International Journal of Solids and Structures 51 (2014) 3996–4014

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

# Mechanics of the implosion of cylindrical shells in a confining tube

Sachin Gupta [a], James M. LeBlanc [b], Arun Shukla [a,*]

[a] Dynamic Photo Mechanics Laboratory, Department of Mechanical, Industrial and Systems Engineering, University of Rhode Island, Kingston, RI 02881, United States
[b] Naval Undersea Warfare Center (Division Newport), Newport, RI 02841, United States

ARTICLE INFO

*Article history:*
Received 4 March 2014
Received in revised form 15 July 2014
Available online 2 August 2014

*Keywords:*
Implosion
Implodable volume
Collapse
Pressure waves
Computational modeling
Fluid structure interaction
Water hammer
Confined environment

## ABSTRACT

A fundamental experimental investigation, with corresponding computational simulations, was conducted to understand the physical mechanisms of implosions of cylindrical shells occurring within a tubular confining space which has a limited potential energy reservoir. In particular, attention was focused on studying the generation of pressure waves from the implosion, the interaction of the pressure waves with the confining tube walls and end caps, and the collapse mechanisms of the implodable volume. Experiments were conducted with three implodable volume geometries which had similar critical collapse pressures. The implodable volumes were aluminum 6061-T6 cylindrical tubing and were placed concentrically within the confining tube. Pressure histories recorded along the length of the confining tube during the experiments were utilized to analytically evaluate the deformation of the implodable volume using fluid–structure coupled deformation models. Computational simulations were conducted using a coupled Eulerian–Lagrangian scheme to explicitly model the implosion process of the tubes along with the resulting compressible fluid flow. The numerical model developed in this study is shown to have high correlation with the experimental results and will serve as a predictive tool for the simulation of the implosion of different cylindrical geometries as well as various tube-in-tube implosion configurations. The experimental results show that the limited hydrostatic potential energy available in a confined environment, as compared to a free field, significantly influences the implosion process. The wall velocities of the implodable volume during the collapse, as well as the extent of the collapse progression, are largely affected by the sudden decrease in the available hydrostatic potential energy. This energy is shown to be partially transformed into elasto-plastic strain energy absorbed in the deformation of the implodable volume, as well as the kinetic energy of the water during the implosion process. Experiments also show that the extent of the collapse progression of an implodable volume can potentially be inhibited within a closed environment, which can lead to the arresting of an implosion event prior to completion for larger implodable volumes. The pressure waves generated during collapse comprise of waves emitted due to the impact of the implodable volume walls, the arrest of rushing water and contact propagation along the walls. These processes later evolve into water hammer type axial wave behavior.

## 1. Introduction

A comprehensive series of experiments were conducted to study the mechanics of the implosion of cylindrical shells (implodable volume) in a tubular confining space. The emphasis was on understanding the physical mechanisms of implosion of cylindrical shells occurring within a confining space with limited potential energy reservoir. The implodable volumes consisted of aluminum 6061-T6 cylindrical tubing, and were placed concentrically and longitudinally centered within the confining tube. The collapse pressure was held approximately constant throughout the study. The pressure histories generated by the implosion event were captured by dynamic pressure transducers mounted on the inner surface of the confining tube.

Understanding the fundamental mechanisms associated with the implosion process has been a topic of interest since the early 1950's, especially in the marine pipelines and naval communities (Isaacs and Maxwell, 1952; Palmer and Martin, 1975; Turner, 2007; Urick, 1963). Typical examples of implodable volumes include deep ocean submersibles, submarines, underwater remote operated vehicles, underwater pipelines, and underwater sensors (Turner and Ambrico, 2012). An implodable volume can be defined as any structural shell or body that is acted upon by external pressure and contains internal gas at a lower pressure (or vacuum). In simple terms, the implosion of a structure can be understood as

---

* Corresponding author. Tel.: +1 401 874 2283; fax: +1 401 874 2355.
*E-mail address:* shuklaa@egr.uri.edu (A. Shukla).

http://dx.doi.org/10.1016/j.ijsolstr.2014.07.022
0020-7683/

a sudden loss of stability due to a net external force causing the structure to collapse onto itself. The resulting collapse of the structure is violent and results in rapid release of energy in the form of shock pressure waves, high velocity fluid motion, and sound (LeBlanc et al., 2014). An axial/lateral loading, uniform hydrostatic pressure or a combination of both can be the initiating and driving forces for the implosion of a structure. In underwater environments, this collapse is a dynamic process with duration of the order of milliseconds. At the onset of collapse, the implodable volume walls gain inwards momentum and the surrounding water rushes in to fill the resulting void generated in the collapse process. The fast inward traveling water surrounding the receding walls of a collapsing structure stops suddenly when the walls come into contact. However, the acquired momentum of the in-rushing water causes it to over-compress against the structure and produces strong outwardly radiating shockwaves. Such pressure pulses/ shock waves can be large enough to potentially damage or even lead to the implosion of adjacent structures (Diwan et al., 2012; Farhat et al., 2013; Harben and Boro, 2001; Ikeda, 2012; Ling et al., 2013; Orr and Schoenberg, 1976; Turner and Ambrico, 2012; Vath and Colletti, 1968). A classical example of such an event is the 2001 accident at the Super-Kamiokande facility in Japan, where about 7000 photomultiplier tubes were destroyed by a sympathetic implosion event (Cartlidge, 2001).

In the past, many researchers have theoretically investigated the buckling of cylindrical shells to predict the critical hydrostatic collapse pressures (Timoshenko and Gere, 1963; Von Mises, 1929). The effect of imperfections and various defects has been presented in several research articles (Budiansky and Hutchinson, 1966; Simitses, 1986). It was concluded that the initial ovality of the cylindrical shell can significantly reduce the collapse pressure, while the variation in wall thickness has a minimal effect on the collapse pressure (Kyriakides and Corona, 2007). The propagation of buckles in offshore pipelines has also been widely studied (Charter et al., 1983; Kyriakides and Babcock, 1981; Kyriakides and Netto, 2000; Mesloh et al., 1973; Palmer and Martin, 1975).

Although the problem of buckling has been extensively investigated from the structural point of view, there have been very few studies reported which aim to understand the fluid motion and pressure wave emissions during underwater buckling of structures. In the early 1900's, Rayleigh (1917) developed analytical expression for the collapse of a spherical bubble inside an incompressible fluid. According to this theory, a pressure difference between the bubble and ambient internal pressure causes the bubble to collapse or grow, which results in an oscillatory bubble pulse. In the problem of a closed structure imploding in an underwater environment, the low pressure gas is contained inside a structure. Due to this fact, this structure plays a key role during the collapse process and the complex fluid–structure interaction between the structure and water governs the dynamics of the implosion. In the early 1960's, the implosion of glass spheres was used to generate acoustic signals for underwater applications (Isaacs and Maxwell, 1952; Urick, 1963). Orr and Schoenberg conducted implosion experiments using pre-weakened glass spheres (by grinding a flat spot) in the ocean and concluded that the implosion depth is dependent on the thickness of the flat spot (Orr and Schoenberg, 1976). Harben and Boro conducted implosion experiments with five glass spheres bundled together for boosting the amount of implosion energy released (Harben and Boro, 2001). Turner conducted near-field pressure measurements during the implosion of glass spheres and concluded that the failure time history of the structure has a significant influence on an implosion pressure pulse (Turner, 2007). Recently, Turner and Ambrico (2012) and Farhat et al. (2013) studied the implosion of aluminum cylindrical tubes. Turner and Ambrico (2012) concluded that there are four primary features of the implosion process in metal tubes: (1) the initial collapse phase, prior to wall contact, is accompanied by a smooth decrease in pressure in the surrounding water, (2) at the moment that contact is made between opposing sides of the collapsing cylinder at the center, a short duration pressure spike is emitted in the surrounding water, (3) a large positive pressure is produced at the instant that contact between the two opposing sides extends the full width of the cylinder, and (4) as the buckle propagates toward the ends, the pressure pulse continues, but at a lower magnitude, until the buckle reaches the end cap and the collapse of the cylinder completes. Farhat et al. (2013) extended this implosion work by studying both mode-2 and mode-4 collapse of aluminum cylindrical shells and demonstrated that the pressure pulse generated is influenced by the mode of buckling as well as the associated localization of collapse.

With advances in computational computing resources and efficiency, the modeling and simulation of implosion phenomenon has gained interest. Early numerical studies involving underwater implosions generally represented the implodable volume as a gas bubble within a high pressure fluid field. Kadioglu and Sussman (2008) utilized an adaptive solution methodology to solve the multi-phase problem of a gas bubble contained within a water field. Farhat et al. (2008) simulated the 2 phase flow problem with a solution methodology known as the ‘‘ghost fluid method for the poor’’ (GFMP). The work extended the original GFMP method to better handle the large discontinuities of pressure and density at the air/water interfaces. These studies have generally focused on the two-phase nature of the fluid flow but have neglected the fluid structure interaction which has been shown to be important in the implosion of a structural body. Turner (2007) utilized the coupled Eulerian–Lagrangian fluid structure interaction code (Dynamic System Mechanics Analysis Simulation code or DYSMAS) to simulate the collapse of glass spheres to determine the influence of the failure rate of the spheres on the resulting pressure histories. The primary conclusion was that a computational model of an underwater implosion event must include the structure that separates the low pressure air from the high pressure water. If the structure is neglected, the model would over predict the peak pressure generated from the collapse. Turner and Ambrico (2012) also utilized the DYSMAS code to simulate the implosion of metallic cylindrical bodies. Farhat et al. (2013) investigated the pressure pulses resulting from an implosion, and the parameters which influence the nature of the pulses, through the AERO software suite. The simulations were shown to accurately capture both the deformations of the structure as well as the pressure waves resulting from the collapse. Recently, Chamberlin and Guzas (2012) developed energy metrics to characterize underwater implosion and used these metrics to examine the energy balance during an implosion event. For a series of test cases involving hydrostatic implosion of ductile metal cylinders, they found that the structure absorbs the majority of the initial energy of the system and the released pressure pulse carries away a small percentage of the initial energy Chamberlin and Guzas (2012).

All these experimental and numerical studies on implosion mentioned above were conducted in a free-field environment, where the net hydrostatic pressure in the surrounding fluid is maintained during the implosion process and the free-field environment acts as an infinite source of hydrostatic potential energy to drive the implosion process. On contrary, in the case of implosion occurring within a confining space, the source of hydrostatic potential energy to progress the implosion is limited. Hence, the ratio of energy required to deform the implodable volume and the initial potential energy available acts as a critical factor to drive the implosion process. Costa and Turner (2008) did study the implosion of a tube occurring within an open-ended confining tube and showed that the implosion phenomenon significantly differs from a free-field implosion, however, due to open ended nature