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Dynamic responses and damage of cylindrical shells under the combined effects of fragments and shock waves

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ABSTRACT

Experimental and numerical investigations were conducted 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. This study investigated the influence of hole-spacing and TNT charge at a certain stand-off distance on the deformation/failure of a cylindrical shell. Three failure modes were observed in the experiments, namely, Mode I, Mode II, and Mode III. The features of each mode are discussed. 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 impact loading. Change in hole-spacing will influence these factors and affect the deformation/failure of cylindrical shell. Serious deformation/failure in the cylindrical shell was observed with decreased charge of stand-off distance. The results of numerical simulations are consistent with the experiments. This finding indicates that the structural response of a cylindrical shell with pre-formed holes can be efficiently modeled using the ALE coupling model. The damage process, measurement of point deflection, pressure distribution, and energy changes were analyzed based on the results of simulation.

1. Introduction

Pipeline systems are widely used in energy industries to transport flammable liquid or gas. A catastrophic event will likely occur when a pipeline is subjected to explosion in impact loading or high-speed fragments during terrorist and military operations. A considerable number of studies have been conducted on the structural damage and destruction generated by shock waves or fragments [1–7].

Limited studies have been conducted on the combined effects of fragments and shock waves. Experiments in this field are difficult to perform given the complexity of its mechanism and the diversity of influence factors. Internal pressure and temperature will increase rapidly after the detonation of conventional ammunitions thereby causing the shell to burst and form a series of fragments [1]. Some internal energy of the ammunition is transferred to the fragments. The remaining energy will then propagate in air in the form of shock waves. When conventional weapons explode, the surrounding structures would fall under the combined effects of shock waves and fragments [3]. According to Forsén [8] and Zhang et al. [9], the combined load of shock wave and fragments that are caused by explosions will produce damage more severe than the sum of damage caused separately by shock wave and fragments. This finding requires investigation into the behavior of a cylindrical shell being subjected to blast shock waves and fragments. Modified design criteria should also be constructed for such structures.

Scholars examined the combined effects of fragments and shock waves. He et al. [10] reviewed the macroscopic effects of protective door under the combined action of shock wave and fragments by conducting an explosion test in prototype tunnel. The speed of fragments was calculated using the Gurney equation through the quality of explosive charge and shell. Liu et al. [11] studied the damage of helicopter gunships caused by warhead when fragments attack the target before the shock waves and built the damage model of target under the combined effect of shock waves and fragments. Hou et al. [12] investigated the damage effect of sandwich bulkhead subjected to combined impacts of shock and fragments using cast TNT and pre-fabricated fragments. The failure modes of the surface plate and sandwich core of the bulkhead were identified and the protective mechanism of sandwich bulkhead was analyzed. Results show large deformation and lots of perforation holes in the front plate under the

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combined impacts of shock waves and high-velocity fragments. Leppanen et al. [13,14] studied the time of arrival of fragments and shock waves generated by conventional ammunition of 250 kg. If the structure was located 5 m away from the center of explosion, fragments and shock waves will simultaneously reach the surface of the structure. If distance was less than 5 m, shock waves will arrive earlier than fragments, whereas if distance was over 5 m, fragments will arrive faster than shock waves.

These studies show the varying arrival time of fragments and shock waves because of their speed differences at various stages. When the target is relatively far from the detonation position, shock waves attenuate rapidly and its speed is slower than that of fragments thereby allowing the fragments to reach the target early. Under the penetration effect of high-speed fragments, through-holes will form on the surface of the target. These holes will not only weaken the strength and integrity of the target, but will also generate stress concentration because of subsequent shock waves thereby increasing damage to the target. The study reported in this paper aims to contribute the knowledge of how deformation and damage in the cylindrical shell is affected by the impacts of shock wave and fragments when the fragments reach the target earlier than the shock wave. The pre-formed holes on the shell wall were selected to simulate the penetration effect of fragments. The experimental set-up was simplified to limit the number of uncertain parameters.

To understand the detailed response of structural members with complex material properties, numerical simulation was applied to the impact analysis of a number of fields [5,7,15–18]. A non-linear finite element code of Ls-Dyna was used to model the large inelastic deformation or complete failure of the structure subjected to blast loading and fragments [1,11,19]. The simulations agree with the experiments.

Experiments were conducted on cylindrical shells with a thickness of 2.75 mm with or without pre-formed holes. The shells were subjected to the impact of explosion of 200 g TNT charge with different stand-off distances. The experiments mainly focused on the effects of spacing of pre-formed holes, TNT stand-off distance on deformations/failure of metal cylindrical shells. The experimental results of cylindrical shells with pre-formed holes were compared with those without pre-formed holes to obtain the failure mechanism of cylindrical shells under the combined effects of fragments and shock waves. Numerical simulations of these impact scenarios that were identical to the experiments were performed using the commercial software LS-DYNA with ALE coupling method. The results obtained were compared with the experimental data.

2. Experimental research

2.1. Experimental setup

The cylindrical shells were made of Q235 steel with 10 cm outer diameter, 2.75 mm thickness, and 1 m length. Five rows of pre-formed holes were set in the middle of the cylindrical shells on the front face. Each row was 400 mm length. The diameter of each hole was 6 mm. The spacing of holes vary from 6 mm to 31 mm. Fig. 1 shows a sketch of a cylindrical shell with pre-formed holes.

Fig. 2 shows sketches of the experiment setup. The cylindrical shells were supported on the bracket. The contact area between the cylindrical shell and the bracket was kept small to ensure that the contact area

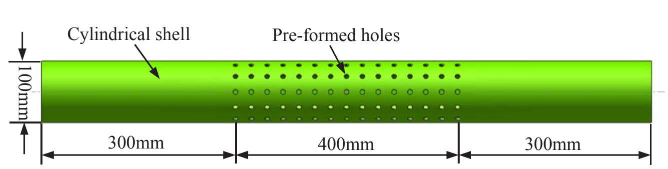

Fig. 1. Sketch of a cylindrical shell with pre-formed holes.

do not influence the experimental results. The sources of explosion were 200 g bulk TNT charge with dimensions of $10 \times 5 \times 2.5$ cm^3. The charge was installed above the cylinder and aligned with a line passing through its center. Stand-off distance (i.e., distance between the cylinder shell and TNT charge) changed from 10 cm to 18 cm to achieve different impulses. The explosive has a density of 1.61 g/cm^3, detonation velocity of 6950 m/s, and CJ energy per unit volume of 6.74×10^6 kJ/m^3. Hole-spacing, permanent displacement, and the final deformed shape profile were recorded for each test.

2.2. Experimental results and discussion

Fifteen tests were conducted in this study. The test numbers ranged from TZ-1 to TZ-15. Table 1 shows the test conditions and results, where H_s denotes hole-spacing (distance between hole edges), R is the stand-off distance, r_1 and r_2 are the minor axis and major axis of the oval concave, δ_{local} is the local deformation value (indicated in Fig. 3), and δ_{global} is the global deformation value (indicated in Fig. 5).

Menkes, Opat et al. [20] studied beam deformation under the action of blast load; they divided beam deformation into three modes, namely, Mode I, Mode II, Mode III. Based on experimental results and previous studies, this report classified the deformation mode of a cylindrical shell under the combined effects of fragments and shock waves into three types:

Mode I: Large plastic deformation;
Mode II: Front zone of cylindrical shell produces local impact damage;
Mode III: Front zone of cylindrical shell is destroyed entirely, which is accompanied by large global deformation.

2.2.1. Analysis of typical deformation mode

Fig. 3 illustrates the typical deformation of a metal cylindrical shell under Mode I. The metal cylindrical shell with pre-formed holes produces local sunken deformation with an elliptical shape. The major axis along the pipe axis direction is denoted by r_2; r_1 was the minor axis perpendicular to the axial direction. As depicted in the side view, significant local deformation occurred in the structure of cylindrical shell, whereas global deformation remained small. The central outline of a cylindrical shell after deformation was observed from the sectional view. The deflection of the middle point was at the maximum and the deflection reduced gradually from the center to both ends. Fig. 4 illustrates the transverse deformation curve on the cross-section of a cylindrical shell in Mode I, where l is the transverse distance from the mid-point of impact. The curve data show that the minor axis r of sunken deformation is 13.5 cm and maximum deformation at the center point is 5.4 cm. Fitting the curve can provide the relationship between sectional deflection (f) and distance from mid-point (l):

$$f = -1.72 - \frac{4.1}{1 + \exp((x - 3.2)/1.42)} \quad (1)$$

Fig. 5 demonstrates the typical deformation of a metal cylindrical shell in Mode II. The front zone of the cylindrical shell was damaged by explosion loading. A shuttle-shaped piercing crack was formed along a row of pre-formed holes in the middle of shell wall. The direction of crack coincided with the direction of pre-formed holes. The maximum deflection in the impact point reached 3.6 cm. The cylindrical shell exhibited local deformation only. Global deformation was not obvious. Fig. 5(c) shows that the center point of the cross-section of the shell exhibit maximum displacement, whereas deformation gradually decreases from the center to the sides of the shell.

Fig. 6 demonstrates the typical deformation of a metal cylindrical shell in Mode III. In this deformation mode, the front zone of the cylindrical shell will be fractured entirely under strong explosive impact thereby forming a rectangular notch with large global deformation.