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The influence of charge geometry on the response of partially confined right circular stainless steel cylinders subjected to blast loading

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ABSTRACT

This article presents an experimental and numerical investigation into the effect of charge geometry on the structural response of right circular cylinders. Thin-walled, seamless 304 stainless steel cylinders were subjected to internal blast loads that were generated by detonating bare cylindrical plastic explosive charges. Charge diameter, charge mass and aspect ratio were varied. Partial confinement was created by closing one end of the cylinder and leaving the other end free to vent to air. The axial impulse, maximum diametric deflection and axial shortening increased with increasing aspect ratio when the charge diameter was kept constant. When the charge mass was kept constant, the long charges caused larger diametric deflections than their mass equivalent shorter charges. The shorter charges transferred more axial impulse to the ballistic pendulum than their mass equivalent longer charges. The concept of effective charge mass (axial and lateral) was used to interpret the results and developed to provide an empirical equation relating deflection to the charge dimensions. Numerical simulations were performed which gave good agreement with the experimental data and predicted similar trends. The model revealed that the longer charges produced more diametric deflections than their mass equivalent shorter charges because a high pressure (above 50 MPa) zone, that covered a larger area and had a longer duration, developed at the cylinder wall in the case of longer charges. The insights from the model are in good agreement with the simple concept of lateral effective charge mass developed herein. When compared to spherical charge detonations in similar steel cylinders, the cylindrical charge detonations produced pressure waves which are more directional, have lower peak pressures and dissipate more gradually. The cylinders exhibited a more pronounced secondary bulge at the clamped boundary for cylindrical charge detonations.

1. Introduction

Explosions, whether deliberate or accidental, are devastating to infrastructure and human life. Confined space explosions are particularly devastating, producing energy concentrations that may be hundreds of times greater than those generated in free air and subsequently cause greater infrastructure damage and higher incidences of primary blast injuries and fatalities [1–3]. Long term quasi-static pressure accumulation may also occur when venting is limited, as would be the case in an elevator shaft, an underground rail system or a pipeline. Methods are being introduced to prevent unwanted explosive detonations in civil infrastructure (for example, reference [4]), but it is unlikely that any approach will completely eradicate the potential threat. Hence, it necessary to understand the response of common structural components, such as deformable thin-walled cylindrical structures to confined explosion loading, and to understand the implications of explosive geometry on the response of such structures.

The response of thin-walled, deformable, cylindrical structures has been investigated experimentally, analytically and numerically by various researchers [5–10]. These investigations examined the influence of end caps [5], filling media [6,7] and charge placement [8] on the structural response of cylinders to blast loading. Duffey and co-workers [5,6] performed experiments on open and closed cylinders loaded by detonating spheres of C4 at the geometric centre of the cylinder. The cylinders were constructed from 6.35 mm thick mild steel and had a diameter of 267 mm. Analytical models were developed to predict the radial strain and it was shown that incorporating quasi-static gas pressure accumulation into the modelling and improved the experimental correlation by increasing the radial strain [5,6].

Analytical modelling [5,6,9] provided useful predictions regarding the potential failure of a structure in the event of an explosion, but are limited to spherical charge detonations within an idealised geometry. For example, Liu et al [10] modelled the response of short sandwich cylinders subjected to internal blast loading using

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LS-DYNA. Spheres of 20–40 g TNT explosive were detonated at the centre of cylinders, resulting in relatively small deformations of the overall structure [10].

Clayton et al [11] and Rushton et al [12] investigated the structural response of open ended cylinders subjected to internal blast loading. The loading was generated by detonating cylindrical PE4 charges at both ends, with the aim of finding the minimum charge mass to cause wall failure of a mild steel cylinder (reported to be 1.225 kg of PE4 [11,12]). The studies were largely numerical supported by a small number of validation experiments.

Langdon et al [8] investigated to the structural response of right circular seamless 304 stainless steel cylinders to blast loading generated by detonating spherical PE4 charges. One end of the cylinder was open to atmosphere and the other end was closed. The charges were placed at the radial centre of each cylinder at different axial locations. The permanent displacement of the cylinders was aligned to with the centre of the charge. The permanent displacement increased linearly with increasing charge mass when the charge was at the axial centre of the cylinder [8]. However, when the charge was situation closer to the open end, the displacements were larger and the relationship was non-linear [8]. The numerical predictions for the axial centre position agreed well with the experiments, but the non-linear increase of displacement with increasing charge mass (when the charge mass was nearer the open end) was not well predicted [8].

In previous work [8], the focus was the influence of axial position while the loading was generated by detonating spherical charges of different mass. In this paper, the influence of charge geometry on the response of thin-walled stainless steel cylinders subjected to internal air-blast loading is reported, but herein the focus is on cylindrical charges and the influence of mass and aspect ratio. The study reports results from laboratory scale blast experiments and numerical simulations using LS-Dyna. The charge diameter, height and mass were varied to ascertain a range of responses in the cylinders and the concept of effective charge height is used to interpret the results. To the author's knowledge, this is the first time that the effective charge height concept has been used to find the lateral effective charge mass and relate that to the lateral deformation of cylinders subjected to air blast loading. The numerical simulations, based on a similar approach to reference [8] are used to elucidate information about the blast wave propagation and transient deflection of the cylinders, and to understand the charge geometry effects shown by the experiments.

2. Experimentation

2.1. Test specimens

The 304 stainless steel cylinders were 330 mm long, with a nominal inner diameter of 150 mm and 2 mm wall thickness, similar to Langdon et al [8]. The first 30 mm of the cylinders were used to clamp the cylinder to the pendulum, leaving a cylinder length of 300 mm to be exposed to the blast. Quasi-static uniaxial tensile tests were performed on singly curved specimens cut from the cylinders. Clamps matching the tensile test specimen curvature were machined to grip the specimens during tensile testing. The tensile test results were used to obtain values for the numerical simulations.

2.2. Blast test arrangement

The cylinders were mounted to an internal circular boss and a 400 mm × 400 mm mounting plate, as shown in the schematic in Fig. 1, which was attached to a pendulum used to determine the axial impulse. The clamped region was 30 mm long, leaving a cylinder with a 300 mm section exposed to the blast loading and able to deform. One end of the cylinder was closed while the other end was open to the surrounding air (creating partial confinement of the blast loading). The pendulum arrangement is shown in Fig. 2. A wall mounted laser displacement sensor, which was attached to an oscilloscope, was used to record the voltage history during the pendulum swing, in order to infer the axial impulse. While the axial direction was not the direction that was anticipated to cause deformation to the cylinder walls, it was measured to assist with validating the numerical simulations. Black dots were placed at equally spaced intervals around the outer circumference and along the deformable length to aid with visualisation of the deformation after testing.

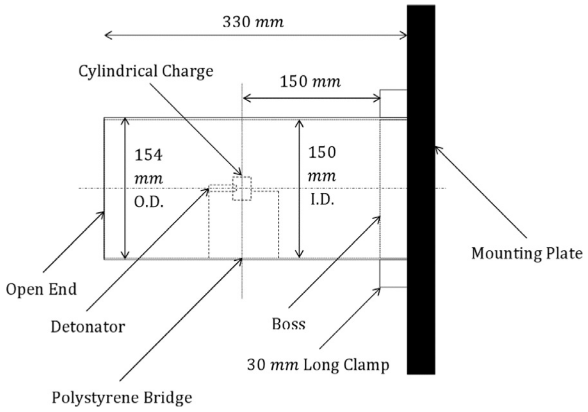

Fig. 1. Schematic of cylinder, boss, clamp and mounting plate (section of side view).

The air-blast loading was generated by detonating cylinders of PE4 plastic explosive in the radial centre of the cylinder using an instantaneous electrical detonator. The detonator was inserted 2 mm into the cylinder, directed towards the closed end, as shown in Fig. 1. To ensure that the axis of the charges aligned with the axis of the cylinder, a polystyrene bridge, shown in Fig. 1, was used and it was assumed that the polystyrene vapourised immediately after detonation. The charge mass, diameter and height were varied to ascertain their influence on the impulse transfer and cylindrical deformation.

The charge mass range was 10 g to 72 g, and four charge diameters of 25, 30, 35 and 40 mm were employed. A full matrix of the charge geometries and masses that were detonated during the experiments is provided in Table 1, grouped according to aspect ratio. The aspect ratios (that is, ratios of charge length to diameter) were chosen to determine the effect of charge geometry on the structural response. The charge matrix was designed so that the results could be grouped by: either constant charge mass with varying the aspect ratio, or constant charge diameter with varying the aspect ratio.

2.3. Effective charge mass theory

Increasing the charge mass being keeping a cylindrical charge diameter constant involved increasing the charge height and hence increasing the aspect ratio of the charge. However, only a portion of the charge mass of a cylinder contributes to the axial impulse. Kennedy [13] reported that as the aspect ratio of a cylindrical charge increased, the charge mass that contributed to axial impulse transfer (to a metal plate) increases up to a plateau limit: beyond this aspect ratio/charge mass, any additional mass did not contribute to the axial impulse. Kennedy [13] stated that the “effective charge mass” (defined herein as the *axial effective charge mass*) can be calculated from a 60° angled cone, while the rest of the charge contributes to the “side losses” (defined for the purposes of this study as the *lateral effective charge mass*). The conclusions of Kennedy [13] are shown schematically in Fig. 3, which depicts two cylindrical charges with different aspect ratios, and their axial effective charge masses.