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Mitigation of implosion energy from aluminum structures

Helio Matos, Arun Shukla*

Dynamic Photomechanics Laboratory, Department of Mechanical, Industrial and Systems Engineering, University of Rhode Island, Kingston, RI 02881, United States

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ABSTRACT

This study aims to develop an experimental scheme to determine the localized energy emitted during the dynamic collapse of aluminum structures. Upon collapse, these structures release damaging pressure pulses into the surrounding fluid; to mitigate this effect, the structures are coated with polyurea. The new energy scheme is used to analyze the energy emission from coated structures. Specifically, aluminum tubular structures with polyurea coatings on their interiors or exteriors are used. Furthermore, the technique combines the information obtained from pressure sensors, located near the collapsing structure, and high-speed images taken during the collapse event. These images are processed through a 3D Digital Image Correlation technique to obtain full deformation and velocity fields. Results show that the energy history can be successfully obtained experimentally. Moreover, the energy emitted from coated aluminum structures is significantly less than the uncoated structures; more so with interior coated structures, and doubling the coating volume does not significantly improve this mitigation effect. Additionally, collapse volume has a direct relationship with energy and is a dominant factor in determining the energy release.

1. Introduction

Submerged hollow structures can become unstable once a critical depth is reached. At this depth, environmental pressures cause the structure to rapidly collapse onto itself (this process is known as dynamic buckling or implosion). During the collapse, the kinetic energy of the surrounding fluid increases and its potential energy decreases, causing a drop in local pressure. When opposite sides of the structure come into contact with one another, sharp acoustic pulses are released. Soon after, the water that surrounds the structure comes to a sudden stop which leads to an abrupt change in momentum, resulting in a considerably high-pressure pulse (Turner, 2007; Turner and Ambrico, 2012; Urick, 1963; Vath, 1968; Orr and Schoenberg, 1976).

Implosion has been of interest since the mid-1900s (Urick, 1963; Vath, 1968; Orr and Schoenberg, 1976). However, there is one key accident that renewed the interest in this topic. This accident was the 2001 Super-Kamiokande laboratory accident in Japan where one photomultiplier tube imploded, and the pressure pulses from this implosion caused adjacent tubes to implode; leading to a chain reaction that destroyed 7000 photomultiplier tubes (Accident Grounds Neutrino Lab, 2001). More recently in 2014, the multi-million dollar underwater vehicle, Nereus, imploded off the coast of New Zealand (Robotic Deep-sea Vehicle Lost on Dive to 6-Mile Depth, 2014). These recent events highlight implosion as an ongoing issue.

Early work on implosion characterized the acoustic pulses emitted during the collapse of glass structures, as well as their potential to damage nearby structures (Turner, 2007; Urick, 1963). This work led to the creation of robust computational models (for fluid-structure interaction during implosion) for the implosion of metallic structures (Turner and Ambrico, 2012). Later work analyzed the implosion of aluminum structures with varying lengths to produce higher modes of failure (modes II and IV) (Farhat et al., 2013). Also, an experimental study on brass structures was made with varying geometries to examine the effect of collapse modes on the emitted pressure pulses (Ikeda et al., 2013). Recently, the pressure pulses from imploding structures were linked to full deformation and velocity fields that were captured through a Digital Image Correlation (DIC) technique coupled with high-speed photography (Gupta et al., 2014; Pinto et al., 2014; Pinto et al., 2015).

Even though full-field measures can be obtained from DIC, only localized measures were used in the discussion and results of previous studies due to the human limitation of comparing four-dimensional fields (three spatial and one temporal). For this reason, most of the information available from the full-field analysis goes unused. To date, there is no work done in the mitigation of the energy emitted during implosion, or in measuring the kinetic energy on the surface of a DIC specimen (Gish and Wierzbicki, 2015). Polyurea has gained research interest regarding blast mitigation due to its dynamic properties, such as its stiff-

* Corresponding author. Fax: +1 401 874 2355.
E-mail address: shuklaa@uri.edu (A. Shukla).

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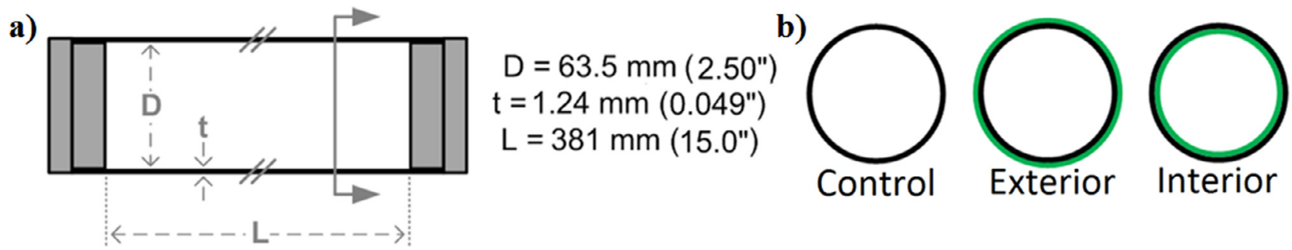

Fig. 1. Specimen details; (a) tubular structure dimensions and (b) polyurea coating locations.

ness increase at high strain rates. Some of the work available on energy mitigation through polyurea coating is on blast/dynamic loading on structures (Tekalur et al., 2008; Bahei-El-Din et al., 2006; Gardner et al., 2012). More recently available is a study on coating thin-walled tubular structures with polyurea to mitigate longitudinal acceleration during crushing due to blast loading (Bonsmann and Fourney, 2015).

This study aims to develop an experimental scheme to determine the localized energy history emitted during the implosion of aluminum structures. Moreover, a numerical method will be established to combine the three spatial domains from the implosion DIC analysis into a volumetric measure. Finally, the new energy scheme will be used to analyze the mitigation effects of polyurea coated aluminum structures and to create an estimation method for the energy released during an implosion process.

2. Experimental details

2.1. Specimen geometry and facility

Each specimen is comprised of a 6061-T6 Al tubular structure with 63.5 mm (2.5″) diameter and 381 mm (15″) length (see Fig. 1). The specimens are sealed from both ends with aluminum end-caps to prevent water penetration. Therefore, during the experiments high-pressure water surrounds the specimen while low-pressure air resides in the specimen.

The experimental facility consists of a 2.1 m semi-spherical pressure vessel and two high-speed cameras. As shown in Fig. 2, the specimen is suspended at the center of the tank, and then the tank is filled with water and pressurized with compressed nitrogen gas which is introduced into the top of the tank. This simulates increasing water depths in an underwater environment. For the experiments performed in this study, all specimens imploded at 1.69 ± 0.03 MPa (equivalent to 164 m below sea level).

During the implosion event, eight pressure sensors (PCB 138A05 from PCB Piezotronics, Inc., Depew, NY) capture localized pressure histories at 2 MHz (through an Astro-med Dash® 8HF-HS from Astro-Med Inc., West Warwick, RI). The sensors are located above and behind the specimen at an 84 mm distance from the surface of the specimen. Also, Sensor 1 and Sensor 5 are mid-length of the tube (see Fig. 3). Moreover, the high-speed cameras (Photron SA1 from Photron USA, Inc.) record the entire implosion event. The stereo images captured are then used to perform the DIC analysis (with the black and white speckled pattern shown in Fig. 3) and obtain the full displacement and velocity fields. Previous work shows the DIC analysis error (for these experiments) to be below 2.5% (regarding out and in-plane displacements) (Gupta et al., 2014).

2.2. Polyurea coating

The polyurea used was the commercially available product HM-VK from Specialty Products, Inc. (Lakewood, WA). This is a two-part polyurea that was manually applied over the aluminum tube as it rotated longitudinally. Tape was used at each end of the tube (set to a predetermined thickness) as a scraper guide to wipe off the excess polyurea. Fig. 4 shows the set up for outside coating. For inside coating, the entire setup is angled so the polyurea can be poured from the center guide's end.

Specimens with polyurea coatings have a uniform coating placed outside or inside of the tube. There are two different coating thicknesses (based on volume ratios) for the outside and the inside coating. In total, there are five cases analyzed in this study as shown in Table 1. Each case studied has been repeated three times to ensure repeatability (discussed in later sections). Also, the inner, V_i, and outer, V_o, volumes shown in Table 1 represent air inside the specimen and water displacement (from a submerged specimen) respectively.

3. Results and discussion

3.1. Pressure and impulse

The tubular structure's cross section during implosion is illustrated alongside local dynamic pressure in Fig. 5(a). The y-axis in this figure is in terms of dynamic pressure where the value of 0 represents hydrostatic pressure (1.68 ± 0.01 MPa). The pressure history can be broken down into three main stages: (I) Structure becomes unstable, (II) emission of low-pressure pulses due to the decrease in potential energy, and (III) emission of high-pressure pulses due to the abrupt change in water momentum. Also, immediately after the low-pressure region, there is a high acoustic spike (at $t = 0$ ms) caused by structural contact. For structures with high diameter/thickness ratio (such as the one in this study), a second acoustic spike is seen when the opposing walls of the structure come into full contact. Fig. 5(b) shows the captured images that can be associated with the pressure history in Fig. 5(a). By comparing the images of $t = 0$ and $t = 0.15$ ms, it can be determined that the center cross section of the tube completely flattens from a "figure-eight" shape, which is the cause of the second acoustic spike. Note that Fig. 5(b) is an in-plane image that illustrates out-of-plane deformation; hence, by focusing on the y-dimension change, the out-of-plane change can be intuitively understood.

Fig. 5(c) illustrates the effects of polyurea coating through the 1 polyurea: 1 aluminum volume cases in comparison to the NC (no coating) case. Applying coatings to the exterior or the interior of the structure show mitigating effects to the low and high-pressure regions of the pressure pulse. Interior coating has a stronger effect then the exterior coating. By doubling the coating volumes (not shown in the Figure) this effect slightly increases.

The pressure data can be better represented in terms of impulse by simply integrating the signal. Doing so will take into account the duration of acoustic spikes as well as their magnitude. After integration, an areal impulse is given in terms of *Pa·s*. This areal impulse is a good representation of the force that adjacent structures