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DYNAMIC INSTABILITY OF REINFORCED CYLINDERS IN A CONFINING
ENVIRONMENT

BY

NIDHI MEHTA BODURTHA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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UNIVERSITY OF RHODE ISLAND

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OF

NIDHI MEHTA BODURTHA

APPROVED:

Thesis Committee:

Major Professor

Arun Shukla

James Leblanc

David Heskett

Nasser H. Zawia

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND

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ABSTRACT

An experimental investigation was conducted to understand the collapse mechanism of internally ring stiffened aluminum cylinders under uniform hydrostatic loading in a limited energy environment, and observe a transition of the mode of failure as the ring thickness of the stiffener is varied. The implosion of ring stiffened cylinders was studied using a combination of state-of-the-art limited energy environment facilities at DPML and 3D Digital Image Correlation (DIC). The results show that as stiffener thickness is decreased, the collapse behavior of the structure transitions from two segments collapsing in mode III with the stiffener acting as a rigid boundary to one uniform mode II collapse where the ring stiffener collapses along with the structure. Thicker stiffeners cause the long tube to behave as two distinct shorter tubes depicting their fundamental modes of collapse. The pressure signature at the confinement end consisted of a drop in pressure followed by a hammer pulse. The drop in pressure was significantly greater for mode II collapses versus mode III. While the strength of the hammer pulse approximately $0.6P_c$ for all the experiments. The ring thickness also effects numerous other parameters such as collapse pressure, radial velocity at the location of the ring stiffener, and dwell time between the collapse of two sections. Furthermore, it was seen that as stiffener thickness increased, the behavior of the structure approached that of two isolated structures divided by a simply-supported boundary condition at the location of the stiffener. An Abaqus FEA model was developed to accurately predict the collapse pressure and mode shape of ring stiffened cylinders. The model gave roughly accurate collapse pressures and modes. The collapse pressures from the model were then used to relate the ring stiffener to the effective length. Lastly, the calculated effective length was accurate for the mode III collapses, however the predictions for a mode II collapse were significantly higher than the mode II results.

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For my loving, supportive, and cherished family
In the memory of Rajnikant Parekh and John Bodurtha

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SECTION 1 - INTRODUCTION

This study investigates the mechanism of collapse for reinforced aluminum cylinders as the thickness of the internal ring stiffener is varied. A state-of-the-art underwater environment facility was used to simulate hydrostatic pressure in a limited energy environment for the experiments. The use of 3D underwater DIC, pressure data, and post-mortem analysis provided a full understanding of the implosion phenomenon. The effect of the ring stiffener's thickness on parameters such as collapse pressure, velocity, and dwell time are also studied. Lastly, using critical buckling pressure for various stiffener thicknesses, obtained from FEA modeling, a relationship between ring stiffener thickness and effective length was developed.

The study of the implosion phenomenon of cylindrical shells has been of interest to researchers since the mid-1900s for collapse behavior studies [1], design of space vehicles [2], and offshore pipelines [3]. However, researchers called for more in-depth understanding of the implosion process. This began with early experiments and computational modeling of the underwater implosion of aluminum alloy tubes and buckling analysis of marine pipelines [4-7]. A numerical and analytical study was done for aluminum 6061-T6 to study the effect on surrounding structures when an implosion occurs [8]. A comparative study was also done for brass and aluminum specimens at different failure modes to understand the differences between the peak pressures [9]. Efforts followed to understand the collapse mechanisms and how to mitigate implosion energy of shells using digital image correlation [10-11]. Lastly, a more recent study derived an equation for potential energy and static equilibrium paths of long, thin cylinders under external pressure [12].

Unlike the vast history of implosion research, research on the implosion of cylindrical structures in a limited energy underwater environment is not as common. The buckle

propagations of long confined aluminum and steel cylindrical shells with initial imperfections were studied for early pipeline and tunnel applications [13]. This led to the investigation of buckle propagation in pipe-in-pipe or confining systems for stainless steel pipes [14]. The collapse mechanism of metallic and composite cylindrical shells and the effects on nearby structures was thoroughly researched [15-17]. This also led to the computational modeling of dynamically initiated instability in a confining environment [18]. Reinforced cylindrical shells have previously been studied as well. Cylinders with ring stiffeners have an added structural integrity depending on the geometry and spacing of the ring. This starts with understanding the collapse behavior of confined rings under external pressure [19]. One of the early applications of ring stiffeners was externally on pipelines as buckle arrestors. The performance and design of these buckle arrestors was thoroughly studied. [20-21]. The collapse pressure and failure modes of ring stiffened cylinders were some of the earliest researched on the topic [22-23]. The optimization of the ring stiffener spacing and ring stiffener diameter have also been previously studied [24-25]. In a recent study, large scale ring stiffened cylinders to understand the local buckling and overall deformation of the structure [26].

While the implosion of metallic ring stiffened cylinders and the implosion of metallic cylinders in a confining environment have both been studied, the combination of both has not been studied. This paper investigates the mechanism of collapse of ring stiffened aluminum cylinders with varying ring thickness using a limited energy facility combined with 3D DIC. The results of the study show a significant link between the deformation sustained by the ring stiffener and the mode of failure of the structure. This results in three types of collapse mechanisms: minimal ring stiffener deformation, partial ring stiffener deformation, and complete ring stiffener collapse. Additionally, the effect that the thickness of the ring stiffener has on collapse pressure, ring stiffener velocity, and dwell time is identified and discussed. Lastly, an FEA model was created to obtain critical buckling pressures of ring stiffened

cylinders for various stiffener thickness. Then a relationship between the stiffener thickness and effective length of the cylinder.

SECTION 2 - EXPERIMENTAL PROCEDURE

The experiments with varying ring thickness were conducted using the state of the art fully confined underwater facilities combined with 3D digital image correlation technology. A brief description of specimen geometry, fabrication, and experimental apparatus are presented in the following sections.

SECTION 2.1 - SPECIMEN GEOMETRY

The experimental specimens used in this study consisted of the cylinder and the reinforcing ring were made of aluminum 6061-T6. Specimens were prepared in two parts. First the cylinders were carefully machined to a length of 260 mm inches. Next the ring stiffeners were bored to the appropriate thickness and then cut to a length of 6.5 mm. Geometric measurement of both the cylinders and the ring stiffeners were measured and recorded. Lubricant is applied to the inside of the cylinder and the ring is then pressed fitted into the center of the cylinder. The lubricant allows the ring to slide into the cylinder without leaving visible scratches or marks in the interior of the tube, as scratches in the interior of the cylinder can have an effect on the critical collapse pressure of the specimen. Each specimen is lastly sealed at both ends with 25.4 mm protruding aluminum end caps with circumferential O-rings.

The tube geometry was chosen such that critical buckling pressure did not exceed 6.89 MPa, the operating limit of the pressure vessel facility described in section 2.1. Since the ring stiffener is placed in the center of the cylindrical tubes, it separates the cylinder into two segments. A maximum ring stiffener thickness of 5.5 mm and a minimum ring stiffener thickness of 1.6 mm so that the thickest ring stiffener would approach simply supported

boundary conditions and the thinnest would act as a deformable boundary condition. An array of ring thickness in between 5.5 mm and 1.6 mm were used to observe the transition of failure modes. A set of unstiffened cylinders were also tested to provide a reference

The measured geometries of the aluminum cylinders and the ring stiffeners are shown in Figure 1 and Table 1 below.

Figure 1. Ring and cylinder specimen schematic. Shown above are the significant geometric parameters for the cylinder and ring stiffener which are presented in Table 1.

Table 1. Measured geometric properties of each specimen.

Specimen Name	Ring Stiffener Thickness (mm)	Ring Stiffener Length (mm)	Ring Stiffener Outer Diameter (mm)	Cylinder Thickness (mm)	Cylinder Length (mm)	Cylinder Outer Diameter (mm)
1	5.49	6.96	36.27	0.89	259.94	38.13
2	5.47	6.33	36.27	0.89	261.59	38.05
3	4.90	6.54	36.22	0.89	260.71	38.10
4	4.85	6.46	36.31	0.89	260.05	38.23
5	4.11	6.58	36.32	0.89	260.10	38.07
6	4.01	6.54	36.25	0.89	260.32	38.10
7	3.25	6.45	36.25	0.89	260.15	38.07
8	3.15	6.49	36.22	0.89	260.12	38.07
9	2.69	6.46	36.24	0.89	260.38	38.10
10	2.66	6.38	36.24	0.89	260.99	38.07
11	2.20	6.31	36.32	0.89	263.53	38.10
12	2.15	6.34	36.30	0.88	262.94	38.07
13	2.14	6.44	36.24	0.88	260.48	38.07
14	1.64	6.35	36.30	0.89	260.10	38.10

15	1.64	6.40	36.26	0.89	260.43	38.13
16	N/A	N/A	N/A	0.90	259.92	38.12
17	N/A	N/A	N/A	0.90	260.12	38.12

SECTION 2.2 - EXPERIMENTAL FACILITY

The limited energy environment facility consists of a 2.29 m long, 177.8 mm diameter tubular vessel with a wall thickness of 19 mm, shown in Figure 2. The pressure vessel was constructed from seamless low-carbon steel (SA106-B). It is divided into three sections; the middle section contains a 63.5 mm thick flat acrylic window and spans a total length of 457 mm. The acrylic window allows for approximately 216 mm x 102 mm viewable area used for non-contact deformation analysis through high-speed photography. Since the volume inside the pressure vessel is not much larger than the volume of the specimen, this is defined as a limited energy environment. The sealed aluminum specimens are placed concentrically in the pressure vessel so that the center of the specimen and the center of the pressure vessel are aligned. The protruding endcaps on each end of the specimen are supported by threaded spooled with rubber tips. This minimizes the interference of axial pressure and fluid motion inside the pressure vessel during the dynamic instability event. The pressure vessel is filled with water using a hydrostatic test pump while any air in the system is eliminated through a bleed valve on the vessel. The water is pressurized at a rate of 0.01 MPa/s until an audible noise is heard from the pressure indicating wall contact in the specimen. The pressure history of the implosion event is captured using dynamic pressure transducers (PCB 113B22, PCB Piezotronics, Inc., Depew, NY) mounted flush throughout the pressure vessel at locations shown in Figure 2. The pressure transducers have a sensitivity of 1 mV/psi in general, however the sensitivity can drift slightly after extended periods of time under dynamic conditions. Thus,

the transducers were calibrated by pressurizing the vessel to a specific pressure and then quickly dropping the pressure using a release valve. The corresponding voltage drop for each transducer is used to calculate the sensitivity [17]. 3D digital image correlation (DIC) was conducted using two high-speed cameras (Photron SA1, Protron USA, Inc.) along with two high-intensity light sources were mounted facing the viewing window. The technique is discussed in more detail in Section 3.

Figure 2. The schematic of the experimental setup used for the confined experiments, including the front and axial view of the confining tube, the 3D DIC high speed camera configuration, specimen as viewed by the high speed cameras, and the pressure sensor locations.

SECTION 2.3 - RESEARCH OUTLINE

The research begins with specimen fabrication and optimization of the fabrication method. Preliminary experiments were done to verify if von Mises' equation [28] could accurately predict the mode of collapse for three different ring stiffeners. During these experiments, the fabrication of specimen caused scratches on the inside of the cylinder. The scratches led to lower collapse pressures of the specimen so the cylinder was lubricated to prevent the scratches. Next, the implosion experiments were done using the experimental facility discussed in Section 2.2 combined with 3D DIC, which is discussed in Section 3. The results from the experiments are then post processed using the pressure data from the sensors along the length of the facility and analysis of the high speed images from the DIC. The high speed images provide radial displacement which can then be plotted and used to calculate the radial velocity color map along the length of the cylinder. Using this information, the mechanism of collapse and its evolution can be understood. Additionally, using the pressure data at the confinement end, the effect of the collapse on other structures can be understood. Furthermore, other parameters such as collapse pressure, midpoint velocity, and dwell time were then studied as a function of the ring stiffener thickness. A finite element model was developed to simulate the collapse pressure and mode shape of the ring stiffened cylinder. Using the collapse pressures from the model, a relationship between the ring stiffener thickness and effective length can be approximated. The effective length can be used to understand how much of the cylinder that will buckle. Lastly, the post mortem analysis combined with the 3D DIC gives a full understanding of the implosion phenomena. A flow chart of the research approach is given in Figure 3.

Figure 3. Research approach

SECTION 3 - DIGITAL IMAGE CORRELATION

Digital image correlation is a non-contact technique used to acquire full field displacements and deformation [27]. The technique utilizes high speed cameras to capture images of an event or test, which can then be analyzed to extract in plane or out of plane displacements. In order to obtain out of plane displacements, two high speed cameras are needed. Generally in a two camera system, there is a small stereo angle between the two cameras [27]. This stereo system model is shown in Figure 4 below. 3D DIC is based on binocular vision of the pinhole camera model [27]. The pinhole camera model is used to relate 3D points to a 2D sensor plane for each camera. Thus, the specimen's coordinate system can be related to each camera coordinate system. In order to relate each of the camera's coordinate systems to each other, the cameras have to be calibrated. If the positions of the two cameras relatively to each other, the magnifications of the lenses and all imaging parameters are known, the absolute 3-dimensional coordinates of any surface point in space can be calculated. If this calculation is done for every speckle or dot on the specimen surface, the 3D surface contour of the object can be determined in all areas.

Once the 3D reference contour has been determined, the second step in 3D digital image correlation is the measurement and determination of the three-dimensional deformation of the specimen's surface. This process is carried out by correlation of the images, taken by both cameras with their original reference images. After the deformation of specimen's surface is known, the strains can be calculated.

Figure 4. Two camera stereo imaging configuration

In this study, the two high speed cameras recorded the implosion phenomena exhibited by the specimen at a rate of 30,000 frames per second. The calibration procedure used is tedious and can be found in Appendix B. The specimen contained a high contrast speckle pattern on the surface using a white paint background and black dots, painted prior to the experiment. The images captured by the high-speed cameras of the implosion phenomenon are analyzed using VIC 3D software. The results yield full field deformation of the specimen during the implosion event.

SECTION 4 - RESULTS AND DISCUSSION

The experimental results of all the specimens tested in this study are summarized in Table 2 below. To verify the repeatability of the experiments, at least two experiments of every ring thickness were conducted. A large array of collapse behavior was observed throughout the experiments, this is further discussed in the following sections.

Table 2. The resulting critical buckling pressure and mode of collapse for each specimen.

Specimen Number	Average Collapse Pressure (MPa)	Mode of Collapse
1	6.52	Both segments collapsed in Mode III
2	6.56	Both segments collapsed in Mode III
3	6.82	One segment collapsed in full and one in partial Mode III
4	6.08	One segment collapsed in full and one in partial Mode III
5	6.27	One segment collapsed in full and one in partial Mode III
6	6.71	One segment collapsed in full and one in partial Mode III
7	6.55	One segment collapsed in full and one in partial Mode III
8	6.17	One Mode III and one Mode II
9	6.49	Both segments collapsed in Mode III
10	6.70	Both segments collapsed in Mode III
11	5.29	Single Mode II
12	5.19	Single Mode II
13	4.65	Single Mode II
14	4.24	Single Mode II
15	3.83	Single Mode II
16	1.88	Single Mode II
17	1.81	Single Mode II

SECTION 4.1 - COLLAPSE BEHAVIOR

The implosion of a ring-stiffened cylinder in a limited energy environment results in four stages of collapse [6]. In the first stage, the increase in hydrostatic pressure results in the compressive radial and axial loads which cause small initial deformations on the cylinder.

These initial imperfections can dictate the collapse pressure and affect the mode of failure of the structure. The second stage occurs when the cylinder walls have reached a point of instability and begin to buckle inward. The maximum compressive or negative velocity occurs just prior to wall contact. As the walls of the structure accelerate inwards, a drop in local pressure is seen as water expands to fill the newly-created void. The third stage begins at the point of wall contact between two sides of the cylinder. During this stage, shortly after wall contact, the hydrostatic pressure surges as the momentum of the fluid surrounding the structure is arrested, and kinetic energy is converted into strain energy in the surrounding fluid. In the last stage, the buckle propagates through the unsupported length of the cylinder. The hydrostatic pressure during this stage oscillates around an equilibrium point as the fluid stabilizes after the collapse. In Figure 5 below, these four stages of collapse can be seen for two mode III collapses and one uniform mode II.

Figure 5. 3D DIC images showing the four stages of collapse in radial displacement for a uniform mode II failure and two mode III failures. The four stages of collapse can be seen once for the collapse of each segment.

The experiments in this study can be grouped into three categories based on behavior dictated by the ring stiffener. The first category contains specimens 1 and 2 from Table 2, in which the ring stiffener acts a simply supported boundary condition, so the cylinder collapses in two segments of full mode III collapses. In the second category are specimens 3 through 13 from Table 2, which exhibit behavior transitioning from mode III collapses to mode II. In the last category of experiments are specimens 14 and 15, which exhibit a single complete mode II collapses. The experiments in each category show similar amounts of deformation of the ring stiffener. So the three types of collapse behavior are:

1. minimal ring stiffener deformation: radial deformation of 0 to 2 mm
2. partial ring stiffener deformation: radial deformation of 3 to 15 mm
3. complete collapse of ring stiffener: radial deformation of 16 to 19 mm

In the following section, these three types of collapse behaviors are further explained and illustrated using pressure data and DIC analyses. However, not every experiment is discussed only the key experiments from each category are shown.

SECTION 4.1.1 - COLLAPSE WITH MINIMAL RING STIFFENER DEFORMATION

In this type of collapse, the cylinder collapses in two separate segments. The ring stiffener in the center of the cylinder is supposed to act as a rigid boundary. A rigid boundary is defined as a length of the cylinder that remains undeformed or minimally deformed during the implosion phenomenon. The endcaps fitted at either end of the cylinder also serve as rigid boundaries. The rest of the cylinder remains unsupported, thus the buckle propagates throughout the unsupported length. Specimen number 1 from Table 2 is shown in Figure 6 as

an example of the first type of collapse behavior. In this experiment, the cylinder has two unsupported segments spanning approximately 100.3 mm each. Additionally, an image of the collapse specimen can be found in Section 7. The first stage of collapse is at $t = -0.8$ ms as the vessel is being pressurized, and very minor radial deformations of about 0.5 mm can be seen. In the second stage, the hydrostatic pressure in the vessel reaches a critical point of instability at $t = -0.5$ ms as the deformation propagate on the cylinder and the segment begins to collapse in mode III. The first segment valley reaches a maximum compressive velocity of 31.6 m/s. Just prior to the moment of wall contact of the first valley is reached, the dynamic pressure reaches a minimum value which is defined as $t = 0$ ms. In Figure 6b the ring stiffener shows a radial deformation of roughly 1.5 mm as the dynamic pressure decreases. In the third stage, first segment of the implodable structure reaches wall contact and the surrounding fluid's momentum is arrested. The surge in the dynamic pressure is cause by the pressure wave reflecting from the ends of the pressure vessel towards the axial center of the vessel. Since the DIC software lost correlation during the collapse of the first segment, the full deformation of the segment is not seen in Figure 6a. During the collapse of the first segment, the second segment expands radially due to the bending of the cylinder as the first segment pulls material inward to reach wall contact. Next, the implosion of the first segment spreads throughout the unsupported length.

Note that there is a slight delay between the collapse of the first section of the tube and the second section of the tube. This duration of this delay will be defined as the dwell time for the sake of this discussion, and is shown in Figure 6a. At $t = 0.3$ ms, the second segment reaches a point of instability and begins to show deformation, reaching a maximum compressive velocity of 36.2 m/s. Next, the segment valley reaches wall contact at $t = 0.7$ ms in a mode III failure. There is a delay in the drop of dynamic pressure after the second segment collapse due to the pressure waves from the each collapse super imposing over each other. Additionally, this

also explains why the pressure surge after the first collapse is not very large. During the second segment collapse either the ring stiffener expands outward slightly or just the cylinder wall expands outward, it is hard to distinguish the two from DIC data. Lastly, the wall contact spreads throughout the unsupported length of the segment. After the second segment collapses, the ring stiffener recovers from the expansion with a maximum compressive velocity of 8.3 m/s. The ring stiffener returns to approximately 0.6 mm deformation from its pre-implosion value. As a result, the second segment collapse also undergoes stages two, three, and four of general collapses, and the two segments act in a similar manner as two separate simply supported cylinders of 100.3 mm length.

The collapse of the first segment, dwell, and then collapse of the second segment is shown clearly by the radial displacement data given Figure 6c. As the first segment is collapsing, the full length of the cylinder has a compressive velocity. However, the ring stiffener and the second segment have tensile (positive) velocity following the tail end of the first segment collapse. This is due to the bending of the rest of the cylinder as it is pulled toward the valley of the first segment. This results in the tearing of the cylinder along the boundary of the ring stiffener. After the first segment collapse, the ring stiffener slowly decreases in velocity until it reaches zero just prior to the second segment beginning to collapse. Next the second segment collapses, during which the ring stiffener has a small positive velocity as the cylinder is pulled inward toward the valley of the second segment. The ring stiffener's velocity drops after the second segment collapse, as it reaches its post-collapse deformation equilibrium point.

Figure 6. DIC and pressure data for the first type of collapse behavior showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of ring stiffener, and (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in two segments of full mode III. The deformation in each valley was roughly the same, however due to the bending of the cylinder the DIC software lost correlation so the full displacement could not be seen in the DIC results. The ring has negligible deformation compared to the two valleys. The pressure highlight key events in the implosion phenomena. As seen in (c) the two segments collapse completely separate of each other. The area where the ring stiffener is located only has a small compressive velocity after the second collapse.

SECTION 4.1.2 - COLLAPSE WITH PARTIAL RING STIFFENER DEFORMATION

In this type of collapse, the cylinder still collapses in two separate segments. However, the ring stiffener does not act fully like a rigid boundary and causes the second segment to only

partially collapse. The experiment shown below in Figure 7 is experiment 3 from Table 2. The cylinder has two segments each 101.5 mm in unsupported length. Additionally, an image of the collapse specimen can be found in Section 7. In the experiment, the first stage of collapse of the first segment begins as the hydrostatic pressure is increasing in the pressure vessel and the cylinder shows about approximately 1 mm of initial deformation at $t = -1.8$ ms. At $t = -0.3$ ms, the segment reaches a point of instability. The maximum compressive velocity of the valley of the first segment is 37.0 m/s. During this stage, the dynamic pressure begins to drop until it reaches a minimum at time zero just prior to wall contact of the first segment. This drop is due to the surrounding fluid rushing in towards the collapse and away from the sensor. The third stage of collapse begins as wall contact is reached and the segment collapses in a full mode III failure. The maximum deformation of 17 mm is reached in the collapse as shown in Figure 7a. The pressure surges due to the surrounding fluid reversing the direction of its momentum; it reflects off the ends of the pressure vessel toward the axial center of the pressure vessel. During the collapse of the first segment, the ring stiffener and the second segment both expand outward due to the bending moment created by the material being pulled toward the collapse, seen in Figure 7b. This results in tearing at the boundary of the ring stiffener. In the last stage, the wall contact spreads throughout the unsupported length of the first segment and stabilizes at $t = 0.5$ ms.

There is a short dwell time of 1.1 ms between the collapses of the two segments, shown in Figure 7a. The second segment reaches instability and deforms as it begins to buckle inward. The maximum compressive velocity of the second collapse is 35.7 m/s. At time zero, the second segment begins to buckle and the dynamic pressure again drops to a minimum as the surrounding fluid rushes in toward the buckle. During this stage, the ring stiffener deforms to about 4.5 mm, and by doing so it absorbs some of the energy driving the second segment's collapse. Therefore, there is no longer enough energy in the system to reach wall contact

resulting in the partial mode III failure of the second segment. As the ring stiffener is deforming, it reaches a maximum compressive velocity of 9.1 m/s. At $t = 1.5$ ms, the second segment reaches its maximum deformation of roughly 15 mm. The dynamic pressure surges after the collapse of the second segment. By $t = 1.2$ ms, the second segment has stabilized. Post-collapse, the whole structure rebounds slightly, seen in Figure 7a and b.

Additionally, the mechanism of collapse is depicted by the radial velocity as a function of time and length across the cylinder of experiment 3, shown in Figure 7c. As the first segment collapses, small compressive velocity oscillations can be seen across the length of the ring stiffener and the second segment. This velocity after the collapse of the first segment drops to approximately zero. However, during the dwell time between collapses, the ring stiffener again has a small compressive velocity due to surge in dynamic pressure after the first collapse. Due to this, the ring stiffener deforms slightly. Just as the second segment collapse is initiated, the ring stiffener again has a compressive velocity, but this time the deformation is significant. This partial collapse of the ring stiffener prevents the second segment from fully collapsing.

Figure 7. DIC and pressure data for partial ring collapse behavior showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, and (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full and one partial mode III segment. Note that the deformation in the two valleys is roughly the same. However, the ring stiffener stabilizes the second segment collapse, causing the partial mode III collapse in the segment. As observed from (c) above the first segment collapses with a large compressive velocity, however the second segment collapses with a much smaller velocity. The location with the ring stiffener shows a small compressive velocity during the second collapse which would indicate that it absorbed some of the energy from the system thus resulting in partial collapse of the second segment.

Another example of a collapse with partial ring stiffener deformation with a different mode of failure than the previous example is the experiment 10 from Table 2, shown in Figure 8. The cylinder still collapses in two separate segments, however the ring stiffener partially acts like a rigid boundary and has an effect on the mode of the second segment's collapse. Each segment

has an unsupported length of 101.1 mm. In the first stage of collapse in this experiment, the cylinder shows approximately 1 mm of initial deformation at $t = -0.9$ ms. The second stage of collapse begins at time $t = -0.4$ ms. At this time, the instability initiates in the first segment and a sudden increase in compressive velocity is seen. The maximum compressive velocity of the first segment is 35.0 m/s. During this stage, the dynamic pressure drops to a local minimum as the surrounding fluid again is pulled toward the collapse at time zero. In Figure 8a, the second segment has already begun to buckle as the first segment reaches wall contact. The first segment has a maximum deformation of 17 mm and failed in a full mode III collapse. During the first segment collapse, the ring stiffener deflects radially outward to compensate for the collapse of the first segment. After wall contact is reached there is a surge in dynamic pressure. In the last stage of the collapse, the wall contact propagates axially along the unsupported length of the segment at $t = 0.1$ ms. The second segment continues to buckle inward until it reaches wall contact at time $t = 0.6$ ms and fails in a full mode III. The maximum compressive velocity and maximum radial displacement for the second segment was 23.1 m/s and 17 mm, respectively. The dwell time between wall contact of the first and second segment collapse is very short. The dynamic pressure drops to a minimum value after a small lag time due to the pressure waves from the first and second collapse superimposing on each other. Post collapse, there is another surge in the dynamic pressure. During the second collapse, the ring stiffener has a maximum compressive velocity of 12.6 m/s and deforms to approximately 7 mm which can be seen in Figure 8b. At $t = 1.3$ ms, the second segment continues to deform and bend. The bending of the second segment also causes the ring stiffener to deform to a maximum of roughly 10 mm. Post-implosion, the ring stiffener and the second segment rebound by approximately 3 mm.

The color map of radial velocity as a function of time and length across the cylinder is shown in Figure 8c. At the start of the first segment collapse, there is a positive tensile velocity

at the ring stiffener location, whereas the second segment has a compressive velocity. This is due to the ring stiffener counteracting the collapse of the second segment. At the start of the second segment collapse, the ring stiffener has a compressive velocity as it deforms to about 7 mm because it cannot sustain further load after the first segment collapse. At the tail end of the second segment collapse, the segment begins to bend indicated by the positive velocity at $t = 1.3$ ms, causing the ring stiffener to deform another 3 mm. The deformation results in a compressive velocity at the ring stiffener location. Afterwards, both segments have fully collapsed and the ring stiffener velocity oscillates about zero as it stabilizes. These oscillations are due the pressure oscillations in the surrounding fluid.

Figure 8. DIC and pressure data for another example of partial ring collapse behavior showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, and (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in two mode III segments. Thus, the deformation in the two valleys is roughly the same. As observed from (c) above the first segment collapses with a large compressive velocity, however the second segment collapses with a much smaller velocity. The location with the ring stiffener shows a small tensile velocity during the first collapse and a compressive velocity during and after the second collapse. This would indicate that it the ring stiffener has buckled too far, resulting in the full collapse of the second segment.

SECTION 4.1.3 - COLLAPSE WITH COMPLETE RING STIFFENER COLLAPSE

In this type of collapse, the ring stiffener does not act like a rigid boundary. In this case the entire structure collapses uniformly. The experiment shown below in Figure 9 is experiment

15 from Table 2. The cylinder has a full unsupported length of 206.2 mm including the length of the ring stiffener. Note that in this case, the implodable does not collapse in sections, but as one single structure. Additionally, an image of the collapse specimen can be found in Section 7. In the first stage of collapse the cylinder shows approximately 1.5 mm of initial deformation shown in Figure 9a. At $t = -0.7$ ms, the structure begins to reach a point of instability and deformation begins. The maximum compressive velocities of both valleys are 25.0 and 23.7 m/s, respectively. During this stage, the dynamic pressure has reached a local minimum at time zero just prior to the structure reaching wall contact. This drop is due to the surrounding fluid rushing in towards the collapse and away from the sensor. The third stage of collapse begins as the structure reaches wall contact and collapses in a mode II failure. The maximum deformation of 18 mm is reached by both valleys. During the collapse the ring stiffener deforms very similarly to the two valleys. The ring stiffener begins deforming even before the remaining structure begins failing. A maximum compressive velocity of 31.0 m/s was reached by the ring stiffener. The ring stiffener had a maximum radial deformation of 17 mm, depicted in Figure 9b. After the collapse, the dynamic pressure surges due to the surrounding fluid reversing the direction of its momentum; it reflects off the ends of the pressure vessel toward the axial center of the pressure vessel. In the last stage of collapse, the wall contact spreads throughout the unsupported length of the cylinder at $t = 1.2$ ms.

The mechanism of collapse is shown by the radial velocity as a function of time and length across the cylinder in Figure 9c. As shown in the color map, the two valleys on either side of the ring stiffener have a compressive velocity as the instability is initiated in the structure. The ring stiffener does not have a compressive velocity until slightly after the valleys begin collapsing. Approximately at time zero, the ring stiffener location reaches a maximum compressive velocity. This is due to the rest of the structure driving the collapse of the ring stiffener. As the wall contact spreads throughout the unsupported length of the cylinder, a

compressive velocity is seen at both ends of the cylinder. The location of the ring stiffener post-collapse shows a positive tensile velocity as the structure slightly rebounds from wall contact.

Figure 9. DIC and pressure data for the third type of collapse behavior showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, and (c) the radial velocity color map as a function of time and length across the cylinder. From the plots (a) and (b), the deformation in the two valleys and ring stiffener is roughly the same. As observed from the color map above the whole structure feels a compressive velocity as it reaches instability. The location with the ring stiffener shows a large compressive velocity than the valleys as it reaches wall contact.

SECTION 4.1.4 – COLLAPSE WITHOUT RING STIFFENER

In this type of collapse, there is no ring stiffener present inside the cylinder. In this case the entire structure collapses uniformly. The experiment shown below in Figure 10 is experiment 16 from Table 2. The cylinder has a full unsupported length of 206.2 mm. Additionally, an image of the collapse specimen can be found in Section 7. In the first stage of collapse the cylinder shows approximately 4 mm of initial deformation shown in Figure 10a. At $t = -0.7$ ms, the structure begins to reach a point of instability and deformation begins. The maximum compressive velocities of the valleys are 24.4 m/s, respectively. During this stage, the dynamic pressure has reached a local minimum at time zero just prior to the structure reaching wall contact. The third stage of collapse begins as the structure reaches wall contact and collapses in a mode II failure. The maximum deformation of 18 mm is reached by the cylinder. After the collapse, the dynamic pressure surges due to the surrounding fluid reversing the direction of its momentum; it reflects off the ends of the pressure vessel toward the axial center of the pressure vessel. In the last stage of collapse, the wall contact spreads throughout the unsupported length of the cylinder at $t = 1.2$ ms.

The mechanism of collapse is shown by the radial velocity as a function of time and length across the cylinder in Figure 10b. As shown in the color map, the central portion of the cylinder has the largest compressive velocity as the instability is initiated in the structure. As the wall contact spreads throughout the unsupported length of the cylinder, a compressive velocity is seen at both ends of the cylinder.

Figure 10. DIC and pressure data for a collapse without a ring stiffener showing (a) normalized pressure and radial displacement versus time at the valley and (b) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full mode II. Note full wall contact was reached. As observed from (b) above the cylinder with uniform velocity.

SECTION 4.2 – PRESSURE SIGNITURES AT THE CONFINEMENT END

The pressure signature at the confinement end can provide insight into the pressure signatures experienced by surrounding structures. During the collapse, the instability of the cylinder is initiated when the critical buckling pressure. As discussed in previous sections, just as the first segment or the specimen as a whole begins to collapse, the pressure of the surrounding fluid drops at the axial center. This is the fluid rushes toward the specimen to compensate for the volume change. After 0.7 ms the confinement end experiences a drop in pressure as the low pressure wave finally reaches it from the collapse of the specimen. After the low pressure wave reflects from the confinement end, the net velocity of water still remains towards the axial center of the confining tube. This causes the pressure to increase or surge at the axial center. The resulting high-pressure waves reflect outward and eventually interface with the confining end, which until this time had experienced low pressure. This high pressure wave that hits the confinement end is known as a water hammer pulse. A hammer pulse is a

pressure surge caused when a fluid in motion is forced to stop or change direction suddenly; a momentum change. The strength of this pulse is a function of volumetric displacement [17].

In this study, water hammer can be seen at either confinement end of the vessel for each specimen. Figure 11 below shows the pressure data for the axial center and confinement end of specimen 1, 3, 10, 15, and 16. In Figure 11a, which shows pressure data from specimen 1, the pressure drop at the axial center is $0.65P_c$ and $0.94P_c$ at the confinement end. The strength of the hammer pulse at the confinement end is $0.68P_c$. Figure 11b, which shows pressure data from specimen 3, the drop in pressure at the axial center is $0.68P_c$ and $1.04P_c$ at the confinement end. The strength of the hammer pulse at the confinement end is $0.57P_c$. In the next Figure 11c, which shows pressure data from specimen 10, the pressure at the axial center and confinement end are $0.66P_c$ and $0.99P_c$, respectively. The strength of the hammer pulse at the confinement end is $0.57P_c$. Figure 11d shows the pressure data from specimen 15. The pressure drop at the axial center and confinement end are $0.80P_c$ and $1.14P_c$, respectively. The strength of the hammer pulse at the confinement end is $0.61P_c$. Figure 11e shows the pressure data from specimen 16. The pressure drop at the axial center and confinement end are $0.77P_c$ and $1.16P_c$, respectively. The strength of the hammer pulse at the confinement end is $0.57P_c$. Overall, the drop in pressure at the confinement end after the first segment collapse or specimen collapse is significantly larger when the specimen collapses in mode II. This is most likely due to the larger change in volume when the whole specimen collapses compared to a segment of the specimen collapsing. However, the strength of the hammer pulse after the first segment collapse or specimen collapse is unaffected by the mode of collapse.

Figure 11. The pressure data from the sensor at the axial center and confinement end for specimen a) 1, b) 3, c) 10, d) 15, and e) 16. From the figure, it can be observed that the pressure drop at the confinement end is between $0.94P_c$ and $1.16P_c$ for each of the experiments. The strength of the hammer pulse is between $0.68P_c$ and $0.57P_c$ at the confinement end.

SECTION 4.3 - RELATIONSHIP OF RING STIFFENER THICKNESS TO PRESSURE, MIDPOINT VELOCITY, AND DWELL TIME

In sections 4.1.1-4.1.3 the effect of the ring thickness on the collapse mechanisms of an imploding structure were discussed. However, the thickness of the ring stiffener has an effect on various other parameters as well. One of the most interesting parameter that ring thickness affects is collapse pressure due to the mode of failure being dependent on the ring thickness. In Figure 12 below shows the average ring thickness plotted against the average collapse pressure. The figure depicts that the average ring thicknesses from 5.5 mm to 2.7 mm have approximately the same collapse pressure. This is due to the specimens with those ring thicknesses collapsing in mode III as the ring stiffener acts a rigid boundary. As the ring stiffener becomes a deformable boundary, there is a drop in collapse pressure. The average ring thickness of 2.16 and 1.64 mm had consistent mode II failures. The average collapse pressure for these specimens is closer to the expected mode II collapse pressures, of 3.45 MPa. Overall, Figure 12 gives a good overview of the relationship between ring thickness and collapse pressure.

Figure 12. The average critical buckling pressure is plotted against average ring thickness. The collapse pressure remains around 6.5 MPa until it declines to around 4.5 MPa as the mode of failure changes.

Figure 13 below shows the average radial velocity at the location of the ring stiffener plotted as a function of average ring thickness. Similar to the average collapse pressure, the average radial (or compressive) velocity at the ring stiffener location is a relatively constant value of 6.5 meters per second for average ring thicknesses of 5.5 mm to 2.7 mm. The average radial velocity for the 2.16 and 1.64 mm average ring thicknesses is higher than the velocity seen for the thicker rings. It is seen that the average radial velocity of the stiffener varies greatly with stiffener thickness. It is observed that average velocity values vary widely with failure mode, with lowest velocities occurring in mode III collapses and the highest velocities occurring in the mode II collapses. Additionally, there is an inverse relationship between

collapse pressure and velocity at the ring stiffener. The cause of this relationship could be due to the portion of the outer cylinder loading the ring stiffener. The ring thicknesses that collapse in mode III have a smaller portion of the outer cylinder loading the ring stiffener. The smallest average ring thickness has the largest average velocity because the ring stiffener collapses in this case, where it does not in cases of larger thickness.

Figure 13. The average ring stiffener velocity plotted against average ring thickness. Similar to the collapse pressure, the velocity at the location of the ring stiffener remains constant at approximately 6 meters per second until a sudden increase as the mode of failure changes.

The last parameter that ring thickness has an effect on is the dwell time between collapses. Figure 14 shown below depicts the average dwell time as a function of average ring thickness. The plot shows that as the average ring thickness decreases the average dwell time reaches a

maximum value and then drops to near zero. The maximum average dwell time for an average ring thickness of 4.1 mm is due to the mechanism of collapse for the ring stiffener. The partial deformation of the ring stiffener reaches an optimum point where the stiffener deforms just enough to prolong the second segment from collapsing. The drop in average dwell time occurs due to the transition towards mode II failure. In mode II collapses the structure collapses uniformly, therefore the time between collapses is almost zero.

Figure 14. The average dwell time plotted against average ring thickness. From the figure, as the ring thickness decreases the dwell time slowly increases to a maximum of 1.5 ms and then drops to nearly zero. This peak dwell time is due to the collapse mechanism discussed in the previous section for partial deformation of the ring stiffener.

SECTION 5 - FINITE ELEMENT MODELING

Two computational models of the implosion experiments for a ring stiffened cylinder were developed using Abaqus/CAE. The models were developed to give more accurate pressures to compare to the experimental data and formulate a relationship between the effective length of the cylinder to the ring stiffener. In order to develop a realistic model, a contact modeling technique was employed for the first model. In this model, the ring stiffener and cylinder are created as two separate parts or unbonded to the cylinder. Each part is given the material properties of Aluminum 6061-T6 and each part is placed into an individual shell sections. The thickness of each shell section is defined at this point. Next, two instances are created to assemble the ring stiffened cylinder. The cylinder can be partitioned using three datum planes. The ring stiffener and the cylinder are then meshed. Next, distributing coupling is used to simulate the contact between the cylinder and stiffener. To do this, a reference point is created in the center of the cylinder. The coupling constraints can be added to the reference point and the surface of the cylinder shown in Figure 15 below. Next, an interaction property is made for the normal and tangential contact behavior. The contact is then defined as between the outer surface of the ring stiffener with the inside surface of the cylinder. Next, a buckle step is created and the boundary condition for the endcaps is specified. Lastly, an axial load on the edge of the cylinder and a hydrostatic load on the outer surface of the cylinder are placed.

The second model generated was a more simplistic model compared to the unbonded model discussed above. This model simulated the ring stiffener as a part of the cylinder or bonded to the cylinder. First the cylinder is partitioned using two datum planes at the boundaries of the ring stiffener which is shown in Figure 15 below. The part is given the material properties of Aluminum 6061-T6 and the section between the two datum planes is assigned its own shell

section which the rest of the cylinder is assigned its own shell section. The thickness of the stiffener section and the cylinder shell section is defined at this point. The stiffener shell section thickness is the thickness of the cylinder plus the thickness of the stiffener. The cylinder and ring stiffener sections are then meshed. Similar to the first model, a buckle step is created, the boundary condition for the endcaps is specified, and an axial load on the edge of the cylinder and a hydrostatic load on the outer surface of the cylinder are placed. Now, the models can be run to solve for the eigenvalues of pressure and buckling mode.

Figure 15. Finite element model of a) the unbonded geometry and b) the bonded geometry.

Table 3. Pressure results of mode 2 and 3 solutions from the finite element modeling for a ring stiffened cylinder.

Ring Thickness (mm)	Unbonded Mode 2 Solution (MPa)	Unbonded Mode 3 Solution (MPa)	Bonded Mode 2 Solution (MPa)	Bonded Mode 3 Solution (MPa)
0.00	2.526	5.602	2.533	6.270
0.03	2.636	5.947	2.548	6.273
0.10	2.669	6.043	2.585	6.278
0.20	2.728	6.163	2.653	6.287
0.30	2.815	6.317	2.737	6.295
0.40	2.920	6.460	2.840	6.303
0.50	3.044	6.586	2.963	6.312
0.60	3.189	6.636	3.106	6.320
0.70	3.355	6.644	3.270	6.328
0.80	3.540	6.652	3.455	6.336
0.90	3.746	6.660	3.659	6.344
1.00	3.972	6.668	3.885	6.352
1.10	4.214	6.675	4.126	6.359

1.20	4.469	6.682	4.386	6.367
1.30	4.739	6.689	4.661	6.374
1.40	5.022	6.695	4.951	6.381
1.50	5.316	6.701	5.252	6.388
1.60	5.620	6.708	5.563	6.394
1.70	5.931	6.713	5.881	6.401
1.80	6.246	6.719	6.205	6.407
1.90	6.564	6.724	6.531	6.413
2.00	6.881	6.730	6.857	6.419
2.50	8.188	6.753	8.412	6.445
3.00	8.237	6.771	9.712	6.486
3.50	8.280	6.786	10.701	6.502
4.00	8.318	6.799	11.421	6.527
5.00	8.380	6.818	12.318	6.547
6.00	8.429	6.832	12.806	6.567

The pressure results of both finite element models are given above in Table 3. The expected mode and pressure corresponding to each ring stiffener thickness is highlighted in green. Figure 16 below shows the combination of mode II and III pressures expected from the bonded and unbonded FEM results. Compared to the experimental data, the bonded model does a better job of predicting mode III collapse pressures than the unbonded model. However, the expected mode II pressures given by both finite element models overestimate the collapse pressure. This could be due to the models predicting the ring stiffener to have more structural integrity than the experiments. Additionally, the finite element models do not account for a confining environment which as previously discussed plays a role in collapse pressure and mode of collapse. Another major limitation of these models is the exclusion of fluid-structure interaction. This after the point of critical buckling, the model becomes invalid. Overall, the bonded model is more accurate than the unbonded model, but more work can be done to improve it such as using solid elements for thicker ring stiffeners, including fluid structure interaction, and refining the mesh with 8 node elements or 20 node hexahedrals instead of 4

node quads. Due to time limitations, these additional improvements for not able to be made for this study.

Figure 16. Pressure versus ring stiffener thickness for the results of the bonded and unbonded finite element models compared with the experimental results.

SECTION 6 - RELATIONSHIP BETWEEN RING STIFFENER THICKNESS AND UNSUPPORTED LENGTH

The previous section discussed the contact modeling technique used to simulate the ring stiffened cylinder. This section relates the ring stiffener's thickness to a parameter referred to as the effective length of the ring-stiffened cylinder. The effective length factor can be defined as an equivalent length of an unstiffened cylinder whose collapse pressure equals the collapse pressure of a stiffened cylinder of a fixed length but with a given stiffener thickness. This effective length, when normalized by the fixed length of a stiffened cylinder, is 1 when there is no ring stiffener and approaches 0.5 as the ring stiffener thickness increases it begins to act like a simply supported boundary condition, effectively dividing the cylinder in half. In the latter case, the collapse pressure of the stiffened cylinder is effectively the collapse pressure of just one half of the cylinder. In order to relate the effective length to the ring stiffener thickness, firstly von Mises' equation as a function of cylinder length had to be modeled using a simple curve-fit method, in a range of full specimen length to half the specimen length and for the cylinder thickness, radius, and material. A power fit shown by Equation 2 below was used to model the curves for mode 2 and 3 buckling shapes with a 0.99 correlation factor for both modes. The following equation was used to power fit for mode 2 and 3:

$$P_{cr}^n = K_n * L_{eff,n}^{\gamma_n} + A_n \quad (2)$$

Where P_{cr}^n is the critical buckling pressure, $L_{eff,n}$ is the effective length of the cylinder, K_n , γ_n , and A_n are constants that are graphically determined for $n = 2$ or 3 . The equation can be rearranged to solve for the effective length. However, to obtain collapse pressures of the ring stiffened cylinders for a range of stiffener thicknesses, Abaqus FEA was used. The geometry of the specimen in Abaqus FEA was modeled so that the ring stiffener is a part of the cylinder

or bonded to the cylinder. A linear perturbation buckling analysis was conducted using Abaqus, which identified the buckling pressure of the stiffened structure. Using the collapse pressures that the FEA model provided, effective length was calculated for each thickness. Figure 17a below shows the normalized effective length factor plotted as a function of the ring stiffener thickness. In the figure, the effective length factor for modes 2 and 3 is shown. Graphical examination of these two curves should allow one to identify the transition point from mode 2 to mode 3, allowing for a curve of true solutions to be determined which correlates with experimental values. This is given by the expected length factor line in Figure 17a and b. The expected length factor line, determined from the FEA solutions, was curve fitted using a bi-exponential line fit given by Equation 3 below.

$$G_n(h) = H_n * e^{-b_n h} + C_n \quad (3)$$

Where G_n is the expected length factor, h is the ring stiffener thickness, H_n , b_n , and C_n are constants that are graphically determined for $n = 2$ or 3 . The correlation factor for $n = 2$ and 3 were 0.992 and 0.989 respectively. Figure 17b also contains the experimental data points for seven average ring thicknesses. The experimental data points align with the expected length factor line very well, except for the two smallest ring thicknesses. This could be due to inaccuracies in the FEA model that give the ring stiffener more structural integrity than the machined ring stiffeners. Figure 17c below shows the stiffening factor plotted as a function of ring stiffener thickness. The stiffening factor was calculated by dividing the collapse pressure corresponding to each ring thickness by the collapse pressure of cylinders with the same dimension without a ring stiffener. As observed in Figure 17c the stiffening factor increases with ring stiffener thickness, however after the mode change at 2 mm ring stiffener thickness that stiffening factor levels out. The figure additionally shows experimental points for the seven average ring thicknesses. A similar trend can be seen in the correlation between the expected

and experimental results as in Figure 17b. While this method of modeling this not 100 percent accurate for mode II collapses, it comes very close for the mode III collapses. In addition, further work can be done to improve the finite element model.

Figure 17. The effective length factor versus ring stiffener thickness (a) plotted for mode II and III using the power fit and (b) plotted as a combination of mode II and III with a bi-exponential fit and experimental data. The stiffening factor as a function of ring stiffener thickness is given in (c) along with experimental data points.

SECTION 7 - POST MORTEM

Figure 18. Post mortem images from specimen a) 1, b) 3, c) 10, d) 15, and e) 16 of the front and side views of the structure.

The post mortem images of the three types of collapse behavior are shown above in Figure 18. Figure 18a shows the specimen discussed in Section 4.1.1 which failed in two mode IIIs. From the figure, tearing at the boundary of ring stiffener and the endcaps can be seen. This tearing is likely due to the bending moment created when each segment was collapsing and the material is pulled toward the valley. The ring stiffener location seems mostly undeformed. Additionally, the side view of each segment shows complete wall contact. Figure 18b shows the first specimen discussed in Section 4.1.2 which failed in one full and one partial mode III. From the figure, tearing at the boundary of ring stiffener can be seen. However, there is not tearing at the boundary of the endcaps. This could be due to the velocity of the ring stiffener was not high enough to cause tearing at the endcaps. Once again the location of the ring stiffener looks mostly undeformed. Additionally, the side view of each segment shows complete wall contact on the segment on the left, while the segment on the right has not reached full wall contact. Similarly to part a, 20c shows the second specimen discussed in Section 4.1.2 which failed in two mode IIIs. Once again, there is only tearing at the ring stiffener boundary, but no tearing at the endcaps. The ring stiffener is visibly deformed. The side view also shows complete wall contact on both sides. The segment on the left shows a significant amount of bending of the lobe seen in the front view. This could be due to the structure bending axially during the collapse. Figure 18d shows the specimen discussed in Section 4.1.3, which collapsed in a single mode II. There is only tearing at the one end cap and the ring stiffener has completely been crushed. The side view shows the complete wall contact on each end. Lastly, Figure 18e shows the specimen discussed in Section 4.1.4, which collapse in a single mode II and contained no ring stiffener internally. The side view shows complete wall contact and there is no tearing at the boundaries of the end caps.

SECTION 8 - CONCLUSIONS

An experimental study was conducted to observe the transition failure mode III to failure mode II and understand the various collapse behaviors of reinforced aluminum cylinders. The results of these experiments are summarized by the following conclusions:

- The failure mode of the structure depends on the amount of deformation sustained by the ring stiffener as the thickness of the ring stiffener is varied. The deformation can be broken down into three types of collapse behavior: **minimal ring deformation, partial ring deformation, and complete collapse of the ring.**
- The drop in pressure at the confinement end after the first collapse is much larger for mode II collapses. The strength of the hammer pulse at the confinement after the first collapse is approximately $0.6P_c$.
- The collapse pressure is relatively the same for mode III failures, however as mode II failure is reached the pressure drops.
- The velocity at the location of the ring stiffener is inversely proportional to the collapse pressure as the ring thickness varies.
- The dwell time slowly increases as the ring thickness decreases, reaching a maximum value and then dropping to near zero.
- The bonded finite element model gave more accurate resulting pressures than the unbonded finite element model compared to the experimental pressures.
- The effective length approximation as a function of ring stiffener thickness shows good correlation for the experiments collapsing in mode III, however the experiments collapsing in mode II were not as close to the expected effective length.

- The post mortem analysis showed large tearing at the location of the ring stiffener and end caps for some specimen along with some visible deformation of the ring stiffener.

SECTION 9 - FUTURE WORK & RECOMMENDATIONS

Future Work

- Energy calculation for ring stiffened cylinders in a confining environment and further refinement of the FEA model
- Ring stiffened cylinders of the same geometry in the Big Tank to compare collapse results to this study
- Multiple ring stiffeners in a cylinder – however, the expected collapse pressures will exceed every facility available at DPML so a new facility or upgrades to current facilities are needed
- Ring stiffened composite cylinders in open ocean and confining environment – this topic is not as highly studied as metallic ring stiffened structures
- Shock blast of composite metal hybrid plates – this would be interesting since there are hybrid ship hulls made of steel and composites

Recommendations

- Writing more standard operating procedures for equipment in the lab so that knowledge does not get lost or incorrectly passed down through generations of students – this is also a very practical skill for industry work
- Conducting preventative maintenance instead of waiting for equipment to break or fail and waiting to repair broken and damaged equipment until it is needed – getting rid of the “it’ll be fine mentality”
- Scheduling monthly trainings where students who are skilled in certain software or important applied theoretical work very commonly used in the lab, giving an hour or two hour lecture on the topic or technique – this will hopefully facilitate widespread

learning among all the students and older, more experienced students learn good teaching skills while new students are able to train on various topics.

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APPENDIX A: DISPLACEMENTS, PRESSURE, AND VELOCITY DATA AS A FUNCTION OF TIME FOR EACH EXPERIMENT

Specimen 2:

Figure 19. DIC and pressure data for specimen 2 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in two mode III segments, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is roughly the same, however due to the bending of the cylinder the DIC software lost correlation so the full displacement could not be seen in the DIC results. The full deformation of the valleys can be seen in (e). The ring has negligible deformation compared to the two valleys. As observed from (c) above the first segment collapses with a large compressive velocity, however the second segment collapses with a much smaller

velocity. Additionally, the pressure drop at the confinement end is $1.01P_c$ and the strength of the hammer pulse is $0.56P_c$.

Specimen 4:

Figure 20. DIC and pressure data for specimen 4 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full and one partial mode III segments, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is roughly the same. The full deformation of the valleys can also be seen in (e). The ring has negligible deformation compared to the two valleys. As observed from (c) above both segments collapse with approximately the same compressive velocity. Additionally, the pressure drop at the confinement end is $1.08P_c$ and the strength of the hammer pulse is $0.61P_c$.

Specimen 5:

Figure 21. DIC and pressure data for specimen 5 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full and one partial mode III segments, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is roughly the same, however one segment rebounds. The full and partial deformation of the valleys can also be seen in (e). The ring has slight deformation after the second segment collapses. As observed from (c) above the first segment collapses with a larger compressive velocity than the second segment. Additionally, the pressure drop at the confinement end is $0.96P_c$ and the strength of the hammer pulse is $0.71P_c$.

Specimen 6:

Figure 22. DIC and pressure data for specimen 6 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full and one partial mode III segments, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is not roughly the same. The full and partial segment collapses of the valleys can also be seen in (e). The ring has slight deformation after the second segment collapses. As observed from (c) above both segments collapse with approximately the same compressive velocity. Additionally, the pressure drop at the confinement end is $0.94P_c$ and the strength of the hammer pulse is $0.63P_c$.

Specimen 7:

Figure 23. DIC and pressure data for specimen 7 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full and one partial mode III segments, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is roughly the same, however after wall contact on both segments the DIC correlation was lost. The full and partial segment collapses of the valleys can also be seen in (e). The ring has slight deformation after the second segment collapses. As observed from (c) above both segments collapse with approximately the same compressive velocity. Additionally, the pressure drop at the confinement end is $0.93P_c$ and the strength of the hammer pulse is $0.62P_c$.

Specimen 8:

Figure 24. DIC and pressure data for specimen 8 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full mode II and one full mode III segments, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is roughly the same, however first segment rebounds after wall contact. The collapsed segments can also be seen in (e). The ring has slight deformation after the second segment collapses. As observed from (c) above both segments collapse with approximately the same compressive velocity. Additionally, the pressure drop at the confinement end is $0.99P_c$ and the strength of the hammer pulse is $0.56P_c$.

Specimen 9:

Figure 25. DIC and pressure data for specimen 9 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in two full mode III segments, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is roughly the same, but does not reach -18 mm which is the radius of the cylinder. This could be due to the DIC software lost correlation. The full segment collapses of the valleys can also be seen in (e). The ring has slight deformation after the second segment collapses. As observed from (c) above both segments collapse with approximately the same compressive velocity. Additionally, the pressure drop at the confinement end is $1.01P_c$ and the strength of the hammer pulse is $0.61P_c$.

Specimen 11:

Figure 26. DIC and pressure data for specimen 11 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full mode II, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is roughly the same. The full specimen collapse can also be seen in (e). The ring completely deforms along with the cylinder. As observed from (c) above both segments collapse with approximately the same compressive velocity. The ring stiffener has a larger compressive velocity than the two segments. Additionally, the pressure drop at the confinement end is $1.10P_c$ and the strength of the hammer pulse could not be seen since the pressure data was cut off.

Specimen 12:

Figure 27. DIC and pressure data for specimen 12 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full mode II, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is roughly the same. The full specimen collapse can also be seen in (e). The ring completely deforms along with the cylinder. As observed from (c) above both segments collapse with approximately the same compressive velocity. The ring stiffener has a larger compressive velocity than the two segments. The confinement end sensor malfunctioned during this experiment so no pressure data could be seen.

Specimen 13:

Figure 28. DIC and pressure data for specimen 13 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full mode II, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is not roughly the same. This is due to the specimen collapsing with the lobe facing the camera and DIC correlation is lost at the actual valley. The full specimen collapse can also be seen in (e). The ring completely deforms along with the cylinder. As observed from (c) above both segments collapse with approximately the same compressive velocity. The ring stiffener has a significantly larger compressive velocity than the two segments. Additionally, the pressure drop at the confinement end is $1.14P_c$ and the strength of the hammer pulse could be seen since the pressure data got cut off.

Specimen 14:

Figure 29. DIC and pressure data for specimen 14 showing (a) normalized pressure and radial displacement versus time at the two valleys, (b) at the location of the ring stiffener, (c) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full mode II, (d) the pressure pulses from the center and confinement end, and (e) the post mortem of the specimen. Note that the deformation in the two valleys is roughly the same. The full specimen collapse can also be seen in (e). The ring completely deforms along with the cylinder. As observed from (c) above both segments collapse with approximately the same compressive velocity. The ring stiffener has a significantly larger compressive velocity than the two segments. The confinement end sensor malfunctioned during this experiment so no pressure data could be seen.

Specimen 17:

Figure 30. DIC and pressure data for specimen 17 showing (a) normalized pressure and radial displacement versus time at the valley, (b) the radial velocity color map as a function of time and length across the cylinder as the structure collapses in one full mode II, (c) the pressure pulses from the center and confinement end, and (d) the post mortem of the specimen. Note that DIC correlation was lost so full wall contact cannot be seen, however the full specimen collapse can be seen in (d). As observed from (b) above the cylinder with uniform velocity. Additionally, the pressure drop at the confinement end is $1.13P_c$ and the strength of the hammer pulse is $0.62P_c$.

APPENDIX B: TUBE-IN-TUBE CALIBRATION STANDARD OPERATING PROCEDURE

Specimen Knowledge and Preparation:

1. For any isotropic material, check the Von Mises' paper and calculate the collapse pressure of your specimen based on its geometry. For any composite or anisotropic materials, check previous papers on the DPML website for the collapse pressure for that specific geometry and material. For composites a rule of thumb is to use geometries that have already been tested before.
2. When measuring tube specimens, use the sample spreadsheet for measuring tubes. The thickness measurements should be taken with a micrometer while, the rest of the measurements can be taken using standard calipers. If the specimen is not a tube, a new standard measuring spreadsheet should be made.
3. Before speckling, identify the thinnest measured mark of the tube and measure the same distance on each side of the mark. Tape those distances (Usually in a tube measured with 12 lines once the thinnest line across the tube is identified, we go 3 marks on each side of the line and tape on those lines) across the tube. The area marked between the two pieces of tape should cover roughly half the tube or cover a little more than the field of view.
4. Spray the area between the two pieces of tape with white spray paint. Spray multiple light coats to cover any writing or marks under paint. Speckle the area after the white paint has dried. Always put a unique speckle in the very center of your specimen as to easily identify the middle when placing in the specimen in the tube in tube.

Calibration Procedure:

(a) When moving the cameras, be sure to unplug all of the wires before moving. Cap the lenses and the cameras after removing the lenses from the cameras.

(b) Slide the cameras onto the tripod as shown below

(c) Following the figure below, plug in the wires as shown.

(d) Calculate the depth of field for the lenses being used in the experiment. Typically 85 mm lenses are used with a distance of 66-72 inches from the tube in tube midplane to the edge of the tripod fixture. There is an app that is commonly used for calculating this called Digital DoF. The camera in any online depth of field calculator does not matter. Make sure the depth of field is larger than your specimen radius so any outward deformation does not cause the software to easily loose correlation.

(e) Remove the following two sensors using a torque wrench.

If there is black tape on the sensor wire, then the wire cannot be disconnected from the sensor for easy removal. The torque wrench attachment should have a space for the wire to turn as the sensor is taken out. However if there is no black tape carefully turn and disconnect the sensor wire from the sensor then use the torque wrench to take the sensor out.

(f) Take the appropriate calibration (typically we use a 12 dots by 9 dots with 7 mm spacing) grid and tape a rubber band to the back. Insert the extendable rods into the rubber band as shown below. Be sure to write down all the parameters on the back of the grid before filling the tank.

Next, insert the extendable rods into the tube in tube and extend until they stay in place. Now take a plastic cord and tape one side on the back on the calibration grid. Run the other end through one of the sensor opening on the tube in tube and then back in through the second sensor opening. Tape the second end of the cord to the back of the calibration grid as shown below.

(g) Next make sure the cameras are parallel with the tripod mounting fixture using calipers as shown below:

First, extend the calipers out slightly. Next, press the edge of the calipers into one side of the tripod mount and check the distance reading on the caliper. Repeat these steps again on the other side. If a very close reading is seen on both sides, then the cameras are roughly parallel to the tripod mount. Finally, lock the cameras in place.

- (h) Set the aperture of the lenses to 8. This is what we normally use for standard implosion experiments. However, in some previous work an aperture of 5.6 was used as well.
- (i) To check if the tripod mount is parallel to the tube in tube, use a measuring tape, measure from the tube in tube to the edge of the tripod mount.

(j) Next, to center the cameras to the window on the tube in tube, very slightly unlock the cameras and move both cameras left to right until the image (seen on the FastCam Viewer) on each camera is the same. Lock one camera to the mount. Tape a protractor to the camera as shown below:

(k) Move one camera at a time until the window is centered on the FastCam Viewer software as shown below. Usually with 85 mm lenses with a distance of 72 inches the angle for each camera should be roughly 5 degrees. So the total angle seen on the protractor should be roughly between 9-11 degrees.

- (l) Carefully clean the window with kimwipes and methanol (and gloves!! You MUST wear gloves while using any chemical like methanol). Start at the center and be careful to check that there isn't any rust or brown substance on the kimwipe. Pushing around rust or abrasive particles on the window can cause scratches.
- (m) Place the window in the tube in tube. Next place the fixture on the window and begin putting in the bolts in a star pattern. Usually we put in bolt on the top and bottom first to hold the window (do not let go of the fixture) then begin to put in the rest of the bolts.
- (n) To fill the tank open (parallel) the inlet valve and make sure the outlet valve is closed (perpendicular). At this point it does not matter if the bleed valve is open or not.

(o) Begin filling the tank and be sure to not let the tank over fill since the two sensor holes are open due to the calibration grid being in place. As the tank is filling, place the lights in front of the cameras so that the lights don't melt the cameras. Move the lights so that the lighting on the specimen is even and no glare is seen by the cameras.

(p) Once the tank is full, focus the cameras in water using the FastCam Viewer software. The best way to focus is to zoom into the grid and lower the aperture one notch. Now focus the lenses first by going to one extreme and then work your way back to the most focused point.

(q) Place a level on the tube in tube above the window. Make sure the window is level before taking any images as shown below.

- (r) On the FastCam Viewer software, right click on the camera 1 window. In the drop down menu that appears, click camera options. A small window will pop up, on the thumbnails on the left click O/I. Set Trig TTL In to Trig Neg and Sync In to On Camera Pos. Now click Apply at the bottom of the pop up window. Next left click on the camera 2 window. The same small window will pop up, on the thumbnails on the left click O/I. Set Trig TTL In to Trig Neg. Now click Apply at the bottom of the pop up window.
- (s) To shade the cameras, place the lens caps on the camera lenses. Now on the FastCam Viewer software click shading on the menu on the right. Any time parameters are changed in the FastCam Viewer software, you must shade again.
- (t) Lastly set the trigger mode on the menu on the right on the FastCam Viewer software. Select Random and set the number of frames from 50 to 1.
- (u) Now you are ready to start taking your calibration images. Two people are needed to calibrate any setup in the lab. One person sits at the laptop and clicks the trigger to take pictures while the other person slowly moves the grid around covering all degrees of freedom. For a standard implosion experiment we generally take around 300 pictures. You need at least 30 good images to get a calibration score in the VIC 3D software.
- (v) Save the images in the appropriate folder. Be sure that the file name for the camera one images are dic_0_ or refdic_0_ and the camera 2 images are dic_1_ or refdic_1_.

(w) Open the VIC 3D software on the laptop (You must have the DIC Key inserted in the laptop before opening the software). Under common tasks click Calibration Images. Next import all images from the folder of calibration images. Next click the black calipers on the top left corner.

(x) A pop up window should appear on the window, click the drop down menu for grid size and choose the appropriate grid size (12x19 -7mm). Now click edit and make sure all the parameters match the ones on the back of the grid used. Hit OK if the parameters match.

(y) Next, hit analyze and pull the DIC Key out of the laptop. Once the analyzing process is done a score should appear on the bottom right of the pop up window. The score should be below 0.05, however for the best results with this setup we aim for as low of a score as possible. You can scroll through the images and delete any bad scores on the top right of the pop window.

(z) The final check that you have a good calibration is to check the Y in the angles and see if it is a max of 5 degrees off the actual reading on the protractor. The reason that we will never see the exact angle as on the protractor is because the light has to travel through the 2 inch acrylic window and water to the specimen and back to the cameras so the light will be slightly refracted. Thus the software will think the cameras are at a larger angle than they are. Check the X under Distances as well since that should be roughly equal to the distance between the center of one lens to the center of the second lens.

If you have a good calibration click accept at the bottom right of the pop up window. Save the calibration by click File on the top left on the software. Click Save As and save the z3d file in the same file as the images.

* If you do not have a good score or the VIC 3D software doesn't pick up enough images, try taking the images again. If the new images still do not work, then make sure the cameras are parallel to the tube in tube or that the cameras are centered or that one camera isn't turned more degrees than the other. Lastly if all else fails drain the tank by opening (parallel) the outlet valve and closing (perpendicular) the inlet valve and try the calibration first in air so without the window then in glass by the putting the window back. If these two calibrations work, then move on to water again. If the glass calibration doesn't work, then try cleaning the window again. If the air calibration does not work, then you made a fundamental mistake somewhere in the setup so ask another more experienced student for help.

Experimental Procedure:

- (a) Take the window fixture and window out once the tank has drained. Take the calibration grid, extendable rods, and plastic cord out.
- (b) To place the sensors back, first clean the threads. Next wrap the threaded part of the sensor with thin Teflon tape. Using the torque wrench, screw the sensors back into the opening (Do not exceed 40 inch pounds). Once the sensor is flush with the inside of the tube in tube, do not turn the sensors any more. If the sensor is not flush by 40 inch pounds, then you need to go back and clean the sensor opening thread again or put less Teflon tape on the threads.
- (c) First take off the side of the tube in tube tank. Undo the bolts and gently place the side on the fork lift.
- (d) For tube specimens place the end caps in your specimen and screw on the spokes. The best way to make sure they spokes will slide into the tube in tube through the side to measure

from the center of the end cap to the end of the spoke to make sure they are all slightly under 3.5 inches since the tube in tube diameter is 7 inches.

- (e) Center the specimen and turn the spokes until the specimen will not move. Make sure the specimen is level so the one end of the tube is not higher than the other.
- (f) Place the side of the tube in tube back and put the bolts back in place. Put the window in as well and screw in the window fixture.
- (g) Using the fork lift, (make sure there is metal plate between the fork lift and the tube in tube before lifting) lift the tube in tube slowly as far as it will go.
- (h) Before turning on the pump, make sure the inlet valve and the bleed valve are open (parallel) while the outlet valve is closed (perpendicular). Turn the pump on to fill the tank.
- (i) Once the tank is full, slowly let the fork lift drop so that it is not supporting the tube in tube anymore.
- (j) Check to see that the tube in tube has not rotated by repeating step (r) from calibration. If the tank has rotated then use the wrench and hex key to make the window level.
- (k) Now on the FastCam Viewer software set the trigger mode to end trigger.
- (l) Make sure the AstroMed is on and the capture software is open. Go up to Capture and click Capture Settings in the drop down menu. Depending on the type of experiment we set the percent pre trigger. For a standard implosion experiment we set it to 75 percent. Make sure the sampling rate is 2 million. Click OK to go back to all the channels.

- (m) Now click Setup then click Amplifier Channel Settings in the drop down menu. Select channels 1-7, and click on span and set the Span and Center based on the pressure that will be seen in the experiment. For a standard implosion experiment we set the Span to 2.5 and the center to -0.25. Click OK when done.
- (n) Now go back to the FastCam software, click record twice until it says endless record.
- (o) Next on the AstroMed click the image with a graph and a green arrow below pointing to a grey box. A small window should pop up and say recording pretrigger data.
- (p) Test the trigger by hitting the trigger. If the AstroMed triggered without you pressing the trigger, check the wiring on the cameras. One of the wires could be loose. Or the trigger wire on the AstroMed is faulty.
- (q) If the test trigger worked, repeat step (n) and (o).
- (r) Take reference (roughly 5 images) images of your specimen and save them the same way you saved the calibration images. Open the VIC 3D software and click Calibration in the top left corner. Click "From Project File" in the drop down menu. Open the z3d calibration file you saved. Now import your reference images as speckle images.
- (s) Select the speckled region of your specimen. Click the green arrow on the top left corner. Select the appropriate subset size by roughly checking that each grid box contains about 9 dots. A window will pop up, in the window click Run. Let the analysis run and click close when it is done.

(t) Now click Data, click Coordinate Tools, and then Compute Cylindrical Transformation in the drop down menu. A window should pop up, hit Accept on the bottom right.

- (u) The computed radius should be close to the actual radius of the specimen.
- (v) Close the bleed valve on the tube in tube. Turn the pressure gauge on as well. Lastly, turn on the pump and begin recording the pressure readings. Previously, we used a phone on selfie mode to record the pressure as we pressurize.
- (w) One person should be at the pump valve to pressurize while the other person has their hands on the trigger and reading the pressure out loud.

Pump Valve
used to
pressurize
the tank

- (x) Slowly pressurize the tank. Once you hear a large crack hit the trigger quickly. You might hear small crackling while pressurizing, however when your specimen implodes, it will be large loud crack. Quickly turn the pump off and close the inlet valve. To depressurize slowly open the bleed valve until the pressure sensor reads 0 psi.
- (y) Go to the FastCam Viewer software and make sure you got the implosion in the recording. Chop the implosion event to about 1000 images at most. Play back the chopped segment to make sure you didn't accidentally chop the implosion. Save the images to a folder.
- (z) Now insert a flash drive into the AstroMed, click File on the top left corner. Select Archive File and Entire File in the drop down menu. A window will pop up, click the folder with a magnifying glass in the bottom left corner. In the pop up window find the flash drive and the folder designated for the pressure data and save the data.

Data Analysis:

Since there are various types of data analysis for implosion experiments, please reference the VIC-3D manual and Dr.Shukla's Experimental Solid Mechanics book for DIC analysis. For pressure analysis import your saved pressure data into the AstroView software. Select the region with your data and save it as an excel file. Next import the data into Matlab and write a code to filter and normalize the pressure data or use a previously written code.

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