Introduction

Pipeline systems are widely used in chemical industries such as ocean platform, gas and petroleum pipeline to transport liquid or gas. Metallic cylindrical shells which are also important structural elements in building are also applied broadly in airports, stations, bridges and other building structures. When these cylindrical shell structures are subjected to impacting loads, disastrous consequences may occur. During terrorist attacks and military operations, the engineering structures composed of metal cylindrical shells may suffer from blast impact more than once, this blast includes natural gas pipeline explosion and weapon bombing attack. The metal cylindrical shells will be deformed and damaged under blast load. Under this condition, remarkably severe damage may occur if the shells are subjected to explosion impact again. Thus, the dynamic response mechanism should be investigated, the deformation and buckling failure modes of metal cylindrical shell structures subjected to multiple explosions should be analysed, and the design criteria for such engineering structures should be modified.

During the past few decades, numerous theoretical, experimental, and numerical studies have been conducted on the deformation, cracking and perforation of thin-walled structures such as plates and cylindrical shells subjected to blast loading. The fracture damage of the structure was severe under strong explosion loading; the crack shapes were diverse and varied with the strength of explosive load [1,2]. The simple theoretical solution developed by Wierzbicki and Hoo Fatt [1]

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can be used as a quick first approximation in a design cycle. Gao et al. [2] and Clubley [3] experimentally and numerically investigated the damage of water-filled cylindrical shell subjected to explosion impact. The results indicated that the presence of the water provides a 'foundation' pressure to resist the deformation. Yuen et al. [4] presented a comprehensive investigation (including experimental, numerical, and theoretical analysis) on the response of cylindrical shells subjected to a lateral blast load detonated at very close proximity. The experimental results indicated that for a constant stand-off distance, the permanent mid-point deflection increased as the mass of the explosive increased. Larger load diameters appear to cause more damage for the same charge mass. Song et al. [5] established a mathematical model to analyse the deflection and the deformation angle of the steel circular tubes subjected to lateral blast loads. The calculation results agree well with experiment observations when the deformation is relatively small. Song et al. [6] studied the dynamic response of X70 grade steel pipeline under localised blast loading. Typical failure features of cylindrical shells such as large inelastic deformation, tearing from the mid-point have been observed in experiments. Results revealed that the deflection and damage level of pipeline increased with the increase of explosive mass and contact area. Wu et al. [7] conducted experimental and numerical investigations on the dynamic response of a metal cylindrical shell under the combined effects of fragments and shock waves. Pre-formed holes were selected to simulate the penetration effect of fragments. Results demonstrated that the pre-formed holes on cylindrical shells will easily lead to stress concentration which may decrease the anti-blast ability of cylindrical shells. The pre-formed holes will also reduce the load area which may weaken the effect of blast loading. Other studies have focussed on the response of square tubes [8], laminates [9,10], plates [11,12] and sandwich panels [13] to either uniform or localised blast loads.

Thin-walled structures are also a type of popular design for energy absorbing-devices. Lu and Yu [14] focused on the manner in which structures and materials, such as ring systems and cylindrical shells, can be most remarkably designed to absorb kinetic energy in a controllable and predictable fashion. Jama et al. [15,16] studied the square hollow sections subjected to transverse blast, and derived the formula of energy absorption for the flexural deformation and local deformation of the square tube. Karagiozova et al. [17] discussed the energy absorption of circular and square aluminium alloy tubes subjected to an axial explosive load, which was transmitted to a tube via a small attached mass. Analysis showed that material properties play an important role in the formation of the buckling pattern.

Owing to the increasing security concerns in practical applications, notable experimental and numerical investigations on the response of structures to multiple blast loads have been conducted. Zhang et al. [18] simplified the multiple blast loads as a series of shock loads with sufficient intervals, and numerically simulated the nonlinear responses and damages of reinforced concrete and double T-steel beams. Kumar et al. [19] investigated the dynamic response of semi-buried structures subjected to noncontact multiple blast loadings originating from conventional weapon detonation. The peak displacement of the semi-buried structure was determined by the combined effects of peak overpressure and positive phase duration. Simultaneous blasts presented higher peak incident overpressure than successive blasts at regular interval of 1 ms; however the positive phase duration of simultaneous blasts was shorter. When the time interval of successive blasts ranged between 0 ms and 5 ms, the peak displacement of the structure was larger than that of simultaneous blasts. Therefore, the blast design of a structure is also governed by the time interval between successive blasts, and not merely by a single blast of the given amount of explosive. Henchie et al. [20] and Yuen et al. [21] experimentally and numerically studied the response of circular steel plates to repeated uniform blast loads. The results indicated a decrease in the incremental mid-point deflection and an increase in the Vickers hardness of the plate at the boundary and the central region as the number of witnessed blast loads increased. The combination of residual stresses and work hardening in the test plates as a result of the impulsive repeated blast loading inhibited the deformation of the test plates.

In the aforementioned investigations, scholars have mainly studied the dynamic response of engineering structure and its calculation method for the case of single explosion. However, research on the failure mode and the dynamic response of engineering structures under multiple blasts is scarce. These limited studies mainly focused on testing the multiple blast performance of reinforced concrete, steel beams and rocks. Nevertheless, there are only few published studies on the deformation and damage of metal cylindrical shells subjected to multiple explosions.

This article presents certain experimental data and observations recorded from double-explosion experiments on cylindrical shells. Cylindrical shells (with wall thicknesses of 2.0, 2.75 and 3.5 mm) were subjected to explosion impact first using 100 g of trinitroluene (TNT) charge, and then using 160 g of TNT charge for different stand-off distances. This experiment was mainly focused on the effects of double explosions, stand-off distances, and wall thicknesses on the deformation and damage of metal cylindrical shells. For comparison, explosion impact experiments were conducted on cylindrical shells of the same thickness and stand-off distance by only subjecting them to 160 g of TNT charge. The experimental results of the cylindrical shells subjected to double explosions were compared with those subjected to single explosion to obtain the differences in energy absorption and transformation of cylindrical shells by employing the energy absorption theory. Five types of failure modes were observed during the experiments.

2. Experimental research

2.1. Experimental setup

Fig. 1 shows schematic of the experimental setup. The cylindrical shells in the double- and single- explosion tests were made of Q235 steel (outer diameter: 114 mm; wall thickness: 2, 2.75 and 3.5 mm; length: 100 cm). The chemical composition of the specimens is listed in Table 1 and the mechanical properties are summarised in Table 2. Fig. 2 shows the stress–strain curves of the Q235 specimens at different strain rates obtained from quasi-static tensile tests.

The sources of explosion were 100 and 160 g of column TNT charge with dimensions of $\Phi 48 \times 34\ mm^3$ and $\Phi 48 \times 54\ mm^3$, respectively. The key parameters for TNT are shown in Table 3. The experiments were conducted in the field test site. In preparation for the experiments, the ground was flattened before the steel brackets were installed. The

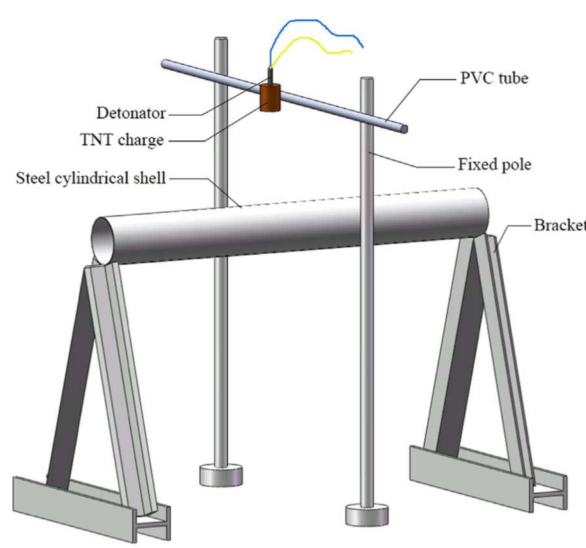

Fig. 1. Schematic of experimental setup.

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