2019

DYNAMIC INSTABILITY OF COMPOSITE CYLINDERS IN UNDERWATER CONFINING ENVIRONMENTS

Christopher J. Salazar
University of Rhode Island, sallyzar610@gmail.com

Follow this and additional works at: <https://digitalcommons.uri.edu/theses>

Recommended Citation

Salazar, Christopher J., "DYNAMIC INSTABILITY OF COMPOSITE CYLINDERS IN UNDERWATER CONFINING ENVIRONMENTS" (2019). *Open Access Master's Theses*. Paper 1451.
<https://digitalcommons.uri.edu/theses/1451>

This Thesis is brought to you for free and open access by DigitalCommons@URI. It has been accepted for inclusion in Open Access Master's Theses by an authorized administrator of DigitalCommons@URI. For more information, please contact digitalcommons-group@uri.edu.

DYNAMIC INSTABILITY OF COMPOSITE
CYLINDERS IN UNDERWATER CONFINING
ENVIRONMENTS

BY
CHRISTOPHER J SALAZAR

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING AND APPLIED MECHANICS

UNIVERSITY OF RHODE ISLAND

2019

MASTER OF SCIENCE THESIS

OF

CHRISTOPHER J SALAZAR

APPROVED:

Thesis Committee:

Major Professor

Arun Shukla

David Taggart

Jason Dahl

Nasser H. Zawia

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND

2019

ABSTRACT

A comprehensive series of experiments was conducted to understand the effect of confining environments on the mechanics of implosion of carbon/epoxy composite cylinders. In the case of implosion, a confining environment can be defined as any environment which limits, restricts, or otherwise manipulates particle motion towards an implodable volume during an implosion event. As such, the implosion of composite structures within two different types of confining environments was investigated: implosion within full confinement, and implosion within partial confinement. It was found that a fully-confining environment considerably limits the energy available to drive implosion, and thus two implosion phenomena can result: full implosion and partial implosion. Full implosion occurs when the energy contained in the compressed water bounded by the confining structure is sufficient to cause wall contact in the implodable. This resulted in water-hammer pressure spikes at the ends of the confining chamber due to the formation and subsequent collapse of large cavitation bubbles. Partial implosion occurs when the energy contained in the compressed volume of water bounded by the confining structure is not sufficient to cause wall contact in the implodable structure, causing an arrest in the implosion process and resulting in structural oscillation of the walls of the implodable. This resulted in pressure oscillations of the same frequency throughout the confining chamber, with oscillations increasing in amplitude with distance from the axial center. In partially-confining environments, it was found that the implosion of composite structures resulted in pressure oscillations which behaved as a damped harmonic oscillator of frequency f , amplitude ΔP_{max} , and damping ratio ξ . Pressure oscillations were experimentally

characterized, and an analytical investigation was conducted in which expressions for f and ΔP_{max} were derived, showing good agreement with experimental results. Finally, it was experimentally shown that by decreasing the energy stored in the compressed volume of water bounded by the partially-confining structure, implosion with dwell can be achieved, in which there is a short pause in the implosion process. This phenomenon is analogous to partial implosion within full confinement.

ACKNOWLEDGEMENTS

The author would like to gratefully acknowledge Maximillian Hill and Timothy Preston Pickard, whose dedication, attention to detail, and comradery enabled both the joyful and timely completion of this work. On the note of comradery, the author would also like to acknowledge his colleagues at the Dynamic Photo Mechanics Laboratory, discussions with whom inspired and challenged the work presented here, helping to ensure that it is the best it can be. In addition, the author would like to acknowledge Professor Arun Shukla, whose guidance and teachings not only passed on technical knowledge, but also laid the foundation for the methods of thought necessary to succeed in the field. Finally, the author gratefully acknowledges the financial support provided by Dr. Y.D.S. Rajapakse under Office of Naval Research grant no. N00014-17-1-2080.

DEDICATION

On a rainy and stormy morning just days before the due date of this work, the author sits in a street-side café, looking out the window to a large intersection in the heart of his town. There are few cars at this time of morning, and even with the rain obscuring their view, they pass along slowly, confidently. The noise of mid-day has not yet burdened their minds with rush and clutter. Whether they turn left, right, or keep on straight, they know where they are going. They have risen early enough to do it quietly, peacefully...they have laid their brick...and are indeed on their way.

Watching the lights blink red and green in the quiet commanding of men and machines, the author of this work contemplates a dedication. The author is not often inclined to dedicate his work to one individual or another. The works he has dedicated were usually written for no other purpose than the burning necessity to write...to make tangible and eternal those ideas passing through his head, so abstract and fleeting. They simply had to be written. They are these works that he dedicates to...well, he doesn't really know quite what. He is just thankful that by some cosmic chance, by some divine mystery, that he has found himself on this earth with the flame of thought burning in his mind. He is thankful for the fact that this flame burns deep into the night, forcing him awake, demanding to be made real by pen and paper. He is grateful for the beauties this flame produces by him. The ebbs and flows of the tides of thought pulsating on paper. The author loves this. He is thankful for the flame and the pen and the possibility to be their great catalyst, and so often dedicates his work to some abstract thought of gratitude for being alive.

The work detailed in this thesis does not ebb and flow. It is not born of the same flame which flows out through the fingertips and sparks creation into dead pages. The flame responsible for these pages is that of pure will. The great ode to life written in the preceding paragraph, that beautiful soliloquy of the ebbs and flows of thought...such writing comes natural to the author of this work. He would even say that to write such things is no challenge at all. The work detailed in this thesis challenged the author to the core. It was born not of the free and whimsical brush strokes of the soul, but by the tireless, calculating hammer strokes of the will. The work contained in this thesis was born of a conscious and tempered desire. It was not born of the soul's necessity.

And so it seems obvious to the author that the dedication of this work cannot be abstract, as the results of this work are not abstract. The intent is conscious, the work is definite, its consequences definite, and so too shall the dedication of this work be definite.

The author dedicates this work to a boy who would leap out of bed every day with lightening in his eyes and fire in his lungs and would take off running towards a future he had designed for himself. He knew exactly what it was he wanted, and he was well on his way to getting it. He was laying his own brick, and he knew exactly why. Nine years later the author doesn't quite leap out of bed, it is more of an excited shuffle, but there is still lightening in his eyes and fire in his lungs. Things may have not turned out exactly as the boy had planned, but the brick had been laid, the foundation established, and by consequence these pages exist today.

The foundation upon which these pages were written is essentially the conviction that one must expect his or her life to be the greatest life ever lived. One must wake up every day with that expectation. If one were a playwright offered the opportunity to write only

a single play ever and watch it in the grandest theater on earth, would that play not be the best, most beautiful play of all time? Would its characters not love immensely, profoundly? Would they not climb the highest peaks and erect skyscrapers to match them? Would they not fight a war that would end all wars, face peril, and conquer it? Would they not ponder science deep into the night, alone amidst blinking instruments and equations scribbled about them? Would not any other play seem a waste?

The author has observed that such a conviction will form and temper a will inspired by the immense importance of life and of living. Incredible things can be accomplished with such a will.

Henry David Thoreau seemed to agree: “In the long run men only hit what they aim at. Therefore, though they should fail immediately, they had better aim high.”

This work is also dedicated to all those who live with this conviction.

Christopher J Salazar

April 15th, 2019

PREFACE

The studies detailed in this thesis address the topic of the implosion of carbon composite structures within underwater confining environments. A confining environment can be created by any structure which directs, limits, or otherwise manipulates the flow of water during an implosion event. These studies were conducted at the University of Rhode Island's Dynamic Photo Mechanics Laboratory utilizing state of the art pressure vessel, pressure sensing, and optical facilities. As a result of these studies, new phenomena have been identified, experimental models developed, and analytical methods have been introduced as a way of estimating important variables pertaining to the confined implosion of composite structures. The topic has been divided into two primary chapters. The first pertains to the implosion of composite structures within full confinement, while the second pertains to the implosion of composite structures within partial confinement. A third chapter is included which proposes possible future topics. This thesis is prepared in the manuscript format.

The study detailed in Chapter 1 identifies two dramatically different phenomena resulting from the implosion of composite structures within full confinement. The first is partial implosion, which occurs when the hydrostatic pressure in the system is enough to cause instability in the specimen, however potential energy is insufficient to drive a full collapse. This causes an arrest in the implosion process, which results in structural oscillations in the implodable itself and pressure oscillations in the surrounding fluid. The second is full implosion, which occurs when the specimen is subjected to its critical buckling pressure P_c such that instability is initiated, and the energy in the system is sufficient to continue inward radial deformation until contact is reached. This results in

the high amplitude, short duration pressure pulses at the ends of confinement due to the formation and collapse of small cavitation bubbles on the sensor surface, followed by longer duration, lower amplitude pressure pulses resulting from the formation and collapse of larger cavitation bubbles. This study was published in the Journal of Dynamic Behavior of Materials on July 10th, 2018, and is formatted according to this journal's specifications.

Chapter 2 of this thesis details an experimental and analytical investigation of the implosion of composite tubes within partial confinement. Partial confinement refers to a thick-walled, cylindrical aluminum structure which is closed on one end and open to free-field pressurized conditions on the other end. It was observed that the dynamic pressure histories resulting from the partially-confined implosion of composite structures behaved as a damped harmonic oscillator. Dynamic pressure behavior is thus experimentally characterized for each geometry by determining average values of amplitude ΔP_{max} , frequency of oscillation f , and damping ratio ζ . It is shown that f decreases with increasing implodable volume to confinement volume ratio V_i/V_c , and is theoretically determined with excellent correlation to experimental results. Finally, amplitude of oscillation ΔP_{max} is theoretically determined and used in conjunction with theoretically determined f and experimentally determined ζ to fully define the hammer wave oscillations resulting from partially-confined implosion. It is the author's intent to submit this chapter for publication in an academic journal.

Chapter 3 of this thesis is devoted to identifying possible future research topics related to those covered by Chapter 1 and Chapter 2. If completed, it is the hope of the author

that these topics will expand upon the work presented in this thesis, as well as address any gaps in knowledge existing in current work.

TABLE OF CONTENTS

Abstract.....	ii
Acknowledgements.....	iv
Dedication.....	v
Preface.....	viii
Table of Contents.....	xi
List of Figures.....	xv
List of Tables.....	xx
Chapter 1: Dynamic Instability of Anisotropic Cylinders in a Pressurized Limited-Energy Underwater Environment.....	1
Abstract.....	2
Introduction.....	3
Experimental Procedure.....	6
Composite Tube Specimens.....	7
Experimental Apparatus.....	9
Sensor Calibration.....	11
Results and Discussion.....	13
Partial Implosion.....	13
DIC Results.....	14

Pressure History.....	18
Full Implosion.....	21
DIC Results.....	22
Pressure History.....	24
Post-Mortem Analysis.....	27
Conclusions.....	30
References.....	33
Chapter 2: Implosion of Composite Tubes in an Open-Ended Confining Chamber.....	35
Abstract.....	36
Nomenclature.....	37
Introduction.....	39
Experimental Procedure.....	42
Pressure Vessel Facility with Partial Confinement.....	42
Composite Tube Specimens.....	44
Validation of DIC Methods in a Complex Underwater Environment.....	46
Experimental Results.....	47
Water Hammer Behavior.....	48
Partially-Confined Implosion with Dwell.....	52

Model of $\Delta P(t)$ using Experimentally-Obtained Values.....	54
Discussion.....	60
Preliminary Considerations: The Water Hammer Effect.....	61
Theoretical Determination of Frequency of Oscillation f	63
Determination of Maximum Overpressure ΔP_{max}	67
Conclusions.....	73
References.....	75
Chapter 3: Topics for Future Study	77
Appendices.....	81
Appendix A.....	81
Experimental Details.....	81
Experimental Results.....	82
Conclusions.....	86
Appendix B.....	87
Modification to Fully-Confined Pressure Facility.....	87
Speckle Pattern and Calibration Technique.....	89
Experimental Procedure.....	91
Experimental Results.....	92

Conclusions.....	94
Appendix C.....	95

LIST OF FIGURES

Chapter 1

Fig. 1: Experimental setup showing fully confined tubular pressure vessel, high-speed camera arrangement, axial cross-section of pressure vessel with specimen, and partial and full implosion specimens as viewed by the cameras. Sensor channel locations are displayed throughout the length of the confining chamber, marked by Ch1 – Ch 7.....11

Fig. 2: Applying sensitivity values determined in the calibration process to (A) voltage outputs from a 600 psi drop converts all voltage readings to (B) the same calibrated pressure.....13

Fig. 3: DIC data for 2.34 MPa partial implosion event showing (A) oscillating radial displacement behavior at key moments of the instability event. Line slice data is extracted to give (B) radial displacement and integrated with respect to time to give (C) radial velocity as functions of axial location and time extracted from (D) the length of the lobe as defined by iso-radial lines.....15

Fig. 4: DIC data for 2.06 MPa partial implosion event showing (A) oscillating radial displacement behavior at key moments of the instability event. Line slice data is extracted to give (B) radial displacement and integrated with respect to time to give (C) radial velocity as functions of axial location and time extracted from (D) the length of the lobe as defined by iso-radial lines.....17

Fig. 5: Normalized pressure-time histories at channel 1 (left end), channel 3, and channel 4 (axial center) for partial implosion cases in which (A) $P_I = 2.34$ MPa and (B) $P_I = 2.06$ MPa. The initial drop in normalized pressure, dP_n increases by 0.35 at the left end with

the increase in instability pressure. The change in radius is superimposed over pressure history to illustrate the coupling between specimen deformation and pressure.....19

Fig. 6: DIC data for full implosion cases showing (A) radial displacement data for a typical event at key moments, (B) the line segment taken along the length of the lobe used to extract radial displacement data which is then integrated with respect to time to provide velocity data for (C) 381 mm, (D) 330.2 mm, and (E) 279.4 mm length cases..... 23

Fig. 7: Pressure-time histories from full implosion events showing pressures throughout left section of confining chamber and axial center for (A) 279.4 mm and (B) 381 mm length cases from (C) channel 1 and channel 4 sensor locations. The average change in radius is superimposed over pressure histories to illustrate the effect of specimen deformation behavior on pressure amplitude.....26

Fig. 8: Postmortem images of 330.2 mm carbon/epoxy tube, showing (A) major valley crack, (B) major lobe crack, (C) fiber delamination, (D) interfibrillar matrix crack propagation along the 15° layup orientation, (E) through-thickness cracking, and (F) fiber fracture propagating along the 45° layup. Relatively low critical buckling pressure resulted in less overall damage in this specimen.....28

Fig. 9: Postmortem images of 279.4 mm carbon/epoxy tube, showing (A) major valley crack, (B) major lobe crack, (C) fiber delamination, (D) interfibrillar matrix crack propagation along the 15° layup orientation, (E) through-thickness cracking, and (F) fiber fracture propagating along the 45° layup.....29

Fig. 10: Post-mortem images of 381 mm carbon/epoxy tube, showing (A) major valley crack, (B) major lobe crack, (C) fiber delamination, (D) interfibrillar matrix crack propagation along the 15° layup orientation, (E) through-thickness cracking, (F) fiber fracture propagating along the 45° layup orientation, (G) the intersection of major lobe and valley cracks, (H) separation of large portions of material, (I) fiber pullout, and (J) inter-lamina delamination..... 30

Chapter 2

Fig. 1: Experimental setup showing (A) top view of 2.1m semi-spherical pressure vessel with viewing windows, high-speed cameras, light sources, implodable and confining structures, (B) side view of 2.1m semi-spherical confining structure with nitrogen gas pocket for pressurization, confining structure, and acrylic viewing window, and (C) Confining structure with composite implodable structure, acrylic viewing window, and location of dynamic pressure transducers..... 43

Fig. 2: Validation of DIC measurements taken through multiple media, showing (A) rigid cylinder of varying radii R_1 to R_5 viewed through curved acrylic window and (B) DIC-measured radius values plotted against true radius values alongside corresponding error values.....47

Fig. 3: Water hammer pressure oscillations taken from channel 2 resulting from the partial implosion of implodable geometry B28. Water hammer oscillation is seen to behave as a damped harmonic oscillator, defined by amplitude ΔP_{max} , frequency f , and damping ratio ζ48

Fig. 4: Dynamic pressure histories taken from channels 1-5 resulting from the implosions of (A) implodable geometry A38 and (B) implodable geometry B28, which are the largest and smallest tubes used in this study, respectively. The dotted black line shows the point at which absolute pressure is equal to 0 MPa.....	50
Fig. 5: The stages of implosion with dwell as observed from (A) dR/dt data extracted from a line spanning the viewable length of the imploding tube and (B) dynamic pressure history taken from channels 1-3. All data is given for implodable geometry A38.....	53
Fig. 6: Dynamic pressure history maps presented in the time domain and frequency domain for (A) geometry A38 and (B) geometry A28. The dominant contributing frequency of oscillation for pressure oscillations within confinement is given by a white dotted line, and marked by f	57
Fig. 7: Experimental f is shown decreasing with implodable volume ratio.....	58
Fig. 8: Experimental models determined from equation (3) using experimental parameters from Tables 2 and 3 are given for dynamic pressure histories taken at channels 1 and 3 for (A) implodable geometry B28 and (B) implodable geometry A38.....	59
Fig. 9: Stages of water hammer oscillation occurring over one full period.....	62
Fig. 10: Experimentally obtained wave speed and frequencies compared with theoretically-determined wave speed and frequencies determined using K_{mix} and ρ_{mix}	67

Fig. 11: Experimentally-obtained ΔP_{max} given alongside ΔP_{max} determined from equation (23), showing excellent agreement for low P_c , however deviating for higher P_c 71

Fig. 12: Dynamic pressure history calculated according to equation (1) using theoretically determined ΔP_{max} , theoretically determined f , and experimentally determined average ξ . Dynamic pressure histories are calculated for (A) implodable volume A38 and (B) implodable volume B28, and superimposed over experimental data taken from channel 2 for each respective geometry.....72

LIST OF TABLES

Chapter 1

Table 1: Measured geometric parameters for full and partial implosion specimens..... 9

Table 2: Calibrated sensitivities of dynamic pressure transducers..... 12

Chapter 2

Table 1: Average geometric values and experimentally-obtained P_c and E_c for all implodable geometries..... 45

Table 2: Average experimental $\Delta P_{max,n}$ and ξ_n at each channel n for Case A implodable structures with standard deviations..... 56

Table 3: Average experimental $\Delta P_{max,n}$ and ξ_n at each channel n for Case B implodable structures with standard deviations..... 56

CHAPTER 1:

Published in the Journal of Dynamic Behavior of Materials

Dynamic Instability of Anisotropic Cylinders in a Pressurized Limited-Energy Underwater Environment

by

Christopher J Salazar and Arun Shukla

Corresponding Author:

Arun Shukla

Dynamic Photo-Mechanics Laboratory

Department of Mechanical, Industrial and
Systems Engineering

University of Rhode Island

Kirk Applied Engineering Bldg., 94 Upper
College Rd Kingston, RI 02881, USA

Phone: +1 (401) 874-2283

Email address: shuklaa@uri.edu

Abstract

A fundamental experimental study was conducted to understand the physical phenomena resulting from the dynamic instability of carbon/epoxy composite tubes in an underwater pressurized tubular confining environment. The confining nature of the environment limits the potential energy available to drive instability, resulting in a decrease in hydrostatic pressure with the onset of instability and allowing the carbon/epoxy composite tubes to recover. Unsupported tube length and tube diameter were varied in order to determine the effect of tube geometry on the failure mechanisms of the tube and pressure waves emitted throughout the confining chamber during the instability event. High-Speed photography coupled with Digital Image Correlation techniques were employed alongside the acquisition of pressure-history data from each experiment to relate specimen displacement behavior to resulting pressure pulses. Tubes of 55 mm diameter experienced partial implosion, in which the walls of the specimen oscillated radially with no wall contact. This resulted in pressure oscillations of the same frequency throughout the confining chamber, with oscillations increasing in amplitude with distance from the axial center. Amplitude of pressure and radial structural oscillations were found to be dependent on pressure just prior to instability. Tubes of 35 mm diameter experienced full implosion, which resulted in water-hammer pressure spikes at the ends of the confining chamber due to the formation and subsequent collapse of large cavitation bubbles. Longer tubes were observed to undergo significantly more damage during full implosion, reducing their ability to recover radially and thus effectively reducing the strength of hammer pulses.

1. Introduction

A fundamental experimental study was conducted to investigate the instability of anisotropic filament wound carbon fiber cylindrical shells initiated in a tubular confining chamber. The experiments were conducted to examine the failure mechanisms of carbon fiber shells in a pressurized limited energy environment and understand how their instability affects the local surroundings. In confined conditions, the potential energy available to drive instability is limited and thus begins to decrease with any decrease in specimen volume. This effect gives rise to two very different instability cases: partial implosion and full implosion. Both cases are carefully examined and discussed in this study.

The use of composite materials for marine applications has recently been the subject of extensive research due to the various advantages they offer. Compared with metals, composite materials offer reduced weight, greater corrosion resistance, and greater potential operating depths per unit weight for submerged structures. Furthermore, their low thermal, magnetic, and acoustic signatures make them hard to detect, making them ideal for military applications. For these reasons, composite materials have already been incorporated in the design of various unmanned underwater vehicles (UUV's), submarine bow domes, and ship masts [1]. However, the lack of complete understanding of these materials' behavior, especially under extreme and complex loading environments, remains a hindrance to their widespread application. In naval applications such environments could include the main ballast tanks of a submarine. These are flooded, confined spaces between the pressure hull and outer hull, and often house sensitive equipment related to navigation and weapons systems. For this reason,

the present study investigates the problems of partial and full implosion occurring in a confining, limited energy environment.

An implosion event occurs when a closed, hollow structure of lower internal pressure is submerged in a medium of higher pressure such that the differential results in instability in the structure walls, causing it to collapse inwards on itself. When this occurs underwater, the sudden increase and subsequent arrest in fluid motion emits a pressure pulse into the fluid which can be damaging to and even initiate the implosion of nearby structures [2, 3]. The problem of implosion itself has been a topic of study for many decades, with the first equations for the critical buckling pressure of a hydrostatically loaded cylindrical shell having been derived by von Mises in the early 1900's [4,5]. Early works focusing on the pressure waves released into the surrounding fluid by an imploding volume were conducted by imploding glass structures as a source of underwater acoustic signals [6,7]. The strength of these pressure waves depends in part on the geometry and material of the collapsing volume. In 2001, at Japan's Super-Kamiokande neutrino observatory, the implosion of a single photomultiplier tube released a pressure wave powerful enough to trigger a chain reaction of implosion. This accident resulted in the implosion of nearly 7000 nearby tubes, causing \$20-\$30 million in damage [8]. The danger posed to surrounding structures by implodable volumes has thus sparked investigations from researchers in the naval community.

The implosion of aluminum tubes has been widely investigated, with Turner and Ambrico having identified the key stages of the implosion process in a free-field environment with respect to the local pressure about the collapsing volume [2]. This work also resulted in the development of robust and accurate fluid-structure

computational models. Farhat et al. furthered this work by studying 2 and 4 mode implosion events in aluminum cylindrical shells and using these experiments to verify existing computational models [9]. Gupta et al. then showed that the presence of nearby structures can also have a dramatic impact on the implosion process and resulting pressure histories due to their effect on the fluid motion in the system [10,11].

Compared to metals, the implosion of composite structures has received little attention. The first analytical equations to predict critical buckling pressure of a composite tube were derived from von Mises' original equations as recently as 1993 [12]. Experimentally, Moon et al. conducted studies on the implosion of filament-wound carbon/epoxy composite cylindrical shells to determine the effect of winding angle on collapse mode critical buckling pressure [13]. The critical buckling pressure and collapse modes of carbon/E-glass composite tubes have also been studied by Smith and Ross, who used experimental results to create design tables to aid in the implementation of composites [14, 15]. Most recently [16 - 18], studies designed to capture full field displacement data together with pressure data showed that the complex failure mechanisms behind the implosion of composite tubes resulted in pressure profiles which differed dramatically from those resulting from the implosion of metal tubes. Namely, the brittle failure of carbon/epoxy composite tubes resulted in stronger pressure pulses than aluminum tubes, while the energy intensive damage processes involved in the failure of glass/PE composite tubes resulted in weaker pressure pulses [16]. Similar experiments also showed that the architecture of the composite structure also had a significant impact on resulting pressure profiles [17,18]. These studies have been conducted to examine the physics of an imploding composite structure in a free-field

environment, where the hydrostatic pressure acting on the tube does not change over the course of the implosion. However, it remains unclear how a confining, limited energy environment will affect the implosion process of a composite structure. It was therefore the aim of the present study to examine this phenomenon by employing underwater digital image correlation techniques together with the use of pressure data obtained from strategically-placed pressure sensors.

Experimental results from the present study showed that initiating hydrostatic instability in carbon/epoxy composite tubes within a limited energy confining environment can result in two very different instability events: partial implosion and full implosion. Partial implosion occurred when the potential energy in the system decreased with specimen volume too rapidly to continue the implosion process. This caused the specimen to radially oscillate in a harmonic manner. These oscillations directly affect the resulting pressure-time history, with stronger oscillations seen at the ends of the confining chamber. Full implosion occurred when the potential energy in the system is sufficient to force wall contact in the specimen and result in large pressure spikes at the end of the confining chamber due to the water-hammer effect, and due to the formation and subsequent collapse of small cavitation bubbles on the chamber walls. Full implosion specimens with a greater unsupported length resulted in smaller water-hammer pulses due to more extensive damage incurred in the specimen.

2. Experimental Procedure

A series of experiments was conducted using state of the art facilities to understand partial and full collapse of composite cylindrical structures in an underwater

fully confined environment. A brief description of the material and specimen geometry, experimental apparatus and sensor calibration is presented below.

2.1 Composite Tube Specimens

The specimen geometries used in this study were selected such that one would exhibit full implosion and the other would exhibit partial implosion. The measured geometric features for all cases studied are summarized in table 1.

Experimental specimens for the partial implosion case were cylindrical tubes made of filament wound carbon/epoxy composite organized in a $[\pm 15/\pm 45/\sim 90/\pm 45/\pm 15]$ layup (SKU 35060-S, Rock West Composites UT). At the initiation of instability, the potential energy driving the collapse of the specimen decreases with change in volume of the specimen. Thus, to ensure that these tubes would exhibit partial implosion behavior, the geometry was selected such that, upon instability, the potential energy in the confined system would decrease fast enough to prevent a full implosion. This requires that the buckling pressure of the specimen be low, and that the radius of the specimen be relatively large in order to increase the ratio of specimen external volume (V) to pressure vessel volume (V_c). As such, the partial implosion specimens studied had an outer diameter (d) of 55 mm, a wall thickness of (h) 1.9 mm, and an unsupported length (l) of 381 mm. Three experiments were conducted with this specimen geometry, one of which had lower ovality and wall eccentricity parameters than the other two, resulting in a 13% increase in critical buckling pressure P_c .

Specimens for the full implosion case were fabricated with the same material as the partial implosion case, however the thickness and layup were different. In order to

ensure that the critical buckling pressure of full implosion specimens did not exceed the safe operating pressures of the pressure vessel used, the wall thickness of the full implosion specimens was required to be less than that of partial implosion specimens. According to the filament winding process employed by the supplier, wall thickness is governed by the composite architecture, and thus to achieve the required wall thickness a slightly different layup schedule was selected. The layup schedule for the full implosion case was $[\pm 15/\sim 90/\pm 45/\pm 15]$. In order to increase the total available energy at the time of implosion, the diameter of the specimen for this study was reduced. As such, full implosion specimens studied had an outer diameter of 35 mm and wall thickness of 1.7 mm. In order to understand the effects of unsupported specimen length on resulting pressure history during an implosion event, specimens studied in the full implosion case were divided into three length subcases of 279.4 mm, 330.2 mm, and 381 mm. For each length case, three experiments were conducted. It is important to note that due to the complexities involved in the production of filament wound composite tubes, the thickness and diameter values given above for the full implosion case deviate up to $\pm 7.0\%$ and $\pm 0.7\%$, respectively, from tube to tube. Measured geometric parameters are given in table 1.

In all cases, specimens were sealed at both ends with 12.7 mm protruding aluminum endcaps outfitted with circumferential O-rings, and sealed with a thin layer of epoxy to ensure that the tube remains airtight. It has been shown that initial imperfections, namely ovality and variation in wall-thickness, can play a role in critical buckling pressure of tubes [19]. To quantify these imperfections, the ovality ($\Delta_0 = (D_{max} - D_{min}) / (D_{max} +$

$D_{min}))$ and wall eccentricity ($\Xi_0 = (h_{max} - h_{min})/(h_{max} + h_{min})$) were determined for each specimen prior to experiments.

Table 1 Measured geometric parameters for full and partial implosion specimens

Case type	Wall thickness, h (mm)	Outer diameter, d (mm)	Shell Volume, V (cm ³)	V/V _c	l/d	d/h	Ovality, Δ_0 (%)	Eccentricity, Ξ_0 (%)	Critical Buckling Pressure (MPa)
Partial imp	1.96	54.96	900	0.016	6.95	28.0	0.12	1.62	2.06
Partial imp	1.96	54.99	900	0.016	6.93	28.1	0.07	1.42	2.34
Full imp	1.70	35.20	272	0.005	7.92	20.7	0.25	4.85	4.47
Full imp	1.48	34.72	313	0.006	9.50	23.4	0.22	6.17	3.28
Full imp	1.63	35.03	368	0.007	10.9	21.5	0.25	7.05	4.66

2.2 Experimental Apparatus

The pressure vessel facility used to initiate instability events in a confining space consists of a 2.29 m (90 in) long, 177.8 mm (7 in) diameter tubular vessel with a wall thickness of 19 mm (0.75 in), shown in figure 1. The pressure vessel is made of seamless low-carbon steel (SA106-B) and consists of three modular sections. The middle section has a total length of 457 mm (18 in) and incorporates a 63.5 mm (2.5 in) thick flat acrylic window into the pressure vessel, allowing for a viewable space of approximately 216 mm x 102 mm (8.5 in x 4 in) for high-speed photography. This section is located between two 914 mm (36 in) segments which make up the remainder of the confining pressure vessel. Carbon/epoxy composite specimens were sealed with aluminum endcaps and placed concentrically within the pressure vessel, supported by rubber-tipped spokes such that the axial center of the specimen and the axial center of the vessel were aligned. The spokes ensured minimal interference with axial pressure waves and fluid motion within the confining tube during the instability event. The

pressure vessel was then filled with water such that no air remained in the system, and the water was pressurized at a rate of 0.01 MPa/s by a hydrostatic test pump until instability in the specimen was reached. Instability events released an audible noise which signaled the operators to manually shut off the pump. In partial implosion events, this noise was a tearing, crackling noise, indicative of fiber fracture. During full implosion events, this noise was a much louder, sudden popping noise, indicative of wall contact. In both cases a small amount of water was added to the system before the pump is shut off, however because the rate at which water is added is so small (0.0935 ml/ms), the pressure increase during the events of interest is negligible. Changes in pressure during the instability event were measured by dynamic pressure transducers (PCB 113B22, PCB Piezotronics, Inc., Depew, NY) mounted flush throughout the pressure vessel, including at the endplates and at the axial center. Two high-speed cameras (Photron SA1, Proton USA, Inc.) along with a high-intensity light source were mounted facing the viewing window and record all phenomena exhibited by the specimen at a rate of 30,000 frames per second.

Prior to experiments, a high-contrast random speckle pattern was applied to the surface of the specimen facing the cameras using flat black and white paint. Using wall thickness measurements, special care was taken to ensure that this surface will experience the maximum inward radial deformation. This allows the high-speed images captured during the event to be analyzed using commercially available digital image correlation (DIC) software to provide full-field displacement measurements across the speckled surface of the specimen.

Fig. 1 Experimental setup showing fully confined tubular pressure vessel, high-speed camera arrangement, axial cross-section of pressure vessel with specimen, and partial and full implosion specimens as viewed by the cameras. Sensor channel locations are displayed throughout the length of the confining chamber, marked by Ch1 – Ch 7

2.3 Sensor Calibration: Methodology and Results

The Piezotronic pressure transducers used in this study have a sensitivity of around 1mV/psi, however, the exact sensitivity varies from sensor to sensor, and thus the sensors must be calibrated to determine their exact respective sensitivities. To calibrate pressure sensors, the vessel was pressurized to a value near a given goal pressure, held at this value to ensure that the signal had settled, and the current hydrostatic pressure was recorded. The vessel was then quickly depressurized by opening a valve located on the pressure vessel. Data capture is triggered manually in unison with the release of pressure, and the resulting voltage drop in each sensor was used to determine respective sensitivity, according to the following equation:

$$S_{P,i} = \frac{dV_i}{P_i}$$

To verify repeatability over a range of pressures, this procedure was done three times for each goal pressure of 300, 400, 500, and 600 psi. Therefore, it follows that $S_{P,i}$ denotes the sensitivity of a certain sensor given from trial i . P_i is the hydrostatic pressure just prior to depressurization and dV_i is the resulting voltage drop given by:

$$dV_i = V_{max,i} - V_{min,i}$$

Where $V_{max,i}$ is the average signal prior to depressurization and $V_{min,i}$ is the average signal after depressurization. The sensitivity S for each sensor was then taken as the average of all trials i conducted over all goal pressures P :

$$S = \frac{1}{12} \sum_{P=1}^4 \sum_{i=1}^3 S_{P,i}$$

Table 2 gives the sensitivities of each sensor as determined by the above process:

Table 2 Calibrated sensitivities of dynamic pressure transducers

Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7
Sensitivity (mv/psi)	0.987	1.032	0.997	0.976	0.995	1.079	0.979

To illustrate this process, the deviation between sensor voltage outputs for a 600 psi pressure drop case is shown in figure 2a. There was a notable deviation in response although all the sensors measured the same pressure drop. This deviation was removed by applying the sensitivities shown in Table 2 such that all the sensors measure the same pressure drop, as shown in figure 2b.

Fig. 2 Applying sensitivity values determined in the calibration process to (A) voltage outputs from a 600 psi drop converts all voltage readings to (B) the same calibrated pressure

3. Results and Discussion

The results of the two instability cases are presented and discussed below. In the case of partial implosion, the potential energy in the system was not sufficient to drive a full collapse, and thus wall contact was not achieved. Full implosion cases involved a relatively high amount of potential energy, causing wall contact in the specimen and causing significant pressure spikes (water hammer pulses) at the ends of the confining vessel. 3D-DIC displacement data, pressure data, and frequency information are discussed in depth.

3.1 Partial Implosion

Partial implosion occurs when the hydrostatic pressure in the system is enough to cause instability in the specimen, however the total available energy is insufficient to drive a full collapse. This results in an oscillating radial displacement behavior which causes harmonic pressure pulses throughout the confining chamber. After the initial

instability event, trigger delay allowed further addition of water in the confining chamber causing progressive damage and resulting in subsequent instability events. For the sake of consistency, this study focuses on the initial instability event only. Since the visible damage on the specimen includes the damage that occurred due to subsequent instability events, the post-mortem analysis of partial implosion specimens has been omitted. It is important to note here that all time measurements are taken such that time $t = 0.00$ ms corresponds to the specimen experiencing its first peak inward radial deflection. The pressure at instability is referred to as P_I , and is taken as the hydrostatic pressure the instant prior to instability. Deviations in ovality Δ_0 and wall eccentricity Ξ_0 between partial implosion specimens resulted in specimens with instability pressures of 2.34 MPa and 2.06 MPa. These will be respectively referred to as case (a) and case (b) for the following discussion.

3.1.1 DIC Results

Digital image correlation technique was used to obtain position and velocity data from the instability event to provide additional insight into the failure mechanisms at play. To characterize specific phenomena that occur during the instability event, images of the specimen demonstrating crucial behavior are given in figures 3A and 4A. Radial displacement (dR) data was extracted across a line spanning the viewable length of the tube and is presented in figures 3B and 4B. Position data was then integrated with respect to time to provide radial velocity (v) data, shown in figures 3C and 4C. The data extraction line was positioned such that it followed the axial propagation of the forming valley, whose contour is defined by lines of constant radius. The exact positioning of

Fig. 3 DIC data for 2.34 MPa partial implosion event showing (A) oscillating radial displacement behavior at key moments of the instability event. Line slice data is extracted to give (B) radial displacement and integrated with respect to time to give (C) radial velocity as functions of axial location and time extracted from (D) the length of the lobe as defined by iso-radial lines

the data extraction line is presented in figures 3D and 4D, and ensures that the maximum displacements at every axial position for each point in time are given. It is important to note that in figures 3 and 4, values denoting inward movement (toward the cylindrical center of the specimen) are negative, while values denoting outward movement (away from the cylindrical center of the specimen) are positive.

DIC data for partial implosion case (a) ($P_I = 2.34$ MPa) is presented in figures 3A-3D. Figure 3A shows photographs taken at key moments during the instability event, along with color contours showing dR . As hydrostatic pressure in the confining chamber increased, the specimen experienced initial inward deformation of 0.4 mm at the axial center. This initial deformation, which occurred prior to instability, is shown at time $t = -3.06$ ms. Then, once the hydrostatic pressure reached P_I , the specimen experienced structural instability, and dR suddenly began to change at an increasing rate, accelerating to a maximum inward radial velocity of 4.3 m/s. This sudden change in dR can be seen at time $t = -1.96$ ms, just after the onset of instability. As the instability process continued, specimen volume decreased, causing the potential energy in the system to drop and resulting in an arrest in the implosion process at time $t = 0.00$ ms. It is at this point that the specimen experienced its maximum inward radial deformation of 8.6 mm, and radial velocity was 0 m/s. From here, the specimen walls began recover, shown at time $t = 1.20$ ms, until dR reaches a local maximum at time $t = 1.97$ ms. The specimen then continued to oscillate in a harmonic manner at an average frequency of 267 Hz, and with decreasing amplitude, as shown in the change in radius and radial velocity maps given by figures 3B and 3C.

Photos taken from key moments during partial implosion case (b) ($P_I = 2.06$ MPa) along with color contours showing dR values are shown in figure 4A. As hydrostatic pressure increased, the specimen experienced initial inward deformation of 1.3 mm at the axial center just prior to instability, shown here at -8.53 ms. Then, as the hydrostatic pressure in the system reached P_I , the rate of deformation increased suddenly, signifying structural instability in the specimen. The specimen walls can be seen accelerating

inward at time $t = -4.50$ ms, just prior to reaching a maximum inward velocity of about 1.5 m/s. As in case (a), the volume change resulting from structural instability decreased the potential energy in the system, arresting the collapse process at time $t = 0.00$ ms. The maximum inward radial deflection at this point was 5.3 mm. From this point, the

Fig. 4 DIC data for 2.06 MPa partial implosion event showing (A) oscillating radial displacement behavior at key moments of the instability event. Line slice data is extracted to give (B) radial displacement and integrated with respect to time to give (C) radial velocity as functions of axial location and time extracted from (D) the length of the lobe as defined by iso-radial lines

specimen began to oscillate radially, recovering to a local maximum at time $t = 2.07$ ms. This moment marked the beginning of the second oscillation, during which the specimen experienced a maximum inward deflection of 5.4 mm at time $t = 3.93$ ms. Note that in case (a), maximum inward radial deflection occurred in the first oscillation and did not increase in any successive oscillation. However, case (b) showed increasing inward radial deflection with each oscillation. Furthermore, it can be seen in figure 4B that this deflection begins to accumulate about the axial center of the tube, with larger portions showing greater inward radial deflections with each oscillation. This is due to the increased average pressure acting on the tube for the duration of the event which, as opposed to case (a), was relatively high due to the lower initial decrease in specimen volume. This phenomenon will be further discussed in the following section. Figure 4B also shows, along with figure 4C, the harmonic behavior of the specimen as it oscillates at a frequency of 259 Hz.

3.1.2 Pressure History

The normalized pressure histories at various points throughout the pressure vessel resulting from the partial implosion for the case (a) and case (b) are shown in figure 5A and 5B, respectively. Radial deformation histories extracted from the axial center of the specimens are superimposed over the respective pressure-time histories to illustrate the effect of specimen deformation. The pressure for both cases oscillated harmonically at a frequency equal to that of their respective radial oscillations obtained from DIC data, indicating that the frequency of oscillation of the pressure profile is governed by specimen deformation. The initial drop in normalized pressure (dP_n) at the axial center in case (a) was 2 times that of case (b). This difference in initial pressure

drop is reflected in the difference in initial inward deflection (8.6 mm for case (a), 5.3 mm for case (b)) between the two cases and can be attributed to the difference in instability pressure, since a higher critical buckling pressure provides more driving energy for a longer time. However, dP_n experienced at the ends of the pressure vessel in case (a) was 2.4 times that of dP_n in case (b). This is then reflected in the amplitude of subsequent oscillations, which were considerably greater than those of case (b). This result suggests that while the pressure change at the axial center is directly related to the change in radius of the specimen, the pressure change will increase with longitudinal distance from the specimen as fluid motion begins to play a bigger role in the pressure profiles.

Fig. 5 Normalized pressure-time histories at channel 1 (left end), channel 3, and channel 4 (axial center) for partial implosion cases in which (A) $P_1 = 2.34$ MPa and (B) $P_1 = 2.06$ MPa. The initial drop in normalized pressure, dP_n increases by 0.35 at the left end with the increase in instability pressure. The change in radius is superimposed over pressure history to illustrate the coupling between specimen deformation and pressure

It was noted in the previous section that case (b) experienced progressive inward radial deformation with each oscillation, while case (a) did not. To understand the mechanism behind this phenomenon, it is important to understand the pressure acting on the specimen itself. As the pressure-time history given by Channel 4 is taken very close to the specimen, it can be assumed to be the pressure acting on the specimen. For case (a), it is shown in figure 5A that the normalized pressure near the specimen dropped to 0.6 and oscillated in unison with specimen deformation. For case (b), figure 5B shows that similar pressure oscillations occurred but with lower amplitude. However, because the normalized pressure dropped to 0.8, higher magnitude pressures were imposed on case (b) throughout the instability process than on case (a). Taking the mean normalized pressure acting on the specimens between time $t = 0$ ms and $t = 20$ ms gives 0.62 and 0.79 for case (a) and case (b), respectively. This equates to an average pressure of 1.45 MPa for case (a) and 1.63 MPa for case (b). Thus, while greater amplitudes of deformation and pressure oscillations are seen in case (a), the lower magnitude of ambient pressure acting on the specimen allows it to recover more and more with each oscillation, and the greater ambient pressure acting on the specimen in case (b) results in cumulative radial deformation.

Furthermore, it was seen that the amplitudes of all dR and pressure curves shown in figure 5 decay with time in a logarithmic manner. As such, the average damping coefficient ζ of these curves can be written as a function of the average logarithmic decrement δ according to the equation $\zeta = \frac{\delta}{2\pi}$, where δ is a function of the first amplitude A_o and the n^{th} amplitude A_n of a signal defined by $\delta = \frac{1}{n} \ln\left(\frac{A_o}{A_n}\right)$. Considering

first case (a), ζ for the dR curve extracted at the axial midpoint of the specimen was 0.039. For the same case, ζ for the pressure history taken at channel 1 was determined to be 0.032. For case (b), ζ was higher, with the dR curve exhibiting a ζ of 0.058 and the pressure history at channel 1 exhibiting a ζ of 0.0635. For each respective case, the decay of pressure and structural oscillations can be described by nearly the same ζ , further indicating (along with identical frequencies of oscillation) that there is a direct correlation between structural deformation and pressure oscillations. Aside from geometry and material parameters, it should be noted that both the damping coefficient and frequency of oscillation are a function of two variables: damage experienced by the specimen during the instability event *and* the ambient pressure in which oscillations occur. The greater P_l and deformations experienced by case (a) would indicate that the specimen experienced more damage than in case (b), however the fact that case (a) oscillated about a lower ambient pressure, 1.45 MPa, as compared to case (b), which oscillated about a pressure of 1.63 MPa, makes it hard to identify the exact relationship between damage, ambient pressure, frequency of oscillation, and ζ .

3.2 Full Implosion

Full implosion occurs in a limited-energy environment when the specimen is subjected to a critical hydrostatic buckling pressure P_c such that instability is initiated, and the energy in the system is sufficient to continue radial inward deformation until wall contact is reached. Full implosion experiments were conducted for carbon/epoxy tubes with unsupported lengths of 381 mm, 330.2 mm, and 279.4 mm. To ensure repeatability three experiments were conducted for each length case. It is important to

note that for all cases presented, time measurements are taken such that time $t = 0.00$ ms at wall contact.

3.2.1 DIC Results

A typical sequence of events seen in all full implosion cases is shown in figure 6A. The specimen experienced a certain amount of pre-deformation prior to collapse, as shown at time $t = -1.80$ ms. Due to the steady increase in hydrostatic pressure, deformation lobes began to form on the tube. Once the critical hydrostatic pressure was reached, the specimen began to deform radially inward, as shown at time $t = -0.96$ ms. At time $t = 0.00$ ms, the specimen achieves wall contact, and the buckle began to propagate longitudinally across the specimen. While the buckle propagated, shown at time $t = 0.67$ ms, the center of the tube began to recover, and once the buckle had propagated as far as it will, the rest of the tube showed recovery. This behavior is shown at time $t = 4.47$ ms, when the buckle front is ‘retreating’ back to the center of the tube. Finally, at time $t = 6.00$ ms the buckle was seen propagating and then retreating as the specimen continues to recover. Note that it was the decrease in potential energy with the onset of instability that allowed the specimen to recover, as otherwise the damaged material would be unable to recover with its critical buckling pressure still acting on it after implosion. This recovery behavior continued in an oscillating manner, recovering more and more with each oscillation. Taking the Fast Fourier Transform of radial displacement curves shows that the dominant frequency of this oscillation is 315 Hz for all specimens. It should be kept in mind that the post-collapse behavior of the specimen will be affected by many factors such as loss in stiffness and reflections from hammer-pulses at the ends of the confining chamber, and thus further work will aim to expand

on this frequency analysis and identify the physical mechanisms responsible for these oscillations.

Fig. 6 DIC data for full implosion cases showing (A) radial displacement data for a typical event at key moments, (B) the line segment taken along the length of the lobe used to extract radial displacement data which is then integrated with respect to time to provide velocity data for (C) 381 mm, (D) 330.2 mm, and (E) 279.4 mm length cases

Understanding the radial velocity behavior of the specimen walls is crucial because, assuming that the fluid-structure interaction is continuous, the fluid motion in the local area of the specimen will be identical to the motion of the specimen. Typical radial velocity data is extracted along the line shown by figure 6B, which follows the contour of the deforming valley. The velocity data extracted along this line is given for the 381 mm length, 330.2 mm length, and 279.4 mm length tubes by figures 6C, 6D, and 6E, respectively. Maximum inward radial velocities for each tube were 36 m/s, 32 m/s, and 19 m/s, respectively. For all full implosion cases, inward radial velocity reached a maximum near the axial center of the tube, and then decreased as the buckle propagated along the length of the tube. Furthermore, greater radial velocities resulted in more extensive damage throughout the specimen, which impaired its ability to recover after the implosion process. This in turn had a strong effect on the resulting pressure histories at the ends of the confining chamber, as will be discussed in the following section.

3.2.2 Pressure history

Representative pressure-time histories for the 279.4 mm case and the 381 mm case are shown in Figures 7A and 7B respectively at the sensor locations throughout the left section of the confining chamber and at the axial center of the confining chamber. The average change in radius (dR) over the entire viewable surface of the deforming specimen is included in these figures to allow for comparisons between global specimen deformation behavior and the resulting pressure profiles. At the axial center, a sudden decrease in pressure was observed as the specimen began to deform. Once the specimen achieves wall contact at time $t = 0.00$ ms, fluid motion was suddenly arrested, causing a pressure spike. This pressure spike was registered at all sensors throughout the

confining chamber, *except* for those located at the ends of the chamber due to the absence of water at these locations. For all cases, the implosion event drew water from the ends of the confining tube, creating a vacuum at these locations. This is apparent in the pressure-time history for every case, as the presence of the vacuum resulted in periods of near-zero pressure at the ends of the chamber, which will be referred to as endplate cavitation. Note that the duration of endplate cavitation differed with specimen length according to the amount of water displaced by the implosion event.

For 279.4 mm long specimens, endplate cavitation lasted for 1.3 ms while for the 381 mm long specimens, endplate cavitation lasted for 2.2 ms. Just prior to the formation of the vacuum, liquid in tension was observed as the water separated from the confining chamber walls, given by a drop in pressure below the line denoting endplate cavitation. Once the tube collapse was complete and momentum of water towards the axial center of the confining chamber had arrested, the pressure differential at the ends of the chamber caused this displaced water to accelerate back towards the ends of the confining chamber, creating a high amplitude pressure spike which acted on the endplate for about 2 ms. Meanwhile, as water began to move very rapidly away from the walls of the confining chamber, small cavitation bubbles formed and subsequently collapsed. In most full implosion events, these cavitation bubbles formed directly on the sensor surface. When these cavitation bubbles collapse, they resulted in very high amplitude pressure spikes seen in all plots. While the time duration of these pressure spikes was always very small and thus represented relatively low-energy events, they were seen to reach peaks up to 34.5 MPa. The full amplitudes of these spikes are not shown in Figure 7.

When comparing the 279.4 mm and 381 mm length cases, it can be seen that the pressure profiles at the axial center of the confining chamber were nearly identical. However, the longer tube resulted in smaller water hammer pressure spikes while the shorter tube length resulted in significantly larger water hammer pressure spikes. Post-mortem analysis reveals that longer specimens experienced significantly more damage throughout the implosion process, with increased bifurcation and intersection of major cracks which isolated large portions of material from the main structure of the tube. These damage mechanisms will be further discussed in the following section. Increased damage in the 381 mm long tube resulted in a lower post-implosion stiffness, visible

Fig. 7 Pressure-time histories from full implosion events showing pressures throughout left section of confining chamber and axial center for (A) 279.4 mm and (B) 381 mm length cases from (C) channel 1 and channel 4 sensor locations. The average change in radius is superimposed over pressure histories to illustrate the effect of specimen deformation behavior on pressure amplitude

from the relatively slow average recovery speed of 0.23 m/s shown by the average change in radius curve. Likewise, decreased damage in the 279.4 mm long tube allowed the tube to recover at a faster rate of 0.84 m/s after the implosion event. It was shown in the partial implosion case that the dynamic pressure measured throughout the pressure vessel was heavily dependent on the amplitude of structural oscillation in the deforming specimen, especially at the ends of the confining chamber. In full implosion, the magnitude of the hammer pulse is dictated by the amount of water displaced at the ends of the confining chamber and the velocity at which that water returns. Much like the partial implosion case, the recovering tube acts like a spring which, coupled with the pressure differential between the cavitation/liquid interface, forces water towards the ends of the confining chamber at a greater velocity. This is evident also in the subsequent pressure oscillations seen in figure 7A between time $t = 6$ ms and time $t = 8$ ms, and in figure 7B between time $t = 6$ ms and time $t = 10$ ms. In these regions, a greater amplitude in pressure is still observed in 279.4 mm tube, corresponding with its greater velocity of radial recovery.

3.2.3 Post-Mortem Analysis

An in-depth post-mortem analysis was conducted to understand the failure mechanisms at play in the implosion of carbon/epoxy tubes, and to identify how they vary with tube length and critical buckling pressure. Post-mortem images of 330.2 mm, 279.4 mm, and 381 mm long composite epoxy tubes are shown in Figures 8, 9, and 10, respectively, and highlight all visible failure mechanisms observed in this study. All specimens imploded in a mode 2 collapse, resulting in 4 major cracks; 2 at the lobes of the buckle (A) and 2 at the valleys (B). For cases of lower critical buckling pressure (P_c

= 3.28 MPa), shown in Figure 8, very little through-cracking is observed, and major cracks propagate at an angle mostly dominated by the exterior layup orientation ($\pm 15^\circ$). In these events, the majority of visible damage takes the form of delamination (C) and interfibrillar matrix cracking along the exterior layup orientation (D). For cases of high critical buckling pressure ($P_c = 4.66$ MPa, $P_c = 4.41$ MPa), large amounts of through-thickness cracking (E) is observed at the lobes along the exterior fiber orientation, and the angle at which the major valley cracks propagate becomes more influenced by the second outer-most layup orientation ($\pm 45^\circ$).

Fig. 8 Postmortem images of 330.2 mm carbon/epoxy tube, showing (A) major valley crack, (B) major lobe crack, (C) fiber delamination, (D) interfibrillar matrix crack propagation along the 15° layup orientation, (E) through-thickness cracking, and (F) fiber fracture propagating along the 45° layup. Relatively low critical buckling pressure resulted in less overall damage in this specimen

The fact that the second outer-most layup orientation plays a larger role in the behavior of the major valley cracks has a significant effect on the failure mechanics of the tube. Figures 9 and 10 show increased fracture in the outer fibers as failure propagates along the second-outermost fiber orientation (F). Furthermore, the steep angle of crack

propagation causes the major valley crack to approach the major lobe crack, causing the two to intersect (G). If these two cracks are through cracks, as shown in Figure 10, this intersection can separate a large portion of material from the tube structure (H), which can also lead to fiber pullout (I). Looking closely at this separated piece of material, it can be seen that the specimen also undergoes inter-lamina delamination (J).

Fig. 9 Postmortem images of 279.4 mm carbon/epoxy tube, showing (A) major valley crack, (B) major lobe crack, (C) fiber delamination, (D) interfibrillar matrix crack propagation along the 15° layup orientation, (E) through-thickness cracking, and (F) fiber fracture propagating along the 45° layup

When comparing specimens of differing length, it can be seen from figures 9 and 10 that the 381 mm long tubes experience more extensive through-thickness cracking along the lobes, and the major valley crack branches off to more surface areas. This allows it to intersect with the major lobe crack in more locations, in turn isolating larger amounts of material from the tube structure. These more extensive damage mechanisms at the valley can be attributed to the higher inward radial velocities experienced in this region during the implosion process, shown in figures 7D and 7E. The 279.4 mm long tubes

also experience branching along the major valley crack, but to a lesser degree. Because of branching, the major valley crack does intersect with the major lobe crack in some areas, however because of the reduced amount of through-thickness cracking, these intersections fail to isolate any large portion of material and thus the tube remains relatively intact.

Fig. 10 Post-mortem images of 381 mm carbon/epoxy tube, showing (A) major valley crack, (B) major lobe crack, (C) fiber delamination, (D) interfibrillar matrix crack propagation along the 15° layup orientation, (E) through-thickness cracking, (F) fiber fracture propagating along the 45° layup orientation, (G) the intersection of major lobe and valley cracks, (H) separation of large portions of material, (I) fiber pullout, and (J) inter-lamina delamination

4. Conclusions

A fundamental experimental study was conducted to understand the effects of partial and full implosion of carbon/epoxy composite tube specimens occurring in a limited-energy environment. During experiments, high-speed images were captured which, together with the application of 3-D DIC techniques, provided full-field displacement data for the surface of the specimens. Furthermore, dynamic pressure data

was captured at various points throughout the confining chamber to provide insight as to how the fluid interacted with the deforming shell and with the confining chamber. Finally, post-mortem analysis of full implosion specimens was conducted to further understand the failure mechanisms at play in the implosion of carbon composite tubes. Key findings from this study are presented as follows:

- (1) By increasing the volume and decreasing the critical buckling pressure of a composite tube subject to hydrostatic load in a limited energy environment, the energy available to drive implosion was decreased. As a result, dynamic instability events transitioned from a full implosion event, in which wall contact is achieved, to a partial implosion event, in which the specimen oscillates radially without achieving wall contact.
- (2) Partial implosions resulted in multiple pressure surges throughout the vessel, occurring at the exact same frequency at which the specimen oscillated. The amplitude of these oscillations increased considerably near the ends of the confining chamber.
- (3) The amplitudes of pressure oscillations in the partial implosion case were heavily dependent on instability pressure, with a 13% increase in critical buckling pressure causing a 400% increase in peak amplitude of pressure oscillations.
- (4) Full implosion resulted in pressure spikes at the end caps of the confining vessel due to the water hammer effect. The rapid motion of water at the ends of the

confining chamber also lead to the formation and collapse of small cavitation bubbles, which were low energy, high amplitude events.

- (5) Full implosion results in a significant decrease in hydrostatic pressure in the system which allows the imploded specimen to recover in an oscillating manner.
- (6) For full implosion, increased radial velocities during the implosion process increased damage in longer specimens, thereby greatly reducing the velocity at which the specimen could recover. This reduced velocity of recovery resulted in lower amplitude hammer pulses and subsequent pressure oscillations.

5. References

- [1] Mouritz AP, Gellert E, Burchill P, Challis K (2001) Review of advanced composite structures for naval ships and submarines. *Compos Struct* 53(1):21-42
- [2] Turner SE, Ambrico JM (2012) Underwater implosion of cylindrical metal tubes. *J Appl Mech* 80(1):1-11.
- [3] Gupta S, LeBlanc J M, Shukla A (2015) Sympathetic underwater implosion in a confining environment. *Extreme Mechanics Letters* 3:123-129
- [4] von Mises R (1914) The critical external pressure of cylindrical tubes *Zeitschrift des Vereines Dtsch. Ingenieure* 58(19):750-767
- [5] von Mises R (1929) The critical external pressure of cylindrical tubes under uniform radial and axial load. *Stodola's Festschrift* 418-430
- [6] Urick R J (1963) Implosions as sources of underwater sound. *J Acoust Soc Am* 35(12):2026-2027
- [7] Orr M, Schoenberg M (1976) Acoustic signatures from deep water implosions of spherical cavities. *J Acoust Soc Am* 59(5):1155-1159
- [8] Cartlidge E (2001) Accident grounds neutrino lab. IOP Publishing Physicsworld. <https://physicsworld.com/a/accident-gro>
- [9] Farhat et al. (2103) Dynamic implosion of underwater cylindrical shells: experiments and computations. *Int J Solid Struct* 50:2943-2961
- [10] Gupta S, Matos H, Shukla A (2016) Pressure signature and evaluation of hammer pulses during underwater implosion in confining environments. *J Acoust Soc Am* 140(2):1012-1022
- [11] Gupta S, LeBlanc J M, Shukla A (2014) Mechanics of the implosion of cylindrical shells in a confining tube. *Int J Solid Struct* 51:3996-4014
- [12] Koudela K L, Strait L H (1993) Simplified methodology for prediction of critical buckling pressure for smooth-bore composite cylindrical shells. *J Reinforced Plastics and Composites* 12:570-583
- [13] Moon et al. (2010) Buckling of filament-wound composite tubes subjected to hydrostatic pressure for underwater vehicle applications. *Compos Struct* 92(9):2241-2251
- [14] Smith et al. (2009) Collapse of composite tubes under uniform external hydrostatic pressure. *J Phys Conf Ser* 181(1):156-157
- [15] Ross CTF et al. (2009) Buckling of carbon/glass composite tubes under uniform external hydrostatic pressure. *Strain* 47(s1):156-174

- [16] Pinto et al. (2016) Experimental investigation on underwater buckling of thin-walled composite and metallic structures. J Pres Ves Tech 138:060905
- [17] Pinto M, Gupta S, and Shukla A (2014) Study of carbon/epoxy composite hollow cylinders using 3-d digital image correlation. Compos Struct 119:272-286
- [18] Pinto M, Gupta S, and Shukla A (2015) Hydrostatic implosion of GFRP composite tubes studied by digital image correlation. AMSE J Pressure Vessel Technol 137(5):051302
- [19] Kyriakides S and Corona E (2007) Mechanics of offshore pipelines: buckling and collapse. Jordan Hill, Oxford

CHAPTER 2:

To be submitted to an academic journal

Implosion of Composite Tubes in an Open-Ended Confining Structure

by

Christopher J Salazar and Arun Shukla

Corresponding Author:

Arun Shukla

Dynamic Photo-Mechanics Laboratory

Department of Mechanical, Industrial and
Systems Engineering

University of Rhode Island

Kirk Applied Engineering Bldg., 94 Upper
College Rd Kingston, RI 02881, USA

Phone: +1 (401) 874-2283

Email address: shuklaa@uri.edu

Abstract

The results, findings, and analytical investigation of an experimental study conducted on the hydrostatic implosion of filament wound carbon fiber epoxy composite tubes within partial confinement are presented. Implosion in geometries varying in length and diameter was initiated within a tubular confining structure with one end closed and one end open to a free-field, hydrostatic environment. Structural deformation behavior was captured and quantified using high speed cameras in conjunction with 3D digital image correlation (DIC). Water hammer pulses resulting from implosion are measured at various locations in the confining chamber and are shown to behave as a damped harmonic oscillator. Water hammer behavior is thus experimentally characterized for each geometry by determining average values of amplitude ΔP_{max} , frequency of oscillation f , and damping ratio ζ . It is shown that f decreases with increasing implodable volume to confinement volume ratio V_i/V_c , and is theoretically determined with excellent correlation to experimental results. Finally, amplitude of oscillation ΔP_{max} is theoretically determined and used in conjunction with theoretically determined f and experimentally determined ζ to fully define the hammer wave oscillations resulting from partially-confined implosion.

Nomenclature

The following nomenclature contains all variables and constants that appear throughout this manuscript, tabulated alongside their respective definition, units, and value. Note that only constants are assigned values. Furthermore, all variables which are considered constant for calculation purposes, such as temperature T , are also assigned values.

Variable or Constant	Definition	Units	Value (if constant)
A	Cross-sectional area of confining chamber	m^2	0.0248
C_f	Wave speed in a fluid	m/s	-
C_{mix}	Wave speed in a fluid-gas mixture	m/s	-
C_{pc}	Wave speed resulting from a partially-confined implosion event	m/s	-
C_w	Wave speed of water	m/s	1,440
D_c	Diameter of confining chamber	m	0.1778
E_{ac}	Young's Modulus of Acrylic	Pa	3.17e9
E_{al}	Young's Modulus of Aluminum	Pa	69e9
E_h	Hydrostatic potential energy	J	-
F	Energy flux due to 1-d compression wave	J/m^2	-
f	Frequency of oscillation	Hz	-
h_c	Wall thickness of confining chamber	m	0.0254
h_i	Implodable wall thickness	mm	~1.65
K	Bulk Modulus	Pa	-
K_{air}	Bulk Modulus of air	Pa	142e3
K_{mix}	Bulk Modulus of a fluid-gas mixture	Pa	-
K_{water}	Bulk Modulus of water	Pa	2.2e9
L_{ac}	Length of acrylic section	m	0.152
L_{al}	Length of aluminum section	m	0.965
L_c	Total length of confining chamber	m	1.117
M_{air}	Molar mass of air	Kg/mol	0.029
m	Mass of air contained in implodable volume	Kg	-

P_c	Critical buckling pressure	Pa	-
P_l	Hydrostatic pressure of a liquid	Pa	-
R	Gas constant	$\frac{J}{mol \cdot K}$	8.314
R_c	Radius of confining structure	m	0.089
R_s	Shockwave standoff distance	m	-
T	Temperature	K	293
t	Time	s	-
t_1	Lower time limit of integration	s	-
t_2	Upper time limit of integration	s	-
V_{air}	Volume of air within confinement once pressurized to P_c	m^3	-
V_c	Volume contained by confining structure	m^3	0.028
V_i	Volume contained by implodable structure	m^3	-
V_g	Volume of gas trapped in a pipeline	m^3	-
V_l	Volume of liquid in a pipeline	m^3	-
V_{water}	Volume of water within confinement once pressurized to P_c	m^3	-
v_o	Initial velocity	m/s	-
β_w	Compressibility of water	m^2/N	4.6e-10
ΔV_{air}	Change in volume of air within confinement	m^3	-
ΔV_{mix}	Change in volume of fluid-gas mixture	m^3	-
ΔV_{water}	Change in volume of water within confinement	m^3	-
ΔP_{max}	Maximum overpressure resulting from a partially-confined implosion event	Pa	-
$\Delta P(t)$	Dynamic pressure as a function of time	Pa	-
ξ	Damping ratio	-	-
τ	Period of oscillation	s	-
ρ	Density	Kg/m^3	-
ρ_{air}	Density of air at atmospheric pressure	Kg/m^3	1.225
ρ_{mix}	Density of liquid-gas mixture	Kg/m^3	-
ρ_{water}	Density of water	Kg/m^3	997
ω	Radial frequency of oscillation	rad/s	-

1. Introduction

The results, findings, and analytical investigation of an experimental study conducted on the hydrostatic implosion of filament wound carbon fiber epoxy composite tubes within partial confinement. The term “partial confinement” refers to a tubular confining structure that is closed on one end and open to free-field pressurized environment on the other. This differs from full confinement which is closed on both ends, thus limiting the energy available to drive implosion [1,2]. Implosion experiments are conducted using filament wound carbon/epoxy composite tubes of varying implodable volume to confinement volume ratios.

An implosion event begins when a closed, hollow structure of lower internal pressure is submerged in a medium of higher pressure such that the differential results in instability in the structure walls, causing it to collapse inwards on itself. When this occurs underwater, the fluid surrounding the imploding volume experiences a sudden increase in velocity as it rushes in to fill the newly-created void. When the implosion process is complete, fluid motion is suddenly arrested, converting kinetic energy into strain energy in the fluid which propagates outward as a compression wave and can damage or even initiate the implosion of nearby structures [3, 4]. One example of the danger posed by the pressure pulse resulting from implosion event is the disaster at Japan’s Super-Kamiokande neutrino observatory. In 2001, the implosion of a single photomultiplier tube resulted in a chain reaction of implosion, leading to the destruction of nearly 7000 tubes and causing \$20-\$30 million in damage [5]. The problem of implosion has been a topic of study for many decades, with the first closed-form expressions for the critical

buckling pressure, or P_c of a cylindrical shell under uniform radial and axial compression having been derived by von Mises in the early 1900's [6,7].

The mechanics and fluid-structure interaction of implosion in free-field conditions have been well-established for metallic tubes [3,8-10] and composite shell and double-hull structures [11-13]. In one study [3], Turner and Ambrico divided the implosion process of metallic cylinders into 4 main stages, summarized as follows: (1) the initial under pressure region prior to wall contact, shown by a smooth decrease in local pressure; (2) the moment of wall contact, in which the walls of the cylinder make contact at a point and accompanied by a sudden spike in local pressure; (3) point contact propagates outwards across the diameter of the cylinder, accompanied by a large increase in pressure; and (4) buckle propagation, in which the buckle propagates outward along the length of the cylinder and is accompanied by a decay in local pressure, finally completing the implosion. The implosion of composite shells generally follows a similar process, however exhibits various failure mechanisms including matrix cracking and through-thickness fracture at the lobes which significantly affect the resulting dynamic pressure history. It was shown by Pinto et al. that simply changing the architecture of glass fiber reinforced polymer (GFRP) tubes from filament wound to braided greatly reduced the maximum overpressure resulting from implosion at equal P_c [11]. Furthermore, it was shown by Pinto et al. in a direct comparison of the implosion of aluminum, GFRP, and carbon composite tubes that composite tubes release the most energy during implosion, followed by aluminum and then GFRP [14].

Fewer studies have been conducted on the implosion of metallic structures within fully and partially-confined environments. It was shown by Gupta et al. that the mechanics

of implosion of metallic cylinders within full confinement differs substantially from implosion within a free-field environment due to the limited energy available to drive collapse [1]. Then, studies conducted by Matos et al. [15] and Gupta et al. [16] showed that the hydrostatic and shock-initiated implosions of metallic tubes within partial confinement resulted in a large hammer pulse of significant impulse which oscillated throughout confinement at a frequency close to that predicted by water hammer theory. Most recently, Salazar and Shukla [2] conducted a study on the implosion of composite structures within full confinement, showing that if the energy contained by the volume of water bounded by the confining structure was not sufficient to drive a full collapse, a phenomenon known as partial implosion would result. Partial implosion events resulted in an arrest in the implosion process, causing structural oscillations which in turn resulted in pressure oscillations of the same frequency to propagate throughout the length of the confining structure [2]. To date, no studies have been conducted on the implosion of composite structures within partial confinement, and this study aims to address this gap in knowledge.

Since partial implosion can be initiated in composite implodables within confining structures, some of the implodable structures in the present study were designed to implode with minimal energy available within the volume of water bounded by partial confinement. This resulted in a phenomenon known as implosion with dwell, in which the structure began to implode, paused due to lack of sufficient driving energy available in the immediate surroundings, then continued as energy was made available from the open end of confinement. All implosion events detailed in the current study resulted in large pressure pulses due to the water hammer effect. It is observed that the water

hammer pulse behaves as a damped harmonic oscillator defined by amplitude ΔP_{max} , frequency of oscillation f , and damping ratio ξ . As such, the dynamic pressure histories resulting from implosion are characterized by experimentally identifying these parameters. Finally, theoretical expressions which define ΔP_{max} and f are developed and presented, and correlate well with the experimental results.

2. Experimental Procedure

Implosion experiments were conducted in a state-of-the art pressure vessel facility equipped with dynamic pressure transducers and optically-clear windows which allow for the use of 3D digital image correlation (DIC). This section details the facilities used to create partial confinement conditions within a hydrostatic loading environment, and presents tabulated geometric data which fully describe the filament wound carbon/epoxy tubes used. Finally, a brief discussion is given which validates the use of DIC in the complex underwater environment described, and quantifies any expected error.

2.1. Pressure Vessel Facility with Partial Confinement

Implosion events were initiated within a 1.12 m (44.0 in) long, 178 mm (7.0 in) inner diameter cylindrical confining structure with a wall thickness of 25.4 mm (1 in). The structure is cylindrical in shape, open on one end and closed on the other, and placed inside the 2.1 m semi-spherical pressure vessel as shown in Fig. 1A, 1B, and 1C. The confining structure is constructed of three modular sections which are stacked concentrically: the upper section which is open to the hydrostatic loading environment of the pressure vessel, the bottom which is closed to the environment of the pressure

vessel, and an optically clear acrylic middle section which is used to view the implodable structure. Five dynamic pressure transducers (PCB 138A05, PCB Piezotronics, Inc., Depew, NY) which record the pressures in the fluid during the event are located throughout the confining structure in the positions given by Fig. 1. The pressure vessel containing the confining and implodable structures is outfitted with optically clear windows located at the midspan of the vessel which allow for the capture of high speed images using two high speed cameras (Photron SA1, Photron USA, Inc., San Diego, CA). Photographs are captured at 30,000 frames per second through these windows and through the acrylic midsection of the confining structure at a resolution of 256 x 528 pixels, and are later used in conjunction with 3D digital image correlation (DIC) to provide radial displacement and other data pertaining to structural deformation of the implodable.

Fig. 1 Experimental setup showing (A) top view of 2.1m semi-spherical pressure vessel with viewing windows, high-speed cameras, light sources, implodable and confining structures, (B) side view of 2.1m semi-spherical confining structure with nitrogen gas pocket for pressurization, confining structure, and acrylic viewing window, and (C) Confining structure with composite implodable structure, acrylic viewing window, and location of dynamic pressure transducers

To conduct implosion experiments, implodable structures were placed concentrically within the confining structure such that the axial midpoint of the implodable was in-line with the axial midpoint of the acrylic section. The hydrostatic pressure of the pressure vessel was slowly increased by pressurizing a small void at the top of the vessel with nitrogen gas until the critical buckling pressure P_c of the implodable structure was reached. High-speed photographs of the resulting structural deformations, as well as pressure data throughout the confining structure were recorded by the facilities described above.

2.2. Composite Tube Specimens

The specimens used in implosion experiments were cylindrical tubes made of filament wound carbon/epoxy composite organized in a $[\pm 15/\sim 90/\pm 45/\pm 15]$ layup (Rock West Composites UT) which resulted in a wall thickness (h_i) of about 1.65 mm (0.065 in). In order to investigate the effect of implodable geometry on the pressure histories resulting from an implosion event within partial confinement, experiments were conducted using tubes of 41.3 mm (1.625 in) and 63.5 mm (2.5 in) outer diameter (OD) and of unsupported lengths (L_i) of 279.4 mm (11 in), 330.2 mm (13 in), and 381.0 mm (15 in). Thus, six total geometries were used in the study, and as three implosion experiments were conducted for each geometry, a total of eighteen experiments were conducted. Throughout this manuscript, implodable volumes of 63.5 mm OD and 41.3 mm OD will be referred to as Case A and Case B, respectively. Furthermore, each specimen geometry will be referred to as geometry or tube A or B, as per its OD, followed immediately by 28, 33, or 38, which refers to the length of the tube rounded to the nearest centimeter. Thus, a tube of 41.3 mm OD that is 330.2 mm in length will

be referred to as to as geometry B33 or tube B33. Average measured geometric values, including implodable radius R_i , unsupported length L_i , implodable wall thickness h_i , and implodable to confinement volume ratio V_i/V_c given as a percentage are given for each geometry in table 1. Note that the term V_i refers to the volume of air bounded by the implodable structure's walls, and does not account for wall thickness. Due to insignificant variations in V_i/V_c between tubes of the same geometry, no standard deviation is given for this value. Also given are the experimentally-obtained critical buckling pressure P_c and confinement energy E_c , which represents the strain energy stored in the volume of water bounded by the confining structure at the moment of implosion. The confinement energy is calculated according to the following equation:

$$E_c = \frac{\beta_w P_c^2}{2} (V_c - V_i) \left(1 + \frac{P_c}{K_w}\right) \quad (1)$$

Where β_w is the compressibility of water and K_w is the bulk modulus of water.

Table 1 Average geometric values and experimentally-obtained P_c and E_c for all implodable geometries

Tube Name	Radius R_i (mm)	Unsupported Length L_i (mm)	Thickness h_i (mm)	$\frac{V_i}{V_c}$ (%)	Buckling Pressure P_c (MPa)	Confinement Energy E_c (J)
A28	31.8 (± 0.01)	279.9 (± 0.10)	1.66 (± 0.01)	2.89	2.03 (± 0.03)	25.6 (± 0.70)
A33	31.8 (± 0.01)	330.6 (± 0.10)	1.67 (± 0.01)	3.40	1.56 (± 0.01)	14.9 (± 0.13)
A38	31.8 (± 0.01)	381.5 (± 0.27)	1.64 (± 0.02)	3.93	1.22 (± 0.01)	9.11 (± 0.21)
B28	20.7 (± 0.03)	278.4 (± 1.01)	1.67 (± 0.01)	1.14	3.16 (± 0.12)	63.2 (± 4.75)
B33	20.6 (± 0.02)	331.1 (± 0.38)	1.61 (± 0.02)	1.35	2.80 (± 0.04)	49.3 (± 1.42)
B38	20.6 (± 0.02)	380.8 (± 0.40)	1.63 (± 0.02)	1.56	2.68 (± 0.05)	45.3 (± 1.77)

It is important to note that in order to determine average wall thickness values, thickness measurements are taken at evenly spaced increments along the circumference of the ends of each tube (12 points for 41.3 mm OD tubes, 16 points for 63.5 mm OD tubes). Using this data, it can be determined with good consistency for 41.3 mm OD tubes that the buckling mode shape forms with the line of greatest outward radial deformation

(lobe) along the line of least average h , and with the line of greatest inward radial deformation (valley) along the line of greatest average value of h . For tubes of 63.5 mm OD, however, this behavior is differed significantly. It was consistently noted that tubes of 63.5 mm OD collapsed with the valley along the line of least global h . As a result, collapse orientation can be concluded to be governed by both variations in wall thickness and average radius for the filament wound carbon/epoxy composite tubes used in this study.

2.3. Validation of DIC Methods in a Complex Underwater Environment

It has been well-established that 3D DIC is valid for submerged objects viewed through a window so long these additional media (water and window) are included in the calibration process [9]. The experiments conducted for this study required a third media, a curved acrylic viewing window (see Fig. 1) in which lay the possibility for distortion of the object being viewed by high-speed cameras. A process was developed by Senol et al [17] to minimize the error induced by a curved viewing window surrounded by air and filled with water. The resulting errors were no greater than 4%. Thus, a similar scheme was adopted in this work in which the calibration procedure described in [9] was conducted without the curved acrylic window in place, and then DIC measurements of the object in question taken with the inclusion of the curved window. To validate this procedure over a range of tube radii, a rigid cylinder of sequentially varying radii was manufactured, painted with a high-contrast speckle pattern, and the DIC-measured radius of each section compared to its true radius. The cylinder is shown behind the acrylic window in Fig. 2A, alongside the comparison of DIC to true values shown in Fig. 2B. Radii $R_1 - R_5$ are labeled, and range from 9.6 mm

to 28.7 mm. A linear regression line is fitted to all points measured, yielding a slope of $S = 0.95$, meaning there is an average correspondence of DIC-measured radius values to true values of 95%. As this is within experimental error, data obtained from DIC measurements can be considered to be accurate. Furthermore, a correspondence of 95% indicates that on average, DIC-measured values were slightly smaller than true values. As a final precaution, radius measurements of the implodable structure itself were taken prior to every experiment and compared to true radius values. Of these measurements, none deviated more than 5% of the true radius value of the tube implodable structure.

3. Experimental Results

Partially-confined implosion experiments were conducted in the state-of-the-art pressure vessel facility described in section 2 in conjunction with carefully-placed dynamic pressure transducers and the DIC technique. Pressure transducers allowed for the capture of pressure-time data throughout the implosion event, and radial

Fig. 2 Validation of DIC measurements taken through multiple media, showing (A) rigid cylinder of varying radii R_1 to R_5 viewed through curved acrylic window and (B) DIC-measured radius values plotted against true radius values alongside corresponding error values

displacement data and velocity data taken at the surface of the imploding structure were made available from 3d DIC. Note that dynamic pressure, or $\Delta P(t)$, is given as the deviation from P_c . Thus the hydrostatic pressure is equal to P_c when $\Delta P(t)$ is zero, and the hydrostatic pressure is equal to absolute zero when $\Delta P(t)$ is equal to $-P_c$. Note further that in this manuscript, radial deformation towards the axial center of the implodable is denoted as negative (-), while radial deformation away from the axial center of the implodable is denoted as positive (+). These will be referred to as inward dR and outward dR , respectively.

3.1. Water Hammer Behavior

In all cases, implosion within partial confinement resulted in an initial drop in hydrostatic pressure at all locations within confinement which will be referred to the initial under pressure region. This is due to the decrease in implodable volume and results in fluid flow into the confining chamber from the open end. When the imploding

Fig. 3 Water hammer pressure oscillations taken from channel 2 resulting from the partial implosion of implodable geometry B28. Water hammer oscillation is seen to behave as a damped harmonic oscillator, defined by amplitude ΔP_{max} , frequency f , and damping ratio ξ

structure achieves wall contact, fluid motion stopped abruptly and kinetic energy was suddenly converted into strain energy in the water, resulting in a large pressure spike resulting in an over pressure region which will be referred to as the hammer pulse. With analogy to pipe flow mechanics, this behavior is akin to opening a valve long enough for a volume of water equal to the volume of the implodable V_i and with hydraulic head equal to P_c to pass through the duct, then closing the valve suddenly. In all pressure time histories shown in this section, time $t = 0$ at the moment the maximum pressure is observed anywhere in the confining chamber. This maximum over pressure, due to the water hammer effect, will be referred to as ΔP_{max} . It was noted that all dynamic pressure histories observed at channels 1-4 behave generally as a damped harmonic oscillator, described by the equation:

$$\Delta P(t) = \Delta P_{max} e^{-\zeta \omega t} \cos(\omega t) \quad (2)$$

Where ζ is the damping ratio and ω is the radial frequency of oscillation (equal to $2\pi f$, where f is the frequency of oscillation). To illustrate the manner in which these parameters are present in a typical water hammer pulse resulting from implosion, Fig. 3 gives the dynamic pressure taken at channel 2 from implodable geometry B28, annotated with all parameters required to define $\Delta P(t)$ from equation (2).

While six implodable geometries were used in this study, there were no fundamental differences observed between geometries of the same case aside from variations in ΔP_{max} , ζ , and f . As such, this discussion will focus mainly on comparing and contrasting dynamic pressure history and structural deformation phenomena seen in the implosion of geometries A38 and B28, which are the largest and smallest tubes used in

this study. All representative dynamic pressure histories from each geometry can be found in Appendix C, attached to the end of this manuscript.

The oscillatory behavior of the hammer pulse seen in Figs. 4A and 4B shows significant differences between the pressure histories resulting from the largest tube in this study, tube A38, and the smallest tube in this study, tube B28. Note that the y-axis scales and time scales differ from Fig. 4A to Fig. 4B so that the finer features of pressure behavior can be seen. Furthermore, note that a black dotted line is plotted at $\Delta P = -P_c$ to indicate absolute pressure of 0 MPa. Upon initial inspection it can be immediately noted that there is a dramatic difference in the frequency of oscillation f between the two tubes. In fact, the average f of the dynamic pressure history resulting from the implosion of geometry A38 was about 115 Hz, less than half of that observed in geometry B28, which

Fig. 4 Dynamic pressure histories taken from channels 1-5 resulting from the implosions of (A) implodable geometry A38 and (B) implodable geometry B28, which are the largest and smallest tubes used in this study, respectively. The dotted black line shows the point at which absolute pressure is equal to 0 MPa

was about 250 Hz. Generally, it was seen that the frequency of oscillation decreased as implodable volume ratio V_i/V_c increased, and it will be shown in section 4 that f is in fact a function of both P_c and V_i/V_c .

Another significant difference noted between Case A geometries and Case B geometries was that no Case A geometry dropped to 0 MPa during the initial under pressure region while all Case B geometries did. During the initial under pressure region, this phenomenon only occurs at the confinement floor, followed by a brief moment of liquid in tension as fluid separates from the confinement floor, usually lasting between 0.125 ms to 0.2 ms. This separation gives rise to the formation of cavitation at this location, shown by a brief dwell about 0 MPa before the pressure increases.

Implodable structures of Case A never reach 0 MPa in the initial under pressure region, however it can be seen in Fig. 4A that at about 2.4 ms, the second under pressure region does reach 0 MPa, at which point high frequency oscillations are observed until about $t = 6$ ms. At this point, the dynamic pressure proceeds into its second overpressure oscillation and the high frequency oscillations are no longer observed. This behavior was seen only in implodable geometries A38 and A33, with high frequency oscillations of the highest amplitude occurring in geometry A38. Furthermore, it should be noted that the pressure history given by channel 5 in Fig. 4A does indeed drop to 0 MPa and continues to oscillate near this point. This was a phenomenon which occurred in all Case A implodables, indicating the formation of cavitation at this location after the initial overpressure oscillation was completed. When this was first observed, two more dynamic pressure sensors were included at the open end of confinement, each located 31.75 mm (1.25 in) from either side of the sensor given by channel 5. Each of these two additional sensors also captured similar behavior, indicating the formation of a cavitation bubble at least 31.75 mm in radius at the open end of the confining structure. This phenomenon was not seen to any degree in implodable geometries of Case B.

Finally, it should be noted that during the first under pressure region, all implodable geometries of Case A experienced a brief “dwell” period, in which inward dR slows, causing a brief decrease in the rate of pressure drop. This phenomenon is explained further in section 3.2.

3.2. Partially-Confined Implosion with Dwell

The term “implosion with dwell” is given to partially-confined implosion events in which the implodable structure is subject to P_c such that structural instability is initiated, however the energy contained in the fluid immediately surrounding the structure is insufficient to continue inward radial deformation, dR , and thus there is a brief delay in the collapse process. This delay only lasts until energy from the open end of the confining chamber arrives to the implodable structure, at which point inward radial deformation accelerates until wall-contact is achieved and the implosion process is completed. Note that all implodable structures of Case A exhibit this behavior. The energy available to drive collapse from the initiation of instability until the brief moment of dwell is equal to the strain energy in the pressurized volume of water contained by the confining chamber at the moment of implosion. This value, given as E_c , was defined by equation (1) in section 2 but is repeated here for the reader’s convenience:

$$E_c = \frac{\beta_w P_c^2}{2} (V_c - V_i) \left(1 + \frac{P_c}{K_w}\right) \quad (1)$$

Where β_w is the compressibility of water and K_w is the bulk modulus of water. E_c is calculated for all implodable volumes and tabulated alongside geometric data in table 1. Note that geometries of Case A had significantly less immediate energy available to drive collapse than geometries of case B. This is largely due to the fact that, all other

factors held constant, an increase in diameter of a tubular implodable structure will decrease P_c , which is the variable that contributes most to E_c . This decreased E_c resulted in a “dwell” effect that can be broken up into 3 primary stages: partial collapse, dwell, and buckle propagation.

The beginning of the partial collapse stage is not unlike the behavior of an implosion occurring under unconfined conditions prior to wall contact, in that inward radial acceleration is seen initiating at a point near the center of the tube and propagating axially outward. However, as E_c is converted into fluid motion and strain energy in the implodable structure, the strain energy available in the volume of water immediately surrounding the implodable decreases and inward radial deformation slows. The structure then enters the dwell stage, which begins with little to no radial deformation observed at the axial center. Then, inward radial acceleration begins to propagate axially from the end of the structure located nearest the open end of the confining structure. As seen in high-speed images, the end of the dwell phase was marked in all cases by the formation of a crack which occurs at the lobes of the implodable. Upon the sudden loss

Fig. 5 The stages of implosion with dwell as observed from (A) dR/dt data extracted from a line spanning the viewable length of the imploding tube and (B) dynamic pressure history taken from channels 1-3. All data is given for implodable geometry A38

of instability caused by the formation of the crack, the buckle propagation stage begins as the axial center of the tube accelerates inward until wall contact is achieved, bringing the center point to rest. The buckle front then propagates axially outward, eventually causing wall contact throughout the length of the tube and completing the implosion process.

The subtleties of the various displacements occurring throughout each stage along the viewable length of the structure are shown in detail by radial velocity dR/dt data taken from a line segment located at the valley of the implodable, given by Fig. 5A. Each stage, however, is also distinguishable from dynamic pressure data, especially at the locations measured by channels 1, 2, and 3. From the perspective of pressure data, the partial collapse stage is given by a gradual drop in pressure, the dwell stage is given by a leveling off at some hydrostatic pressure below P_c , and then the buckle propagation stage is given by a sudden decrease and subsequent high-magnitude spike in pressure. To illustrate this, a magnified view of Fig 4A is given by Fig. 5B showing only data taken at channels 1, 2, and 3, and divided into the corresponding sections much like Fig. 5A.

3.3. Model of $\Delta P(t)$ using Experimentally-Obtained Values

It can be seen from the pressure-time histories given by Fig. 3 that the water hammer pressure pulse generated from an implosion event behaves very similarly to a damped harmonic oscillator with amplitude equal to experimental $\Delta P_{max,n}$, frequency of oscillation f_n , and damping coefficient ξ_n . Note that n refers to the specific channel or location at which the pressure history in question was measured. This is important

especially with regards to the damping coefficient and maximum over pressure because, as will be shown, ξ_n and $\Delta P_{max,n}$ are dependent on location. Thus, if these parameters are extracted from experimental data, the pressure history at any location n measured by channels 1-4 can be modeled to take the following form:

$$\Delta P_n(t) = \Delta P_{max,n} e^{-\xi_n 2\pi f_n t} \cos(2\pi f_n t) \quad (3)$$

Note that this model only describes the pressure from time $t = 0$ onwards, as the under pressure region does not conform to the behavior of a damped harmonic oscillator. Furthermore, it is seen that the pressure history measured at channel 5 behaves much differently than those measured at channels 1-4, and thus will not be modeled according to equation (2).

To determine the value of $\Delta P_{max,n}$, one need simply to take the first maximum value from each channel n . The first step in determining the damping coefficient of $\Delta P(t)$ from experimental data is to determine the average logarithmic decrement, δ_n , given as:

$$\delta_n = \ln \frac{\Delta P_{1,n}}{\Delta P_{2,n}} \quad (4)$$

Where ΔP_1 and ΔP_2 are the values of two successive peaks in the decaying pressure signal. From δ_n , the damping coefficient can be given as:

$$\xi_n = \frac{1}{\sqrt{1 + \left(\frac{2\pi}{\delta_n}\right)^2}} \quad (5)$$

For each sensor location, the decay constant is determined for each oscillation and then these values are averaged to give a value of ξ_n for the entire signal. Using equations (4) and (5), f_n was determined for all dynamic pressure measured at channels 1-4 and for

all geometries, and is tabulated in tables 2 and 3 alongside corresponding $\Delta P_{max,n}$ values.

Table 2 Average experimental $\Delta P_{max,n}$ and ξ_n at each channel n for Case A implodable structures with standard deviations

	A28		A33		A38	
	$\Delta P_{max,n}$ (MPa)	ξ_n	$\Delta P_{max,n}$ (MPa)	ξ_n	$\Delta P_{max,n}$ (MPa)	ξ_n
Ch. 1	4.72 (± 0.471)	0.104 (± 0.007)	3.64 (± 0.410)	0.144 (± 0.013)	2.34 (± 0.243)	0.146 (± 0.015)
Ch. 2	4.93 (± 0.327)	0.107 (± 0.007)	3.63 (± 0.362)	0.139 (± 0.010)	2.41 (± 0.102)	0.154 (± 0.048)
Ch. 3	4.12 (± 0.235)	0.159 (± 0.050)	3.08 (± 0.216)	0.170 (± 0.010)	2.07 (± 0.210)	0.142 (± 0.012)
Ch. 4	3.02 (± 0.205)	0.213 (± 0.038)	1.95 (± 0.314)	0.179 (± 0.006)	1.41 (± 0.145)	0.178 (± 0.012)

Table 3 Average experimental $\Delta P_{max,n}$ and ξ_n at each channel n for Case B implodable structures with standard deviations

	B28		B33		B38	
	$\Delta P_{max,n}$ (MPa)	ξ_n	$\Delta P_{max,n}$ (MPa)	ξ_n	$\Delta P_{max,n}$ (MPa)	ξ_n
Ch. 1	4.45 (± 0.325)	0.107 (± 0.010)	4.48 (± 0.237)	0.108 (± 0.003)	4.31 (± 0.362)	0.116 (± 0.010)
Ch. 2	4.55 (± 0.375)	0.104 (± 0.019)	4.62 (± 0.097)	0.109 (± 0.019)	4.51 (± 0.512)	0.123 (± 0.033)
Ch. 3	4.04 (± 0.164)	0.122 (± 0.011)	3.55 (± 0.200)	0.127 (± 0.026)	3.27 (± 0.289)	0.117 (± 0.014)
Ch. 4	2.50 (± 0.197)	0.121 (± 0.056)	2.26 (± 0.310)	0.115 (± 0.032)	2.03 (± 0.381)	0.117 (± 0.013)

Note that the variances in the parameters presented in tables 2 and 3 are caused in part by the variances in collapse P_c , which is tabulated in table 1. The average experimental frequency of oscillation f_n can be determined simply by the equation:

$$f_n = I / \sum_{i=1}^I \tau_i \quad (6)$$

Where τ_i is the period of oscillation i , and I is the total number of full, distinguishable oscillations. For Case A, $I = 5$, and for Case B, $I = 6$. However, a more comprehensive understanding of the frequency behavior of the pressure histories resulting from a partially-confined implosion event can be determined by conducting a fast Fourier Transform of the pressure signal. Using a spline function to interpolate pressure data taken at channels 1-5 across the length of confining chamber, an array of pressure-time histories is produced, each of which are transformed into the frequency

domain using a fast Fourier Transform. The result is a color contour showing the contribution of each frequency as a function of axial position within confinement. Fig. 6 thus shows the interpolated pressure histories in the time and frequency domains for tube A38 and tube B28, with all contributions normalized to the maximum contribution seen at the confinement floor. Note that the position within confinement is given to be 0 mm at the confinement floor, and is equal to 1118 mm at the open end. As such, all frequencies contributing to the pressure signal in question can be determined, along with the location in which their contribution is most prominent.

In Fig. 6A it can be seen that the greatest contribution occurs at low frequency at the open end of the tube. This is due to the formation of a large cavitation bubble at this

Fig. 6 Dynamic pressure history maps presented in the time domain and frequency domain for (A) geometry A38 and (B) geometry A28. The dominant contributing frequency of oscillation for pressure oscillations within confinement is given by a white dotted line, and marked by f

region (discussed in section 3.1) which results in oscillations about 0 MPa. This low frequency, however, will not be considered for use in equation (3) as it is the aim of equation (3) to model only pressure histories at locations within confinement. After this low-frequency contribution, the frequency which contributes most to the pressure signal the frequency marked by the white dotted line in Fig. 7. As this value does not vary with position within confinement, it will be considered that $f_n = \text{constant} = f$ for use in equation (3). Thus f was determined for all geometries and is plotted against $\frac{V_i}{V_c}$, given as a percentage, for all experiments in Fig. 6.

Fig. 7 Experimental f is shown decreasing with implodable volume ratio

Finally, using $\Delta P_{max,n}$, ξ_n , and f_n obtained from experimental data, equation (3) can be used to model the dynamic pressure oscillations resulting from a partially confined implosion event. To demonstrate the ability of this method to recreate the pressure signals obtained from channels 1 and 3, the results from equation 3 are plotted over their respective dynamic pressure histories for implodable geometries A38 and B28 in Figs.

8A and 8B, respectively. Note that equation (3) is plotted from time $t = -\frac{\tau}{4}$ onwards to show that the entire initial overpressure region conforms well the proposed model.

As can be seen from Fig.8, the experimental model given by equation (3) correlates well with experimental data, and shows that the dynamic pressure history resulting a partially confined implosion event can indeed be modeled as a damped harmonic oscillator primarily dependent on the contribution of a single frequency. That is to say, that while it is clear from Fig. 6 that $\Delta P(t)$ is the result of the superposition of various phenomena occurring at frequencies other than f , these contributions are largely negligible and can be neglected for modeling purposes. This is especially important for the following discussion, in which ΔP_{max} and f are theoretically derived.

Fig. 8 Experimental models determined from equation (3) using experimental parameters from Tables 2 and 3 are given for dynamic pressure histories taken at channels 1 and 3 for (A) implodable geometry B28 and (B) implodable geometry A38

4. Discussion

As evident from the previous section, the pressure oscillations resulting from the implosion of a tube within partial confinement can be accurately modeled using experimentally-determined parameters when it is assumed that the dynamic pressure history $\Delta P(t)$ behaves as a damped harmonic oscillator, given by equation (2) which is repeated here:

$$\Delta P(t) = \Delta P_{max} e^{-\xi \omega t} \cos(\omega t) \quad (2)$$

Where ΔP_{max} is the maximum change in pressure, ξ is the damping coefficient, ω is the angular frequency of oscillation (equal to $2\pi f$, where f is the frequency of oscillation), and t is time. While ΔP_{max} , ξ , ω , and f can be determined easily from experimental data, conducting experiments is an extremely costly method of determining constants which can be resolved from a more fundamental, theoretical understanding of the problem. Of these parameters, those of most significance are ΔP_{max} and f , as these two parameters provide sufficient information to fully describe the first and strongest overpressure oscillation resulting from implosion. As such, it is the purpose of this section is to determine f and ΔP_{max} from the fundamentals of water hammer theory and by equations which describe the energy partition in a shockwave travelling through water. Theoretical values are then compared to experimental results. For reference, all variables and constants mentioned in this section are defined in the nomenclature located at the beginning of this manuscript.

4.1. Preliminary Considerations: The Water Hammer Effect

A water hammer event occurs in typical pipeline or duct of a given length when fluid passing through the duct at initial velocity v_o is brought to rest by sudden valve closure. For application to the case presented in this study, it will be considered that the confining chamber is the duct in question with length L_c . Furthermore, it can be considered that the flow of water into the confining chamber begins with the initiation of implosion at P_c and occurs at an average velocity of v_o . One complete cycle of a dynamic pressure oscillation due to the resulting hammer wave in a frictionless case is described [18].

The completion of the implosion event is analogous to sudden valve closure, and for the sake of this discussion will be considered to occur at time $t = 0$. At time $t = 0$, fluid is suddenly brought to rest at the closed end of the confining chamber, compressing the fluid causing a sudden increase in fluid pressure as kinetic energy is converted into strain energy in the water. This compression wave propagates as a planar wave towards the open end of the confining chamber at wave speed C_f , bringing fluid to rest as it passes. Once the compression wave has reached the open end of the confining tube at time $t = L_c/C_f$, the fluid within confinement is under additional pressure ΔP_{max} . This additional pressure causes an unbalanced condition at the open end of the confining structure since the pressure of the reservoir remains unchanged. This results in fluid flow back out of the confining chamber beginning at the open end, converting strain energy in the water to kinetic energy. This conversion of strain energy to kinetic energy continues toward the closed end of the confining structure at the wave speed C_f . The wave arrives at the end of the confining chamber at the instant $t = 2L_c/C_f$, at which point the hydrostatic

pressure everywhere in the confining chamber has returned to P_c , and the fluid is flowing out of the confining chamber at v_o .

Because of the closed boundary condition at the bottom of the confining chamber, no fluid is available to continue fluid flow and thus the fluid must be brought to rest by a low pressure wave equal to $-\Delta P_{max}$. Note that if the static pressure is not high enough to maintain a pressure of $-\Delta P_{max}$ above vapor pressure, cavitation will occur as seen in all experiments. The low pressure wave propagates towards the open end of confinement at the wave speed C_f , bringing the fluid to rest and arriving to the open end at time $t = 3L_c/C_f$. As the fluid in the confining chamber is now at a uniform pressure of $-\Delta P_{max}$, there is once again an unbalanced condition at the open end, causing fluid flow back into the pipe at velocity v_o , converting strain energy to kinetic energy at a rate of C_f down the length of confinement until the wave reaches the closed end at the moment time $t = 4L_c/C_f$. At this point the process is repeated, resulting the oscillatory

Fig. 9 Stages of water hammer oscillation occurring over one full period

behavior seen in experiments. Thus each over pressure oscillation lasts $2L_c/C_f$ seconds, and each under pressure oscillation lasts $2L_c/C_f$ seconds, and the total period of oscillation τ is $4L_c/C_f$ seconds. This entire process is illustrated by Figs. 9, where Fig. 9A shows the process at time $0 < t \leq L_c/C_f$, Fig. 9B shows the process at time $L_c/C_f < t \leq 2L_c/C_f$, Fig. 9C shows the process at time $2L_c/C_f < t \leq 3L_c/C_f$, and Fig. 9D shows the process at time $3L_c/C_f < t \leq 4L_c/C_f$.

4.2. Theoretical Determination of Frequency of Oscillation f

From standard water hammer theory, the pressure pulse resulting from a water hammer event must travel a length of 4 times the confinement length, or $4L_c$, in order to complete a full under pressure and overpressure cycle [18]. Thus, the frequency of oscillation of a wave travelling at the speed of sound in the fluid C_f can be given by equation (3):

$$f = \frac{C_f}{4L_c} \quad (3)$$

By definition, C_f is a function of the bulk modulus of the fluid K and the density of the fluid ρ , given by equation (4):

$$C_f = \sqrt{\frac{K}{\rho}} \quad (4)$$

It is commonly known that the speed of sound in water is $C_w = 1440$ m/s, however using equation (3) to determine C_f from the values of f plotted in Fig. 6 shows that the wave speed observed in partial implosion experiments ranged from about 1100 m/s to as low as about 500 m/s, with wave speed decreasing with increasing implodable

volume. According to work done by Kabori et al. and Pearsall [19,20], such a decrease in wave speed is to be expected in any fluid-air mixture. According to their work, the wave speed in such a mixture can be defined simply by equation 2 when the bulk modulus of the mixture K_{mix} and density of the mixture ρ_{mix} are defined by the properties and volume content of the mixture's constituents. By considering the volume contained within confinement to be a mixture of water and the air contained by the implodable V_i , the same method can be applied here. Beginning first with the definition of bulk modulus, K_{mix} can be written by equation (5), substituting in the confinement volume V_c and P_c for the change in pressure and so that:

$$K_{mix} = \frac{P_c}{\Delta V_{mix}} V_c \quad (5)$$

Where ΔV_{mix} can be expressed as the sum of the change in volume of each constituent, or:

$$\Delta V_{mix} = \Delta V_{water} + \Delta V_{air} \quad (6)$$

The change in volume of water can be determined simply from the definition of bulk modulus, such that:

$$\Delta V_{water} = \frac{P_c}{K_w} V_{water} \quad (7)$$

Where K_w is the bulk modulus of water, given to be 2.2 GPa, and V_{water} is equal simply to $V_c - V_{air}$. To determine V_{air} , it is assumed that during the implosion process, all of the air escapes the implodable and is subsequently pressurized to P_c . This is a valid assumption for the implosion of composite structures as the damage sustained by the structure is often sufficient to allow the air contained within to escape. The volume of

air within the confining chamber at P_c can thus be defined by the ideal gas law according to equation (8):

$$V_{air} = \frac{mRT}{P_c M_{air}} \quad (8)$$

Where m is the total mass of the air given by $m = V_i \rho_{air}$, R is the gas constant, T is the temperature in K, and M_{air} is the molar mass of air. Plugging equation (8) into the definition of bulk modulus gives the solution for ΔV_{air} , given by equation (8):

$$\Delta V_{air} = \frac{P_c}{K_{air}} \frac{mRT}{P_c M_{air}} \quad (9)$$

For a gas volume under hydrostatic compression, it can be shown that the bulk modulus is equal to the hydrostatic pressure. Thus, K_{air} is replaced with P_c , yielding equation (10):

$$\Delta V_{air} = V_{air} = \frac{mRT}{P_c M_{air}} \quad (10)$$

Thus, plugging in equations (6), (7), and (10) into equation (5) yields:

$$K_{mix} = \frac{P_c V_c}{\frac{P_c V_{water}}{K_w} + \frac{mRT}{P_c M_{air}}} \quad (11)$$

Now that the bulk modulus of the fluid-air mixture contained within confinement has been determined, the only variable necessary to determine the wave speed is ρ_{mix} , which is given simply by the rule of mixtures:

$$\rho_{mix} = \frac{V_{air}}{V_c} \rho_{air} + \frac{V_{water}}{V_c} \rho_{water} \quad (12)$$

Thus, the wave speed of the water-air mixture C_{mix} is given by:

$$C_{mix} = \sqrt{\frac{K_{mix}}{\rho_{mix}}} \quad (13)$$

The wave speed defined by equation (13) is valid for any water-air mixture contained by V_c which is pressurized to P_c and contains an unpressurized volume of air equal to V_i . However, the effect of the confining structure itself on wave speed has still not been considered. According to Tijsseling et al. [21], the wave speed of a fluid contained within a pipe made of segments of differing materials can be approximated by equation (14), which is a weighted average between coupled wave speeds in the aluminum section and the acrylic section. Thus, the final expression for the wave speed during a partially-confined implosion event, C_{pc} , is given as:

$$C_{pc} = \frac{L_{al}}{L_{al}+L_{ac}} \frac{C_{mix}}{\sqrt{1+\frac{D_c K_{mix}}{E_{al} h_c}}} + \frac{L_{ac}}{L_{al}+L_{ac}} \frac{C_{mix}}{\sqrt{1+\frac{D_c K_{mix}}{E_{ac} h_c}}} \quad (14)$$

Where the length of the aluminum and acrylic sections are given by L_{al} and L_{ac} , respectively, the elastic moduli of aluminum and acrylic are given by E_{al} and E_{ac} , respectively, the diameter of the confining chamber is given by D_c , and the thickness of the confinement walls are given by h_c . Carrying out the process defined by equations 4-13 for each implodable volume used in experiments, theoretical wave speeds are determined and plugged into equation (3) in place of C_f to determine the corresponding frequency. The resulting values are plotted against volume ratio (given as a percentage) in Fig. 10. Theoretical results are superimposed over experimental results to show the exceptional accuracy of predicted values.

Fig. 10 Experimentally obtained wave speed and frequencies compared with theoretically-determined wave speed and frequencies determined using K_{mix} and ρ_{mix}

4.3. Determination of Maximum Overpressure ΔP_{max}

Now that f has been determined, the only remaining parameter required to fully define the first overpressure period is ΔP_{max} , which, as will be shown, is dependent on f . In the derivation of the following expression for ΔP_{max} , it is important to note the following assumptions:

1. Pressure is maintained at a constant value, P_c , at the open end during the influx of water into confinement
2. Energy is conserved throughout the entirety of the first overpressure period
3. Pressure wave propagation is one-dimensional and planar, travelling only up and down the length of the confining chamber. This is the standard assumption in basic water hammer theory

4. Due to the planar nature of wave propagation, the area of the shock front is defined simply as πR_c^2 , the cross-sectional area of the confining chamber

When an implodable volume is subject to hydrostatic pressure from a liquid medium of unlimited driving energy, the hydrostatic potential energy, E_h , is limited only by the work that can be done on the volume by the hydrostatic pressure being applied. In the case of implosion, the hydrostatic pressure is P_c , the implodable volume is V_i , and thus E_h can be given by the equation:

$$E_h = P_c V_i \quad (15)$$

Note that equation (15) requires the first assumption stated above to be true, as otherwise this term would be $\int_{V_1}^{V_2} P(V_i) dV_i$, where $P(V_i)$ would be an unknown function. This assumption is validated based on the relatively little fluctuations in pressure seen at channel 5 during the first hammer wave oscillation. The hydrostatic potential energy is thus equal to the total influx of energy from the open end into confinement due to an implosion event, and is the maximum energy available to create the hammer pulse and cause fluid motion within confinement. According to Urik [22], the energy passing through one unit of surface area from time t_1 to time t_2 due to a one-dimensional planar compression wave, F , can be defined as:

$$F = \frac{1}{\rho c_f} \int_{t_1}^{t_2} (\Delta P(t))^2 dt \quad (16)$$

It is also noted by Chamberlin et al. [10] that a portion of the hydrostatic potential energy is converted to work in compressing the air bounded by the implodable volume, denoted by E_a . Assuming that all the air contained within the implodable volume is compressed

by pressure P_c (shown to be a valid assumption due to the accuracy of theoretical values of f , shown in Fig. 10) and assuming adiabatic compression, E_a can be given by the equation:

$$E_a = -\frac{m}{M_{air}} RT \ln \left(\frac{V_{air}}{V_i} \right) \quad (17)$$

Thus, multiplying the term F by the surface area of the shock front A , adding E_a , and considering the sum equal to E_h yields the energy balance resulting from the implosion of a partially-confined composite structure:

$$E_h = P_c V_i = AF + E_a \quad (18)$$

According to assumptions 3 and 4, the shock front is planar and thus for the case of partially-confined implosion within a tubular confining structure, A is defined as:

$$A = \pi R_c^2 \quad (19)$$

For the determination of ΔP_{max} in a water hammer wave resulting from a partially-confined implosion event, it is convenient to modify equation (2) by eliminating the damping term and considering a phase shift of $\frac{\pi}{2}$ for algebraic simplification. Thus the first overpressure region takes the form:

$$\Delta P(t) = \Delta P_{max} \sin(2\pi f t) \quad (20)$$

Where f is known from section 4.1. Furthermore, the period of oscillation τ can be easily determined from f , as $\tau = \frac{1}{f}$. Thus, the limits of integration for F can be given as the duration of the overpressure region, bounded by $t_1 = 0$ and $t_2 = \tau/2$. Also, it must be considered that the fluid through which the hammer wave is travelling is in fact a

water-air mixture contained by a duct composed of aluminum and acrylic segments. Thus, the terms ρ and C_f in equations (16) and (17) become ρ_{mix} and C_{cp} , which vary from implodable to implodable and are defined in section 4.1. Considering all of these substitutions and inserting equations (19) and (20) into equation (18) yields the relationship between ΔP_{max} and E_h :

$$E_h = P_c V_i = \pi R_c^2 \frac{\Delta P_{max}^2}{\rho_{mix} C_{mix}} \int_0^{\frac{\tau}{2}} \sin^2(2\pi f t) dt - \frac{m}{M_{air}} RT \ln\left(\frac{V_{air}}{V_i}\right) \quad (21)$$

Finally, evaluating the integrals from 0 to $\frac{\tau}{2}$ and solving for ΔP_{max} yields the closed-form expression:

$$\Delta P_{max} = \sqrt{\frac{4C_{pc}\rho_{mix}}{\pi R_c^2} \frac{P_c V_i + \frac{m}{M_{air}} RT \ln\left(\frac{V_{air}}{V_i}\right)}{\tau - \frac{\sin(2\pi f \tau)}{2\pi f}}} \quad (22)$$

Which, because $\tau = \frac{1}{f}$, reduces further to:

$$\Delta P_{max} = \sqrt{\frac{4fC_{pc}\rho_{mix}}{\pi R_c^2} \left[P_c V_i + \frac{m}{M_{air}} RT \ln\left(\frac{V_{air}}{V_i}\right) \right]} \quad (23)$$

Note that the value of ΔP_{max} determined by equation (23) is the maximum value of $\Delta P(t)$ possible in the confining chamber at time $t = 0$, and does not specify where this dynamic pressure will occur. However, it is seen consistently that for the experimental setup used for this study ΔP_{max} occurs at channel 2 (25.4 mm from the confinement floor), and thus can be assumed to occur within this vicinity. The ability to express ΔP_{max} in this way is a very powerful tool in the design of any structure which will be subject to hydrostatic loading and surrounded by partial confinement, as it allows for an array of parametric studies to easily be conducted. Such studies could determine

optimum implodable geometries which meet the design requirements of the structure while minimizing the risk posed to surrounding structures. Also necessary for such a study would be an accurate formulation for P_c , which can be determined for composite and metallic implodable structures based on material properties and geometries [6,7,23]. Using experimentally-obtained P_c and carrying out the entire process defined by equations (2-23) for each implodable structure used in this study to theoretically determine ΔP_{max} gives good agreement with experimental results, as seen in Fig. 11. Note, however, that while excellent agreement is seen for implodable volumes with P_c below 2 MPa, theoretical values begin to deviate from experiments values as P_c increases. This is likely due to two reasons. The first is that implodable volumes of high P_c (namely, all the volumes of 41.3 mm OD) experience much larger radial velocities than implodable volumes of lower P_c (all tubes of 63.5 mm OD). Unless cavitation forms between the surface of the implodable and the water, water can be assumed to be moving at the same velocity as the implodable. Thus, due to greater fluid velocities, turbulent

Fig. 11 Experimentally-obtained ΔP_{max} given alongside ΔP_{max} determined from equation (23), showing excellent agreement for low P_c , however deviating for higher P_c

flow and thus energy dissipated through turbulent losses are more likely. Second, it was noted in section 3 that implodable volumes of high P_c resulted in the formation of cavitation at the closed end of the confining chamber. Thus it is likely that the energy required for the change in phase necessary for cavitation was dissipated through this means, further increasing the deviation between experimental and theoretical P_c . This is to say that as P_c increases, partially confined implosion events exhibit more energy-dissipating phenomena which are not accounted for by equation (23). It should also be noted that losses due to fracture and delamination of the implodable structure have been neglected in equation (23), which also explains why theoretical ΔP_{max} is always greater than experimental ΔP_{max} .

Using the ΔP_{max} and f values defined in this section in equation (1), the strongest overpressure oscillations are plotted in Figs. 12A and 12B alongside experimental data taken at channel 2 for implodable geometries A38 and B28, respectively. Note that, because ξ was not theoretically determined in this section, the corresponding ξ from tables 1 and 2 are used.

Fig. 12 Dynamic pressure history calculated according to equation (1) using theoretically determined ΔP_{max} , theoretically determined f , and experimentally determined average ξ . Dynamic pressure histories are calculated for (A) implodable volume A38 and (B) implodable volume B28, and superimposed over experimental data taken from channel 2 for each respective geometry

Finally, it should be noted that the case derived in this section is identical to a case in which a closed valve of a piping duct containing a volume of gas V_g is suddenly opened for enough time to allow a volume of liquid V_l pressurized at pressure P_l to enter the duct, and then suddenly closed again. The only difference in this case is that V_l would be equal to V_g for the determination of f (equations 2-13) and V_l in equation (23), and P_c would be equal to P_l . Thus the range of applicability for the equations derived in this section expand beyond the case of implosion within partial confinement, and into the realm of pipeline analysis.

5. Conclusions

A comprehensive study of the failure mechanics and dynamic pressure histories resulting from the implosion of filament wound carbon/epoxy composite structures within an open-ended confining structure is presented. It was found that dynamic pressure oscillations can be described according to water hammer theory, and that the frequency of oscillation decreased as implodable to confinement volume ratio V_i/V_c increased. Dynamic pressure oscillations were seen to behave as a damped harmonic oscillator and was characterized according to the amplitude ΔP_{max} , frequency f , and damping ratio ξ for six implodable geometries. Using structural deformation data obtained from 3d DIC in conjunction with dynamic pressure data, a new collapse phenomenon called implosion with dwell was identified, and was observed when instability was initiated with low values of energy within confinement, E_c . Finally, a comprehensive theoretical analysis was conducted to determine the parameters ΔP_{max} and f with good correlation to experimental results. Important conclusions which can be drawn from this study are as follows:

1. Implosion of carbon/epoxy composite structures within an open-ended confining tube results in a large hammer pulse, which behaves as a harmonic oscillator and can be characterized according to amplitude ΔP_{max} , frequency f , and damping ratio ξ .
2. By decreasing the energy contained within the volume of water bounded by the confining structure, implosion with dwell can be initiated in composite implodable structures.
3. Implosion with dwell can be divided into three main stages: partial collapse, dwell, and buckle propagation.
4. The wave speed resulting from a partially-confined implosion event is in fact equal to the wave speed in a fluid-air mixture defined by the amount of air contained within the implodable volume, the volume of water bounded by the confining structure, and critical buckling pressure P_c . This allows for an accurate determination of frequency of oscillation f .
5. Using theoretically-determined frequency of oscillation f , the limits of integration necessary to define amplitude ΔP_{max} can be determined, and thus an energy balance can be used to determine ΔP_{max} with good agreement to experimental results

References

- [1] Gupta S, LeBlanc J M, Shukla A (2014) Mechanics of the implosion of cylindrical shells in a confining tube. *Int J Solid Struct* 51:3996-4014
- [2] Salazar C J, Shukla A (2018) Dynamic instability of anisotropic Cylinders in a pressurized, limited-energy underwater environment. *J Dyn Behav Mater* 4:425-439
- [3] Turner SE, Ambrico JM (2012) Underwater implosion of cylindrical metal tubes. *J Appl Mech* 80(1):1-11
- [4] Gupta S, LeBlanc J M, Shukla A (2015) Sympathetic underwater implosion in a confining environment. *Extreme Mechanics Letters* 3:123-129
- [5] Cartlidge E (2001) Accident grounds neutrino lab. IOP Publishing Physicsworld. <https://physicsworld.com/a/accident-gro>
- [6] von Mises R (1914) The critical external pressure of cylindrical tubes *Zeitschrift des Vereines Dtsch. Ingenieure* 58(19):750-767
- [7] von Mises R (1929) The critical external pressure of cylindrical tubes under uniform radial and axial load. *Stodola's Festschrift* 418-430
- [8] Farhat C, Wang K G, Main A, Kyriakides S, Lee L H, Ravi-Chandar K, Belytschko T (2013) Dynamic implosion of underwater cylindrical shells: Experiments and computations. *Int J Solids Struct* 50:2943-2961
- [9] Gupta S, Parameswaran V, Sutton M, Shukla A (2014) Study of dynamic underwater implosion mechanics using digital image correlation. *Proc R Soc Mah Phys Eng Sci* 470:20140576
- [10] Chamberlin R, Guzas E, Ambrico J (2014) Energy balance during underwater implosion of ductile metallic cylinders. *J Acoust Soc Am* 136:2489-2496
- [11] Pinto M, Gupta S, Shukla A (2015) Hydrostatic implosion of GFRP composite tubes studied by digital image correlation. *J Pressure Vessel Technol* 137:051302
- [12] Pinto M, Gupta S, Shukla A (2015) Study of implosion of carbon/epoxy composite hollow cylinders using 3-D digital image correlation. *Compos Struct* 119:272-286
- [13] DeNardo N, Pinto M, Shukla A (2017) Hydrostatic and shock-initiated instabilities in double-hull composite structures. *J Mech Phys Solids* 120:96-116
- [14] Pinto M, Matos H, Gupta S, Shukla A (2016) Experimental investigation on underwater buckling of thin-walled composite and metallic structures. *J Pressure Vessel Technol* 138(6):060905
- [15] Gupta S, Matos H, Shukla A, LeBlanc J M (2016) Pressure signature and evaluation of hammer pulses during underwater implosion in confining environments. *J Acoust Soc Am* 140(2):1012-1022

- [16] Matos H, Gupta S, Shukla A (2018) Structural instability and water hammer signatures from shock-initiated implosions in confining environments. *Mechanics of Materials* 116:169-179
- [17] Senol K, Shukla A (2018) Underwater mechanical behavior of closed cell PVC foams under hydrostatic loading through 3D DIC technique
- [18] Wylie B E, Streeter V L (1978) *Fluid transients*. McGraw-Hill, New York pp. 7 – 8
- [19] Kabori T, Yokoyama S, Miyashiro H (1955) Propagation velocity of pressure wave in pipe line. *Hiyachi Hydron* 37:33-37
- [20] Pearsall I S (1965) The velocity of water hammer waves. *Proc Inst Mech Eng* 180(5):12-20
- [21] Tijsseling A (2007) Water hammer with fluid-structure interaction in thick-walled pipes. *Compute Struct* 85(11-14):844-851
- [22] Arons A B, Yennie D R (1948) Energy partition in underwater explosion phenomena. *Rev Mod Phys* 20(3):519-536
- [23] Koudela K L, Strait L H (1993) Simplified methodology for prediction of critical buckling pressure for smooth-bore composite cylindrical shells. *J Reinforced Plastics and Composites* 12:570-583

Chapter 3: Topics for Future Study

It is of the nature of scientific research that the process of defining, investigating, and drawing conclusions from a problem results in just as many questions as answers. The investigations detailed in Chapter 1 and Chapter 2 of this thesis are no exception to this, and thus it is the purpose of this third and final chapter to identify some of the questions or topics brought to light by these investigations and suggest methods as to their solution. The topics discussed in this chapter are closely related to the topics of fully and partially-confined implosion, and as such will be divided into two sections: Topics for Fully-Confined Implosion and Topics for Partially-Confined Implosion.

1. Topics for Fully-Confined Implosion

Problem Statement #1: Determination of K_{mix} for Partial and Full Implosion events

In Chapter 2, it was shown that the behavior of the dynamic pressure history resulting from implosion events occurring within partial confinement was heavily dependent on the term K_{mix} , which is the bulk modulus of the gas-fluid mixture bounded by the confining structure. The gas in this mixture is the gas bounded by the implodable structure at critical buckling pressure P_c and fluid is the fluid bound by confinement by the time of implosion. By determining the theoretical K_{mix} and resulting wave speed C_f , it should be possible to predict the frequency of oscillation of dynamic pressure pulses resulting from implosion within full confinement, and by following a similar energy balance method shown in Section 4.3 of Chapter 2, it may be possible to fully define pressure oscillations.

Suggested Solution #1:

It was shown in section 4.2 of Chapter 2 that K_{mix} can be determined from the following equation:

$$K_{mix} = \frac{P_c}{\Delta V_{mix}} V_c \quad (1)$$

Where P_c is the critical buckling pressure, V_c is the total volume bounded by the confining structure, and ΔV_{mix} is equal to the total change in volume of the fluid-gas mixture. In the case presented in Chapter 2, catastrophic failure of the implodable structure was assumed and thus it was considered that the entire volume of air bounded by the implodable V_i was compressed to V_{air} by P_c . In the case of partial implosion, however, catastrophic failure is not seen, and thus it would be of interest to experimentally determine (from experimental wave speed C_f) how this affects the value of K_{mix} . This can be compared to any theoretical predictions, which could assume no compression of the air bounded by the implodable, or could attempt to predict the compression of the air. Furthermore, the process defined in section 4.2 of Chapter 2 could be applied to a full implosion case, and any discrepancies could be determined and analyzed.

2. Topics for Partially-Confined Implosion

Problem Statement #1: Investigation of Water Hammer Oscillations Little to no Interference from an Implodable Structure

It was noted in Chapter 2 that the amplitude of oscillation of dynamic pressure histories resulting from the implosion of composite structures in partial confinement can be estimated using the following energy balance:

$$E_h = P_c V_i = AF + E_a \quad (2)$$

Where E_h is the hydrostatic potential energy, AF is the radiated energy, and E_a is the energy required to compress the air bounded by the implodable structure. It was further stated in Chapter 2 that the energy balance does not consider losses, E_L , which are shown to increase with P_c . These losses can include turbulent losses, losses due to the formation of cavitation, and losses due to fracture in the implodable structure, E_F . While E_F can be crudely estimated based on the energy release rate G_{IC} of the composite material, the energy lost due to fracture could be better estimated experimentally, according to the following two methods.

Suggested Solution #1a:

Instead of using a composite implodable to initiate the water hammer oscillations, it would be beneficial to use a very brittle material such as glass, as this would ensure sudden and total loss of stiffness of the implodable upon implosion. As such, there should be very little to negligible energy lost to fracture in the event, and the pressure pulses resulting could be analyzed and compared to an implosion event using a composite structure at similar P_c to determine the energy lost in the composite structure.

Suggested Solution #1b:

This solution would require skilled signal processing, but would have the advantage of completely eliminating a structure which could absorb energy during implosion. Instead of using an implodable structure to create a change in volume at P_c and initiate a water hammer event, a small explosive could be used to generate a bubble of some volume V_i , which could be determined from the radius of the bubble using DIC. This would be primarily for validating the theory explained in Section 4 of Chapter 2, as large

hydrostatic pressures would be required to maintain a bubble size small enough to be unaffected by the confining structure. This technique would require skilled signal processing to filter out the incident and reflected pressure pulses resulting from the UNDEX event itself, as only the collapse of the bubble is of interest. This should not be impossible as the frequency of the hammer pulse resulting from the collapse of the bubble should be governed by water hammer physics, and thus can be predicted and used as an estimate for any filtering cutoffs.

APPENDICES

Appendix A: Fully-Confined Implosion of Water-Filled Aluminum Structures

This section details a series of three implosion experiments conducted within full confinement (see Chapter 1, section 2.2). Implodable structures were 6061 aluminum cylinders of 38.1 mm outer diameter, 1.39 mm wall thickness, and 279.4 unsupported length. It was the purpose of this series of experiments to understand the effect of implodable volume change ΔV on the water hammer pulse resulting at the ends of the confining structure. For this reason, it was essential to control the maximum possible dV during an implosion event. To accomplish this, each of the three implodable structures were filled with varying amounts of nearly-incompressible fluid (water) equal to 0%, 40%, and 80% of the structure's internal volume. As the volume of each implodable structure was 0.290 liters, each structure was filled with 0 liters, 0.116, and 0.232 liters of water, respectively. The volume of the water was determined from the mass of the water prior to filling each implodable structure. In the following discussions, the implodable structures will be referred to as V0, V40, and V80, respectively.

1. Experimental Details

Prior to being filled with water, each structure was painted with a high-contrast speckle pattern to enable the use of 3D digital image correlation (DIC), which provided real-time structural deformation data during the implosion process. Once filled with its respective volume of water and sealed with aluminum endcaps, each implodable volume was placed concentrically within the confining pressure vessel, such that the axial center of the implodable structure aligned with the center of the acrylic viewing window. The

confining chamber was then filled with water, and it was ensured that no air was trapped in the system. Hydrostatic implosion was initiated by increasing the pressure in the closed system using a hydrostatic test pump. Implosion triggered the capture of high-speed images from two Photron SA1 high speed cameras, recording at 30,000 frames per second, as well as the capture of dynamic pressure data from pressure transducers located at various points throughout the confining chamber. Of particular interest were the pressure histories taken at the axial center of the confining structure and the pressure history taken at the end of the confining chamber, where

2. Experimental Results

The dynamic pressure histories taken at channel 1 (left end of confining chamber) and channel 4 (axial midpoint of the confining chamber) are presented alongside radial displacement taken at the axial midpoint of the imploding structure, for each case. It is important to note that in the case of V0, dynamic pressure data was sampled at a rate of 25 kHz, while in the cases V40 and V80 the sampling rate was 1 MHz. Note further that in this section, radial deformation towards the axial center of the implodable is denoted as negative (-), while radial deformation away from the axial center of the implodable is denoted as positive (+). These will be referred to as inward dR and outward dR , respectively, and for all plots, time will be given as time $t = 0$ when dR has reached a minimum value. Finally, it is important to note that all dynamic pressure histories are normalized to the critical buckling pressure of the structure, P_c , according to the equation:

$$P_n = \frac{\Delta P + P_c}{P_c} \quad (1)$$

Where P_n is the normalized pressure and ΔP is the dynamic pressure. As such, the absolute pressure P is equal to P_c when $P_n = 1$. and is equal to 0 MPa when $P_n = 0$.

a) Unfilled tube, V0

The normalized dynamic pressure data taken at channels 1 and 4 are shown alongside center point displacement during the implosion of the unfilled tube is shown in Fig. A1. It is important to note that the implodable structure never quite achieves wall contact. This is evident from both the radial displacement data shown as well as from examination of the imploded structure after it was removed from confinement, in which a gap is seen between the walls of the deformed structure. Note that there is relatively no spike in pressure seen in the vicinity of the implodable structure (channel 4), due to the fact that wall contact was never made. The slight recovery in dR seen just after minimum dR is reached is due to elastic recovery in the deformed material after being plastically strained. As is common in implosion events occurring within a fully-confined

Fig. A1 Change in radius measured at the axial midpoint of the implodable structure is shown alongside normalized pressure resulting from the implosion of structure V0 taken at left end (channel 1) and axial center (channel 4) of confinement

environment, the maximum inward radial velocity occurred prior to maximum inward dR . In the case of implodable V0, the maximum inward radial velocity was 19 m/s and occurred at time $t = -0.433$ ms.

Also of note is the fact that the implosion event resulted in pressures of 0 MPa at the left end of the confining chamber, indicating the formation of cavitation at this location. This period of cavitation was interrupted by the collapse of a small cavitation bubble, resulting in a short duration, high amplitude pressure spike, and ended with the collapse of a large cavitation bubble which resulted in a long duration, high amplitude pressure spike. Subsequent oscillations in fluid pressure and small oscillations in center point dR are seen.

b) Tube filled with 40% of water, V40

It was stated in the previous section that the unfilled implodable structure V0 did not achieve wall contact during implosion. This resulted in a large amount of the implodable volume still bounded by the structure after the implosion event. This remaining volume was greater than 40% of the original implodable volume, and due to this fact filling the tube with 40% of water had no effect on the resulting dynamic pressure histories taken at channel 1 or channel 4. Because no notable differences were seen between the implosion of structures V0 and V40, discussion of V40 will be omitted.

c) Tube filled with 80% of water, V80

For the case of V80, in which eighty percent of the implodable structure volume was filled with water, it is important to note two phenomena seen in Fig. A2 which distinguish this case from the implosion of V0 and V40. First, the addition of water in the implodable volume was able to prevent wall contact, as evident from the fact that center point displacement reaches a minimum of -12.2 mm. Second, it should be noted that no cavitation is seen at the left end (channel 1), as evident from the fact that the normalized pressure never reaches 0. However, a water hammer pulse is still seen at this location, and is seen to oscillate with decreasing amplitude. It should be noted that the frequency of these oscillations is less than that of case V0, and is likely due to the fact that the bulk modulus of the fluid-air mixture bounded by the confining structure K_{mix} is greater for the case of V80, therefore increasing wave speed C_f . Finally, note also that

Fig. A2 Change in radius measured at the axial midpoint of the implodable structure is shown alongside normalized pressure resulting from the implosion of structure V80 taken at left end (channel 1) and axial center (channel 4) of confinement

the maximum radial velocity has been decreased to 9 m/s, as opposed to 19 m/s in case V0.

3. Conclusions

A series of three implosion experiments was conducted within full confinement in which implodable structures were filled with varying amounts of water equal to 0%, 40%, and 80% of the total volume bounded by the implodable structure. 3D digital image correlation was used to provide structural deformation data, while dynamic pressure transducers captured the pressure-time histories at various points throughout the confining chamber. Key conclusions from this study are as follows:

1. By filling an implodable structure with 80% water, both wall contact and cavitation at the ends of confinement can be avoided.
2. The frequency of oscillation of water hammer pulses resulting from implosion is greater for implodable structures filled with 80% water. This is likely due to the increased bulk modulus of the water-air mixture bounded by confinement, K_{mix} , which increases as the volume of air bounded by the implodable structure decreases.

Appendix B: Technique for Observing Added Mass Effect in Underwater Vibrating Structures

This section details the experimental procedure and results of a novel technique for observing added mass effect in pressurized underwater vibrating structures. The purpose of this technique is to experimentally measure the frequency of structural vibrations of an implodable structure oscillating within a fluid of varying ambient pressures. Measurement of structural vibrations is carried out with the use of 3D digital image correlation, and oscillations are excited in the structure using a slight modification to the fully-confined pressure vessel facility seen in Chapter 1 of this thesis. This modification is discussed in the following section.

1. Modification to Fully-Confined Pressure Vessel Facility

To excite vibrations in an implodable structure submersed in a pressurized fluid, a two-valve assembly was installed in the middle section of the fully-confined pressure vessel facility described in Section 2.2 of Chapter 1. The assembly consists of two high-pressure valves separated by a small brass pipe section of volume dV . The valve separating the brass section from the pressurized fluid in the confining structure is referred to as Valve 1, and the valve separating the brass section from the outside (unpressurized) environment is referred to as Valve 2. The assembly is shown connected to the fully-confined pressure vessel facility in Fig. B1. When the pressure vessel is pressurized, the implodable structure experiences a certain amount of pre-deformation. The opening of Valve 1 will release a small amount of water from the pressure vessel into the brass section. This releases a low-pressure wave that propagates throughout the pressure vessel at the speed of sound in water, C_w . This drop in pressure in the fluid

Fig. B1 Schematic of full confinement pressure vessel facility with the inclusion of dual-valve assembly used for step-wise depressurization. A typical example of the drop in pressure seen in the pressure vessel from the opening of Valve 1 is seen in the left of the figure, where P_1 is the initial pressure of the fluid in the pressure vessel, and P_2 is the pressure of the fluid after Valve 1 has been opened

surrounding the pre-deformed structure excites vibration in the structure, which is measured using DIC. Note that the amount of water transferred to the brass section is not exactly equal to dV , as there will be a certain amount of air trapped in the brass section which will be compressed as pressurized water enters. Note further that Valve 2 **MUST** be closed before opening Valve 1 or else water will spray out of the assembly uncontrolled. Due to the fact that air is trapped in the brass section when Valve 1 is opened, the change in pressure cannot be calculated simply from change in volume of water using the bulk modulus of water, and thus a series of calibration tests were conducted to identify the expected pressure drop resulting from the opening of Valve 1. Calibration tests were conducted by pressurizing the fluid in the pressure vessel to a pressure P_1 , quickly opening Valve 1, and then recording the final pressure of the fluid, P_2 , which is the pressure at which structural vibrations are excited. This was done for many values of P_1 . Initial Pressure P_1 is plotted against final pressure P_2 and a best fit line is determined, as shown in Fig. B2. Using Fig. 2B, the pressure P_1 necessary to excite structural oscillations about any desired pressure P_2 can be determined.

Fig. B2 Initial pressures P_1 and corresponding final pressure P_2 are plotted alongside best fit line to be used for reference when conducting vibration experiments

2. Speckle Pattern and Calibration Technique

The composite implodable structure used for vibration experiments was a filament wound carbon fiber/epoxy tube of 20.7 mm outer radius, 1.67 mm wall thickness, and 280 mm unsupported length. The layup schedule of the tube was $[\pm 15/\sim 90/\pm 45/\pm 15]$. A 51 mm long section of the camera-facing side of the tube was painted with flat white paint, and a very fine black speckle pattern was applied using a “misting” technique. The term “misting” refers to the application of very fine black dots to a surface by very lightly spraying paint at the surface from about 305 mm (~ 1 foot) away from the target surface. Once properly mastered, this technique is an effective and efficient way of applying very small, random speckle patterns to a surface suitable for the use of 3d DIC.

Once the implodable structure was painted and speckled, it was placed in the fully-confining pressure vessel such that the center of the speckled portion of the structure

aligned with the center of the viewing window. The pressure vessel was then filled with water. Then, two high-speed cameras with 100 mm lenses were arranged such that the optical center of each camera's frame of view was aligned with the center of the speckled portion of the implodable structure. The frame rate was set to 67,500 frames per second, and the resolution to 256 x 256 pixels. The cameras were then further adjusted to ensure that the diameter of the implodable tube fit perfectly within the 256-pixel viewable frame. Once the cameras were positioned, the position of the implodable structure within the pressure vessel was measured to ensure that it could later be returned to the same position. The water was then removed and the implodable pushed off to the side to allow for in-air calibration.

Calibration of high speed cameras for DIC purposes was conducted in air using a custom-designed 12 x 5 – 2 mm calibration grid with an offset in X of 2, an offset in Y of 2, a length in X of 9, and a length in Y of 2. The calibration grid is shown from the perspective of the camera in Fig. B3a. The calibration score resulting from calibrations conducted for the experiments detailed in this appendix was 0.15. Note that because vibration experiments were conducted underwater, calibrations conducted in air will not

Fig. B3 Camera-viewed images of (a) the speckled region of interest of the submerged implodable structure and (b) the grid used for in-air calibration

give correct displacement magnitudes during experiments. For the determination of frequency of structural oscillations, however, in-air calibrations are valid as it is only the time-dependent behavior that is of interest.

3. Experimental Procedure

Once the calibration process described in section 2 had been completed, the implodable structure was placed in its original position, such that the optical center of each camera was aligned with the center of the implodable region of interest. After ensuring that Valve 1 and Valve 2 are closed, the pressure vessel was then filled with water, with special care taken to ensure that no air remained in the vessel. At this point, the experimental procedure was as follows:

1. Ensure that cameras are set to the “start” recording option, and begin recording.
2. Using the hydrostatic test pump, pressurize the fluid to the initial pressure P_1 which corresponds to the desired final pressure P_2 . Ensure that P_1 does not reach the critical buckling pressure of the implodable structure.
3. With the camera trigger in one hand, quickly open Valve 1, ensuring that the pressure vessel itself is not moved. Immediately after opening Valve 1, trigger the cameras.
4. Note the final pressure, P_2 , which is the pressure about which structural oscillations have been excited.
5. Close Valve 1, and open Valve 2 to release the water contained in the brass section into a bucket or other container. The compressed air within the assembly will expel the water quickly, and ensure that no water remains in the brass section.
6. Close Valve 2.

7. Save first 1000 or so frames taken from high speed cameras. Save more or fewer frames if necessary, depending on the expected frequency of oscillation.
8. Repeat steps 1-7, if desired.

4. Experimental Results

The experimental procedure detailed in the previous section was conducted for the implodable structure described in section 2 for P_2 values of 253 psi, 133 psi, 54 psi, and 23. Note that these values correspond to 55%, 29%, 12%, and 5% of the implodable structure's experimentally-determined critical buckling pressure of 457 psi, respectively. Radial deformation values were determined from high-speed photos, and then a fast Fourier transform (FFt) was conducted on time-deformation curves to determine the frequency content of oscillations. This process is shown in Fig. B4, which gives a segment of the radial deformation curve and its corresponding FFt plot. From the FFt plot, it can be seen that two dominant frequencies were excited in the structural

Fig. B4 Radial deformation curve taken at center point of implodable composite structure oscillating at $P_2 = 253$ psi shown alongside corresponding FFt plot

behavior of the composite structure. The low-frequency contribution seen in Fig. B4 is referred to as f_L , and is the frequency at which the structure was loaded (the frequency at which Valve 1 was opened). The low frequency contribution is also seen in the radial deformation curve in Fig. B4, given by the upwards trend of the structural oscillations. The high frequency contribution, f_H is also seen from the FFt plot at around 500 Hz. This frequency is the value which corresponds to the natural frequency of oscillation of the structure while under pressure P_2 . Because the signal processing techniques used in the determination of f_H resulted in frequency measurements with a discrimination of 32.9 Hz, the value of f_H determined from the FFt is only approximate and thus was used to divide the deformation curve into time windows of $\frac{1}{f_H}$ in length, and a peak value was determined for each window. Using the time difference between peaks, the frequency of each oscillation was determined, and the average frequency f_A was determined for the entire radial deformation curve. The average frequencies of structural oscillation are given for all P_2 values in table B1.

Table B1 Frequency of structural oscillation with added mass effect at varying pressures P_2

Pressure P_2 (psi)	253	133	54	33
Average Frequency f_A (Hz)	503	512	509	538

Note that with the exception of $P_2 = 54$ psi, f_A decreases with increasing pressure P_2 . This is in agreement with accepted principles of added mass effect, which states that the frequency of oscillation approaches zero as P_2 approaches the critical buckling pressure.

5. Conclusions

A novel experimental technique was developed to measure the frequency of vibration of an implodable structure under hydrostatic pressure, and was verified by conducting a series of 4 experiments. Major conclusions from this study are as follows:

1. 3D digital image correlation can be used to successfully measure small vibrations in implodable structures excited by a sudden drop in hydrostatic pressure.
2. The “misting” speckling technique is an ideal method for measuring small displacements with 3D DIC.
3. Generally, the frequency of vibration of structures submerged in a pressurized fluid can be shown experimentally to decrease with increasing hydrostatic pressure

Appendix C: Supplementary Dynamic Pressure Histories for Chapter 2

The following are representative dynamic pressure history plots for implodable geometries A28, A33, B33, and B38, which were discussed but not shown in Chapter 2 of this thesis. The specific implodable geometry and critical buckling pressure P_c to which each figure pertains is shown in the figure itself and in the captions. Note that time and pressure scales are varied from figure to figure to show finer characteristics.

Fig. C1 Dynamic pressure histories taken from channels 1-5 resulting from the implosions of implodable geometry A28 at $P_c = 2.06 \text{ MPa}$

Fig. C2 Dynamic pressure histories taken from channels 1-5 resulting from the implosions of implodable geometry A33 at $P_c = 1.56 \text{ MPa}$

Fig. C3 Dynamic pressure histories taken from channels 1-5 resulting from the implosions of implodable geometry B33 at $P_c = 2.81 \text{ MPa}$

Fig. C4 Dynamic pressure histories taken from channels 1-5 resulting from the implosions of implodable geometry B38 at $P_c = 2.69 \text{ MPa}$