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Hydrostatic and shock-initiated instabilities in double-hull composite cylinders

Nicholas DeNardo, Michael Pinto, Arun Shukla*

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

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ABSTRACT

The dynamic collapse of hollow and foam-filled double hull composite cylinders is investigated experimentally. Concentric carbon-fiber/epoxy double cylinders with and without parametrically-graded PVC foam cores are collapsed in a large-diameter pressure vessel under critical hydrostatic pressure as well sub-critical hydrostatic pressure and shock loading. Dynamic pressure data is used in conjunction with underwater Digital Image Correlation (DIC) to determine the effect of the double hull structure on implosion mechanics. Buckling initiation and overall collapse behavior are studied, as well as the pressure pulses released during the dynamic event. Incidents of partial collapse are reported, in addition to cases where the entire structure collapses. The physical mechanisms responsible for this behavior are identified, and the time between inner and outer cylinders collapsing is related to buckling phase angle. For hydrostatically initiated implosions, results show heavier foam cores increase critical collapse pressure linearly with foam crushing strength. Pressure pulses emitted during collapse are shown to occur in distinct phases, with an additional under- and overpressure region present if the inner cylinder collapses. Impulse is demonstrated to be primarily a function of collapse pressure, with energy released increasing with core density. For shock initiated cases, specimens are shown to implode below their natural collapse pressure when subject to explosive loading, with the addition of a foam core substantially increasing structural stability and sometimes preventing collapse. Specimens with foam cores are shown to undergo prolonged vibrations before collapsing. Post-mortem specimens are used to elucidate fracture and failure mechanisms.

1. Introduction

This work investigates the stability and dynamic behavior of concentric composite cylinders, with and without foam cores, during underwater implosion. Both the hydrostatic and shock-initiated implosions of these double-hull cylinders are studied. Their failure and fracture mechanisms, dynamic behavior, and fluid-structure interaction are investigated experimentally using a specialized large-diameter pressure vessel, underwater Digital Image Correlation, piezoelectric blast transducers, and post-mortem analysis.

Implosion is a phenomenon which centers around the buckling of a gas-filled shell under external hydrostatic pressure, and the subsequent release of a large-amplitude acoustic pulse into the surrounding fluid medium

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* Corresponding author.
E-mail address: shuklaa@uri.edu (A. Shukla).

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(Turner and Ambrico, 2012; Turner, 2007). Interest in the acoustic signatures from implosion has existed since the mid-twentieth century, however recent accidents involving underwater implosion have reinvigorated research in the field (Urick, 1963; Orr and Schoenberg, 1976; Harben and Boro, 2001; Cartlidge, 2001; Robotic deep-sea vehicle lost on dive to 6-mile depth 2014). Jointly, these emphasized the need for increased understanding of the implosion phenomenon, in terms of both structural stability and implosion pulse mitigation. As such, the goal of this work is to study the underwater implosion of double-hull composite cylinders, which provide increased stability through bending strength, as well as pulse mitigation through foam core crushing.

Several works from the last two decades address gaps in the understanding of hydrostatic implosion. Initial work focused on identifying key stages in the implosion process, and relating those to the pressure-time history in the surrounding fluid (Turner and Ambrico, 2012; Turner, 2007; Farhat et al., 2013; Ikeda et al., 2013; Gupta et al., 2014). Fiber-reinforced composite materials in particular have been the source of considerable interest with regard to implosion, on account of their well-known advantages including excellent strength- and stiffness-to-weight ratios, and corrosion resistance (Hernandez-Moreno et al., 2008; Hur et al., 2008; Moon et al., 2010; Ross et al., 2011; Smith et al., 2009; Yang et al., 1997; Pinto et al., 2015; Pinto et al., 2015; Pinto and Shukla, 2015). Sandwich and double hull composite-structures can further improve on these benefits through increased bending strength and stiffness, and improved acoustic attenuation. The buckling of sandwich and double-hull cylinders under quasi-static external pressure has been studied extensively, but few of those works include experimental validation of results, and none study the pressure-pulse in the fluid following buckling (Han et al., 2004; Hutchinson and He, 2000; Kardomateas and Simitses, 2005; Lopatin and Morozov, 2015; Shen et al., 2015; Ohga et al., 2005; Arjomandi and Taheri, 2011).

It is also possible for a structure to implode at sub-critical pressure when subject to a dynamic pulse, as in the case of a nearby implosion or underwater explosion (UNDEX) (Lindberg and Florence, 1987). This occurs because the shock forces the structure along its load-deflection curve. When the shock causes enough deformation in the structure to reach the matching equilibrium point at the same sub-critical pressure along the curve, the structure implodes (Gupta et al., 2016). Due to this possibility, a variety of work has been done on the shock-initiated implosion of monolayer structures (Gupta et al., 2016; Pegg, 1994; Tanov et al., 1999; Brett and Yiannakopolous, 2008; Hung et al., 2009; Hoo Fatt and Pothula, 2010; Ikeda and Duncan, 2012; Pinto and Shukla, 2016). There has also been extensive work on the behavior of sandwich structures subject to underwater blast; however, this work typically focuses on beams and plates, and does not study buckling in cases of cylindrical geometry (Hall, 1989; Deshpande and Fleck, 2005; Librescu et al., 2006; Liang et al., 2007; McShane et al., 2007; Mori et al., 2007; McMeeking et al., 2008; Avachat and Zhou, 2012; Liu et al., 2010; Arora et al., 2012; Hoo Fatt and Surabhi, 2012). Thus, a significant knowledge gap exists with regards to the shock-initiated implosion of sandwich and double hull structures.

This paper discusses results from a comprehensive series of experiments on the implosion of double hull composite cylinders subjected to hydrostatic pressure and shock loading. Results show a substantial increase in structural stability when the foam core is added, with critical collapse pressure increasing linearly with core crushing strength under hydrostatic conditions, and collapse delayed substantially or prevented under dynamic pulse loading. Results from both full and partial collapse of the structures are discussed. Superimposed dynamic pressure pulses do cause the double hull structures to collapse; however, the collapse occurs when the bubble pulses interact with the cylinders and not during initial shock interaction. Energy and impulse in the fluid medium are evaluated during and after implosion and related to fracture and failure mechanisms observed during post-mortem analysis. The experiments show unique double-pulses that are related to the independent collapse of the outer and inner cylinders.

For ease of understanding, the results of experiments from hydrostatic implosion and shock-initiated implosion are presented separately.

2. Material selection and specimen design

All specimens in this study use filament-wound carbon-fiber/epoxy cylinders for their inner and outer facesheets, and are manufactured by Rock West Composites (West Jordan, UT). Both the inner and outer cylinders have a general purpose $[\pm 15/0/\pm 45/\pm 15]$ layup, with a 1.7 mm wall thickness. The outer cylinder has a 60.4 mm ID and the inner cylinder a 38.6 mm ID. In hydrostatically-initiated implosion experiments, the specimens have a 279 mm unsupported length, which encourages a mode 3 collapse and gives more foam core crushing. In shock-initiated experiments a 356 mm unsupported length is used in order to encourage a mode 2 collapse that aligns well with the shock loading and simplifies data analysis. The outer cylinder has a random, black-and-white speckle pattern for DIC. The inner and outer cylinders are assembled concentrically and fixed in place using aluminum endcaps, which are sealed from outside water and one another using o-rings. To provide an additional backup seal, a thin layer of epoxy is applied to the gap between the end of the cylinder and the endcap.

The PVC foam cores used in the specimens are from the closed-cell Divinycell H series of foams, as produced and provided by DIAB, Inc. (DeSoto, TX). Cores are made by cutting rings of 42 mm ID and 9.2 mm thickness from a sheet of stock material, then stacking the rings concentrically between the inner and outer cylinders. The height of the stack of rings is matched to the unsupported length of the cylinders, with the end result that the volume between inner and outer cylinders is completely filled with foam. Foam cores are not bonded to composite cylinders. For hydrostatic experiments, foam cores of different densities are parametrically graded across trials: experiments are performed with Divinycell H35, H60, H80, and

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