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CYLINDRICAL STRUCTURE UNDER SHOCK LOADING

by

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March 2023

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CYLINDRICAL STRUCTURE UNDER SHOCK LOADING

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Submitted in partial fulfillment of the
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ABSTRACT

Underwater pressure vessels experience a multitude of dynamic and pressure loading when in a submerged environment. Internally, those forces are negligible because of the sound structural integrity the vessel is providing. However, if an underwater explosion should occur—the chances are slim but never zero—the outer shell of that pressure vessel would be affected depending on what is on the other side. This research investigates composite cylinders' response to underwater shock loading through directed pressure loading by compressed air shock pipe underwater release. Two cases are considered, single-wall and double-wall cylindrical structures, to determine the material response and possible failure. Both cases are tested at various stand-off distances, with 0%, 50%, or 100% water levels internally or within the annulus. Fluid-structure interaction effect was discussed for each case. Strain gauges are attached at specific points on the cylindrical structure, and underwater blast sensors are used to record pressures from the directed shock loading. Experimental data is collected and stored using a National Instruments PXIe-1071 processor. By presenting the behavior of composite structures in response to dynamic loading, we provide data for future and present composite vessel design as well as validate current research work.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
AM	additive manufacturing
CASPUR	Compressed Air Shock Pipe Underwater Release
CASS	Compressed Air Supply System
CFC	carbon fiber composite
CTR	Composite Test Rig
DAQ	data acquisition
DOD	Department of Defense
FSI	fluid-structure interaction
NI	National Instrument [™]
PC	polycarbonate
PLA	polylactic acid
STL	stereolithography
STR	Shock Test Rig
UNDEX	underwater explosion
USN	United States Navy

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I. INTRODUCTION

The study of composite material is gaining way throughout the engineering and research industry. From vacuum-sealed lamination to additive manufacturing (AM), composites have seen multiple use cases in tactical and structural environments. Furthermore, three-dimensional (3D) printing, metallic powder sintering, and other emerging shaping techniques offer beneficial improvements in cost effectiveness, strength, and durability [1]. The tactical advantage of composite materials is its strength-to-weight ratio; comparable to metal, it is lighter in weight which results in improved operational performance [2,3]. This work will discuss the effects of fluid-structure interaction (FSI) for two types of material: carbon fiber composite (CFC) and polylactic acid (PLA) composite cylinders under shock loading.

A. BACKGROUND

One of the many unique challenges U.S. Navy (USN) vessels encounter is underwater explosions (UNDEX). Current programs that are specifically employed to test and analyze shock dynamics have the principle thought that a structure or equipment can execute its intended purpose or mission throughout any major environmental situations [4]. Accordingly, shock trials are tests conducted on the lead ship of its class to determine the survivability and any vulnerability of mission critical equipment. However, these trials are not only costly and time-consuming, but potentially dangerous to the vessel and the safety of the crew. Thus, a safety factor is considered, and the design limit is tested up to only two-thirds of its capability [5].

This goes to say that small-scale experimental tests and digital simulations are important with regards to understanding the overall response of the structure or material. Moreover, the current composite structures used by the fleet are manufactured using a large safety factor to warrant structural integrity, which inherently become over-designed where the benefits of the lightweight composites are voided [3]. This is the main reason why this topic has been extensively researched since the mid-20th century with an

emphasis on dynamic response and material application of composites subjected to UNDEX.

In addition, the development of marine structures is slowly turning to the use of non-traditional materials and AM processes concerning ship building [6]. Certainly, there are advantages as well as disadvantages of composites when compared to the conventional metals. For example, composites weigh less than its equivalent metal part by 20 to 25 percent, and more importantly, maintenance cost is reduced by deducting fatigue and corrosion effects; however, composites require specialized training, sophisticated diagnostics, and expensive capital equipment [7].

From a research standpoint, the response of composite materials shows enough relevance to test its boundaries through various environments and loading mechanisms. For instance, a coupled structure comprised of composite plates was subjected to impact loading and analyzed with various water levels in between spacing [8]. A similar set-up was used, with an impact load, only the structure were concentric composite cylinders [9]. Other studies analyzed the response of underwater composite cylinders to impulsive loads [10–12]. In addition, the internal acoustic field of submerged composite materials under external shock loading was investigated [13,14].

Comparatively, a water-filled fiber composite tube subjected to axial shock wave loading was assessed [15]. Shock loading from a shock tube was used to determine the response of 3D woven composite materials [16]. More recently, the analysis of flexible cylindrical shells was tested using multiple blasts, either sequential or simultaneous bursts, in a dry setting [17]. Additional types of composites, such as PLA, have also been examined before and after printing of its mechanical performance [18].

B. OBJECTIVES

The objective of this research is to fabricate, test and analyze the dynamic response of CFC and PLA composite cylinders subjected to underwater shock loading. The CFC cylinder was created using a filament winding process oriented with a $\pm 45^\circ$ layer, and the PLA cylinder was printed using additive manufacturing. A cylindrical shape was chosen to model a pressure vessel submerged underwater. Two variations of

cylindrical structures are tested at different stand-off distances from the loading source while submerged. One case includes a single-walled cylinder with either air or water internal to the structure. The second is a double-walled cylinder that contains different water levels in the annulus, while the inner most cylinder is strictly filled with air.

Experimental testing is conducted inside an anechoic tank designed with angled redwood panels throughout the walls and tank floor. This is intended to minimize the reflected shock waves that can alter the pressure reading resulting from the load source. The shock loading source is provided from previous thesis work from Naval Postgraduate School (NPS) and is utilized in this research. The analysis is focused on the FSI effects of CFC and PLA composite cylinder subjected to underwater shock loading.

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II. EXPERIMENTAL SETUP

The experimental set-up is organized into three sections: Section A discusses the fabrication of each composite material; Section B will discuss post-fabrication and requirements for testing; and Section C will go over the cylinder support structure redesign.

A. COMPOSITE CYLINDER FABRICATION

Originally, the CFC cylinder was the only material to be tested, but due to the nature of the winding process sufficient consistency in the samples being created was not obtained. Therefore, the solution to the inconsistent sample problem was to introduce a more precise method, which is additive manufacturing using PLA material.

1. Carbon Fiber Composite Cylinder

The process of creating a CFC cylinder consists of preparing the winding machine and the resin bath. The dry fibers used in this study is “TORAY” T700S with ProSet[®] M1002 epoxy resin and hardener. Table 1 provides the material properties where E is young’s modulus, G is shear modulus, ν is kinematic viscosity, and ρ is the fluid density. In addition, the subscripts depict the longitudinal and/or tangential directions.

Table 1. CFC Cylinder Material Properties. Source: [9].

E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	G_{TT} (GPa)	ν_{LT}	ν_{TT}	ρ (kg/m ³)
139	7.35	2.18	0.432	0.236	0.216	1485

The basic process of creating the composite sample using the 4-axis winder is described here. The winding machine is operated using the X-winder Designer program, where the cylinder mold parameters are entered based on the diameter and length of the cylinder to be fabricated. Once the program settings are completed, the mandrel will then be prepared with the selected mold to hold the wet fibers that goes through the resin bath.

The dry fiber roll is then placed in the carriage, fed through the feed guides into the empty resin bath, and finally to the mandrel opening.

Following the mandrel preparation, the epoxy and hardener are then combined by weight ratio. A 4.17:1 ratio was used in this research. After mixing for five minutes, pour in a sufficient amount of resin mixture into the resin bath, where the dry fiber is already in place. Pull the dry fiber from the mandrel opening towards the mandrel to ensure the dry fiber is coated with resin prior to start of winding. Cut off the excess dry fiber and tape the start of the fiber that is coated with resin to the prepared mandrel. Select the PLAY button on the X-winder Designer program ensuring there is enough resin mixture to refill the resin bath for a full layer. Figure 1 displays the winding machine with a dry fiber roll loaded and a 7.6 cm (3 in) cylinder mold on the mandrel.

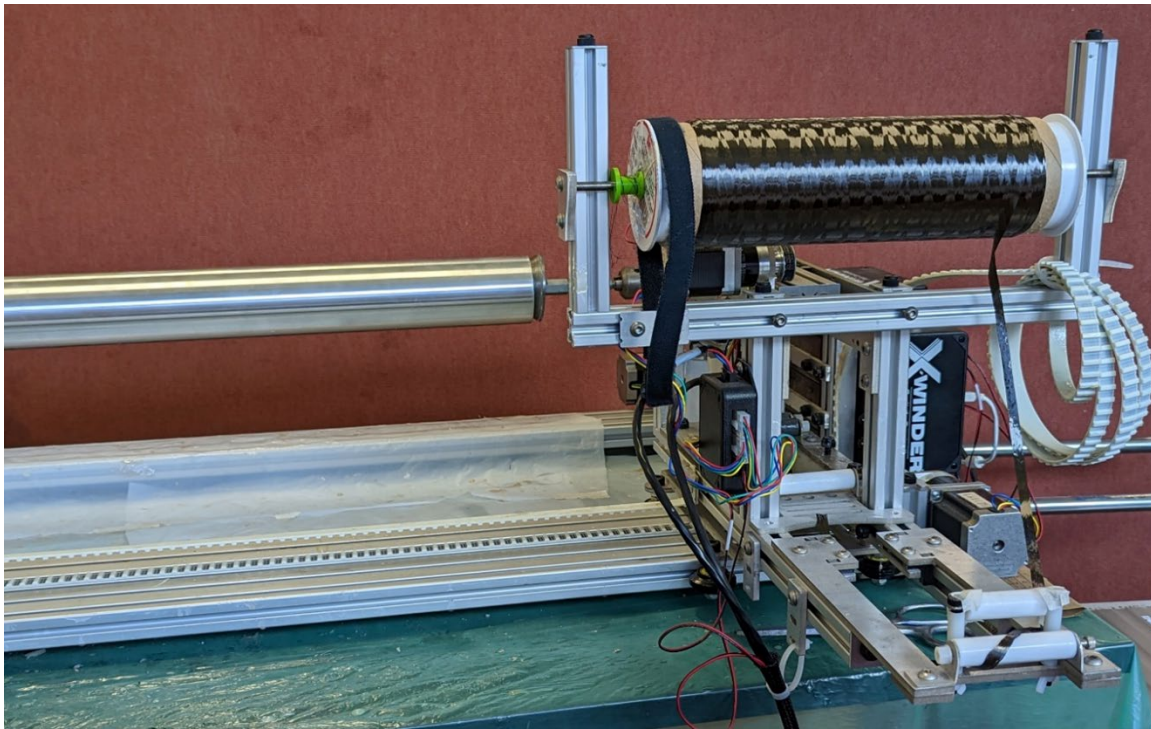


Figure 1. X-Winder Filament Winding Machine

Finally, once the winding process is complete, immediately wrap the wet cylinder with heat shrink tape for a smoother finished surface in preparation of strain gauge

application, to be discussed later in the paper. The curing time for a cylinder this size will take approximately 24 hours to fully cure and depending on the number of layers placed, it may take longer to harden. A total of 10 composite cylinders were fabricated with six cylinders designed to have a 15.2 cm (6 in) diameters and four cylinders with 12.7 cm (5 in) diameters. The cylinder mold for both diameters were designed to produce a 66 cm (26 in) sample length as shown in Figure 2.

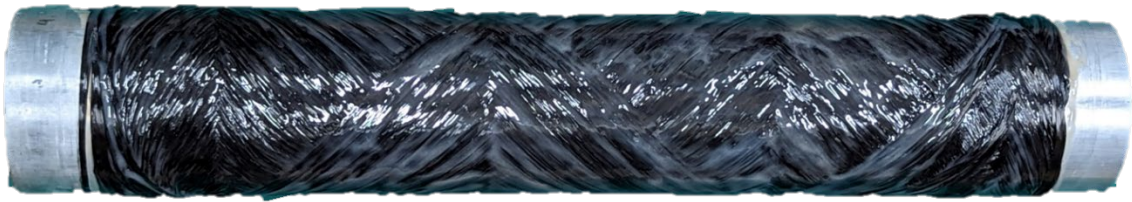


Figure 2. Fully Cured CFC Cylinder with Cylinder Mold, 15.2 cm (6 in) Diameter

The amount of resin mixture per cylinder varied with the number of layers as well as the room temperature at the time of winding. Table 2 provides the weight of resin to hardener mixture used based on the number of layers for each cylinder diameter.

Table 2. Resin Mixture Based on Diameter and Number of Layers

Cylinder Diameter	Number of Layers	Resin [g]	Resin [oz]	Hardener [g]	Hardener [oz]
15.2 cm (6 in)	One	200	7.05	48	1.69
15.2 cm (6 in)	Two	600	21.16	144	5.07
12.7 cm (5 in)	Two	400	14.11	96	3.38
12.7 cm (5 in)	Three	500	17.63	120	4.23
12.7 cm (5 in)	Four	1,000	35.27	240	8.46

2. Polylactic Acid Composite Cylinder

The PLA cylinder samples were designed using SolidWorks computer application, then saved as a stereolithography (STL) file format to be able to be read by the slicer program for printing. The slicer program utilized was the Ultimaker Cura 4.7 Slicer that coordinates with the Ultimaker S5 Pro, which is the fully automated three-dimensional (3D) printer employed. The print area is an enclosed space capable of a build volume of 33 cm x 24 cm x 30 cm (13 in x 9.4 in x 11.8 in) along with a material station that holds six spools for printing and storage.

All PLA samples were printed using the print settings given in Table 3 for a controlled production. These print settings were established from the research of Schmeier, who studied the failure criteria of a notched PLA material [19].

Table 3. PLA Sample Print Settings for Ultimaker Cura 4.7. Adapted from [19].

Print Setting	Value
Layer Height (mm)	0.2
Line Width (mm)	0.35
Wall Thickness (mm)	1
Wall Line Count	1
Infill Density (%)	100
Infill Pattern	Lines
Print Temperature (°C)	185
Build Plate Temperature (°C)	55
Print Speed (mm/s)	45
Build Plate Adhesion Type*	Brim

*Build plate adhesion type used Extruder 2 with Natural PVA material for easy removal after print completion.

The print duration of each cylinder spans between 21 and 24 hours for a finished product and ranges from 120 g (4.23 oz) to 145 g (5.11 oz) of filament material used. Figure 3 displays a finished 15.2 cm (6 in) diameter PLA cylinder.

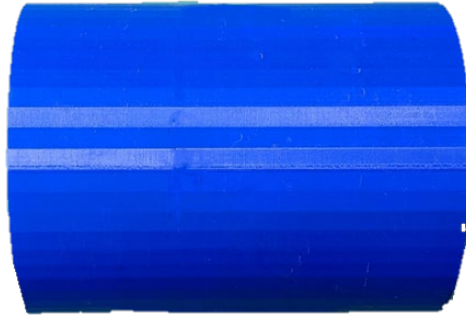


Figure 3. PLA Cylinder Sample, 15.2 cm (6 in) Diameter

After the print is completed, the cylinder sample was removed from the print bed slowly to ensure test sample is not damaged. Select “Confirm Removal” on the Ultimaker S5 Pro display to reset the printer for the next print.

If there is a failed print or an interruption during the printing process, such as insufficient filament, then there is a possibility the completed print will have defects. These include minor spacing from the stopping point of the interruption to the resumed print start; moreover, lacking material fusion between the original and new filament due to the print area temperature cooling down and reheating again. There is also a likelihood of the first few layers unseating from the print bed, which this printer does not detect, and continue to extrude material on an uneven build causing a structure that resembles a bird’s nest.

Since the filament is routed through tubes, called Bowden tubes, with a series of motors moving the material around, old filament could break within these tubes and cause a blockage from the material station to the extruders. This is considered as a failed print. The filament breaks when the spool of filament has been opened for quite some time and become brittle when exposed to the environment. For this matter, disassembling the Bowden tubes and removing the broken filament is required for further use.

B. POST-FABRICATION AND REQUIREMENTS

This section discusses requirements in preparation for sample testing. Both composite cylinders were constructed to have similar dimensions to perform testing with the same testing apparatus.

1. Sizing Measurements

Test sample sizes were made to fit a composite test rig (CTR) designed and built by Achor, a previous NPS student who studied submerged composite plates subjected to shock loading [20]. He also designed the compressed air supply system that generates the underwater shock loading present in this research, to be discussed in Chapter III, “Experimental Procedures.”

In order to brace the cylinders to the CTR, support structures were designed to hold various cylinder diameters and allow water to be filled within the annulus at different water levels. These support structures, which will now be known as end caps, were designed using the SolidWorks program and formatted to be 3D printed on the Ultimaker S5 Pro with polycarbonate (PC) filament as the material of choice. Figure 4 displays a 15.2 cm (6 in) PLA cylinder sample mounted using PC end caps on the CTR.

This design is to mimic a rigid structure environment with very minimal sample movement, for most of the shock loading to be absorbed by the composite cylinder. The opening where the sample is placed measures at 23.9 cm (9.4 in) wide, thus all cylinders are fabricated or cut down to be 20.32 cm (8 in) in length.

Table 4 given is the inner diameter and thickness measurements for both composite materials. To note, multiple CFC cylinders cured at inconsistent thickness and outer surfaces, as mentioned earlier due to the wet fiber winding process, to which only three samples were considered for strain data results. CFC(4) sample was an extra cylinder sample made from previous research work which used the same materials and winding procedures.



Figure 4. Composite Test Rig with PLA Cylinder Mounted

Table 4. CFC and PLA Composite Cylinder Dimensions

Sample	Inner Diameter	Thickness
CFC(1)	152 mm (6 in)	1.78 mm (0.07 in)
CFC(2)	152 mm (6 in)	6.99 mm (0.275 in)
CFC(3)	152 mm (6 in)	6.99 mm (0.275 in)
CFC(4)*	89 mm (3.5 in)	1 mm (0.04 in)
PLA(1)	152 mm (6 in)	2.4 mm (0.09 in)
PLA(2)	152 mm (6 in)	2.4 mm (0.09 in)
PLA(3)	152 mm (6 in)	2.4 mm (0.09 in)
PLA(4)	127 mm (5 in)	2.4 mm (0.09 in)

*CFC(4) sample was an extra sample from a previous research work. Source: [9].

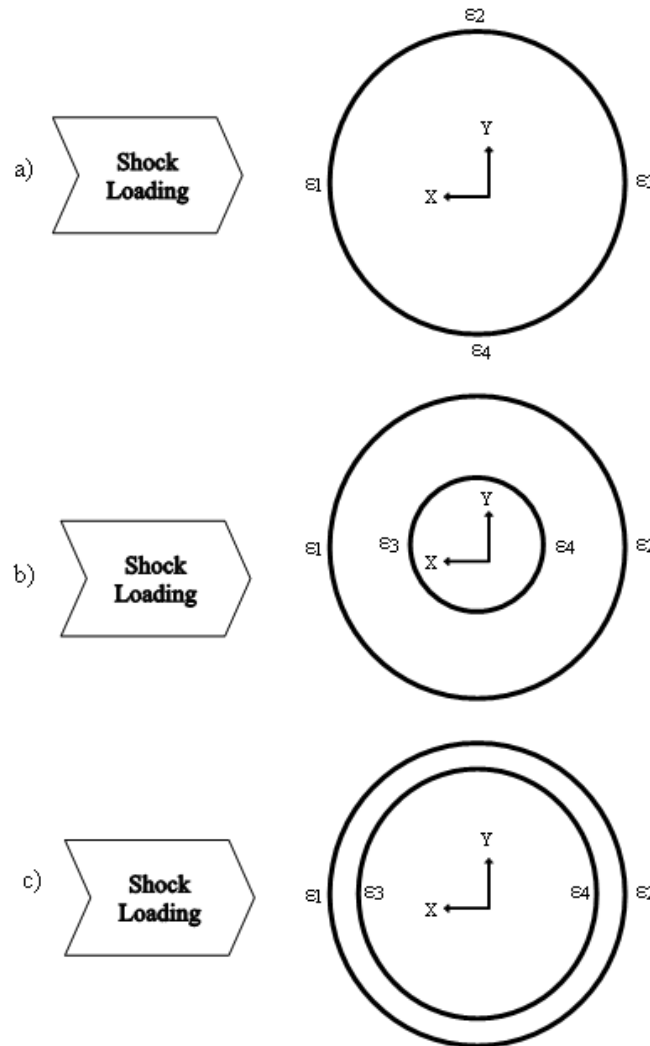
2. Strain Gauge Placement

Location of the strain gauges around the cylinder as well as the inner cylinders are meant to capture the FSI of the shock loading throughout the body of the composites. Test sample structures were limited to a maximum of four strain gauge rosettes in total because of the data acquisition system used, to be mentioned in Chapter III, “Experimental Procedures.”

For single-walled cylinders, the strain gauge rosettes were attached to the outer surface divided into four quadrants. The front of the cylinder is the high impact zone where it is directly in line of the shock loading. This is the location of the first strain gauge rosette. In the right axial view, following the circumferential direction clockwise, are the remaining three strain gauge rosettes in ascending order: top, posterior, and bottom. These strain gauge rosettes are placed in the outer surface for ease of access as well as application.

Double-walled cylinders include more coordination between the inner and outer cylinders. The outer wall for both CFC and PLA materials has two strain gauge rosettes attached on the outer surface; the first placed on the front towards the shock loading, and

the second at the opposite side of the load. In addition, the inner-wall cylinders for the CFC material are placed in the same manner because of the much smaller inner diameter size. The inner-wall cylinders for the PLA material have the same location, but are attached on the inside diameter surface, by design, to accommodate in testing different water levels in the annulus. Figure 5 shows the strain gauge rosette locations of single-wall and double-wall for CFC and PLA cylinders.



a) Single-Wall Cylinders b) Double-wall CFC Cylinders c) Double-wall PLA Cylinders

Figure 5. Strain Gauge Placement on Composite Cylinders

Two types of strain gauge rosettes were used in this research: bi-axial and three-directional. Although, for the three-directional strain rosette, only the 0° and 90° strain gauges were utilized to measure axial and hoop strain. The attachment process for strain gauge rosettes consisted of sample surface preparation, epoxy application, soldering wire connections and finally water-proofing the strain gauge rosettes.

Due to the submerged environment, water-proofing the strain gauge rosettes is a necessary step for data acquisition. A silicone-based room temperature vulcanizing (RTV) coating was used on top of the strain gauge rosette and wire connections to ensure the strain gauges had no contact with water and pliable enough for natural movement of the gauges.

C. CYLINDER SUPPORT STRUCTURE REDESIGN

The CTR was the original test rig to be used as mentioned earlier, but the initial design of the end caps lacked stem reinforcement which underestimated the magnitude of the shock load itself and fractured at the mounting point. Fortunately, the important part of the end caps that can contain the test cylinders is intact but will not be able to utilize the CTR as designed. Therefore, a new test rig was developed to hold the composite cylinders at the same depth as well as maintain different water levels in the test structure.

The redesigned test rig required to have the same depth measurement in order to align the test sample with the underwater shock loading system. To solve this issue, the rig uses a drop line made of vinyl-covered steel wire attached to a hold bar, which is an anchor point for the suspended weight just below the test sample. The weight is to counter buoyancy force when the cylinders are filled with air internally as well as maintain stillness once the test rig is lowered underwater. Turnbuckles and U-bolts are latched on to tighten the end caps together and maintain a closed boundary condition. Figure 6 shows the original end caps with modifications mentioned above.



a) Inside view with grooves displayed. b) Outside view with U-bolts and turn buckles attached.

Figure 6. Original End Caps with Modifications

The grooves inside the end caps can accommodate 15.2 cm (6 in), 12.7 cm (5 in), 8.9 cm (3.5 in) and 7.6 cm (3 in) hollow cylinders and a maximum length of 25.4 cm (10 in). The circular openings on the outside of the end caps are a pass-through for strain gauge wires on a double-wall cylinder configuration. A watertight specimen is key to ensure internal water levels are accurate and the surrounding water is kept outside of the cylinders. Multiple trials of rubber gaskets, silicone coatings, sealant tapes were used in the test runs, but the most water-tight seal is a strip of leather covered in rubber compound also known as tire plugs. They are able to fit between the grooves in the end caps and adhere to the cylinders well enough to keep water in and out of the samples.

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III. EXPERIMENTAL PROCEDURES

The shock load testing procedure is conducted in the same manner for both composites; although, they will not be compared to each other due to the different material properties.

A. TESTING EQUIPMENT

1. Compressed Air Shock Pipe Underwater Release

This system, as mentioned earlier, was designed, and built by Achor [20] for a way to further facilitate underwater shock loading research. The compressed air supply system (CASS) provides the necessary pressure to the shock assembly which is an integral part of the compressed air shock pipe underwater release (CASPUR) system. It includes a Type K high-pressure steel tank with 17.93 MPa (2,600 psi) of industrial grade air with an internal volume of 6.43 m³ (1.65 ft³) [21]. A stainless steel braided flexible hose connection measuring at 9.14 m (30 ft) long transports the compressed air from the tank to the shock assembly.

The shock assembly consists of a rupture disk designed to burst at 2.06 MPa (300 psi) with a $\pm 5\%$ tolerance held in between a disk holder. The rupture disk manufactured by Zook is a 5.08 cm (2 in) cross-scored forward acting stainless steel metal rupture disk under their FAX series. The pre-torque type FAH series disk holder, also by Zook, has an inlet and outlet flange with high strength capscrews to fasten the rupture disk in place which is then bolted on to the shock pipe elbow. Figure 7 shows a single Zook rupture disk specifically made for the CASPUR.

These rupture disks are one-time-use, due to the nature of its purpose which is to burst at a specific pressure and release a shock wave. Therefore, a high supply is needed on hand to complete multiple test runs.



a) Front View b) Profile View

Figure 7. Rupture Disk Manufactured by Zook

2. Data Acquisition System

Experimental data was recorded and organized through the data acquisition (DAQ) system which is made up of a computer processor, data collection programs, and sensors.

a. Computer Processor

Raw data was managed using National Instruments™ (NI) PXIe-1071 processor with a DAQ card called NI PXIe-6358 which gathers the pressure and strain signals from the sensors. NI MAX is the computer program available in the processor to equalize the strain gauge input channels through the Wheatstone Quarter Bridge I potentiometers. In addition, the NI Signal Express (2015) program, performs the processing and recording of the data. A total of 200k sample reading was set with a sampling rate of 20 kHz to capture the full dynamic response.

b. Sensors

Pressure sensors utilized in this research was the Tourmaline ICP underwater blast sensor, manufactured by PCB Piezotronics, equipped with a measurement range of 68,950 kPa (10,000 psi) and a maximum pressure rating for 344,750 kPa (50,000 psi) [22]. Figure 8 displays a single underwater blast sensor, simply referred to as pressure sensors throughout this paper, with a previously modified added weight attached for minimal movement once submerged.



Figure 8. Tourmaline ICP Underwater Blast Sensors by PCB Piezotronics

Strain gauge rosettes, specifically K-series Tee Rosettes, manufactured by Omega were used for the CFC cylinders. In addition, general-purpose three-element 45° rectangular rosettes by Micro Measurements were used for the PLA cylinders. The only reason for the change in strain gauges is supply availability. Gauge factors, which is the sensitivity of the gauge, differed between the two rosettes was updated in the DAQ per the manufacturer's specifications between each test run. The wire connection from the strain gauge on the sample to the DAQ measures at 228.6 cm (90 in) in length for both CFC and PLA cylinders.

As mentioned previously, four strain gauge rosettes are placed on the outer surface spaced into four quadrants for single-walled cylinders; whereas the double-walled cylinders have two strain rosettes located opposite of each other on the outer surface for CFC and PLA composites. The inner cylinders for the double-wall structure also having two rosettes opposite of each other on the outer surface of the CFC composite; although, for the PLA composite the strain rosettes are located on the inner surface.

c. Video Recording

A GoPro HERO 4 camera was used to record the underwater images during testing for FSI with the underwater shock loading. This is to determine the possible cause of a ruptured sample. The viewing angle was from a profile view of the cylinder to capture the shock loading impact on the samples. It is also used to determine the movement of the redesigned suspended test rig compared to the CTR. Figure 9 shows an underwater capture of the shock assembly aligned with the underwater blast sensors and the cylinder sample in the test rig.



Figure 9. Underwater Capture of Experimental Test Set-up

B. TESTING PROCEDURES

All cylinders used the same set of end caps, so the following procedures apply for both CFC and PLA cylinders at all diameters.

1. Sample Preparation

Regardless on the structure configuration, single-walled or double-walled, the prepared sample(s) is placed on one side of the test rig ensuring full contact between sample and end cap. If applicable, the inner cylinder wire connection on the strain gauge

rosettes is fed through the opening of the end cap while guiding the wire away from the edges of the sample to avoid accidental cutting or crimping. After, the other side of the end cap is then secured to the opposite side of the sample.

Final step is to tighten the end caps together using the turnbuckles, at a balanced thread turn, for an even distribution throughout the sample boundaries. Turnbuckles are positioned on the top and bottom of the sample for security and to minimize shock load interference. Figure 10 shows a ready sample on the composite test rig with the drop line retracted on the hold bar.



Figure 10. PLA Cylinder on Composite Test Rig with the Hold Bar

For the test runs involving water levels within the annulus, another opening on the end cap is available to fill to the necessary water levels, and yellow sealant tape is used to plug the opening to the submerged environment.

2. Data Acquisition Start-Up

The DAQ system is powered on from the NI PXIe-1071 processor to start computer programs in addition to the power supply for the sensors to equalize sensors. NI MAX application is selected from the desktop that contains the Test Panel window to check the connectivity from the sensors to the processor. NI SignalExpress is also opened from the desktop which has the window panel, DAQmx Acquire, for recording analog input from the sensors.

Several values and parameters used in this research, on the DAQmx Acquire window, need to be established prior to moving forward to ensure accurate analog strain input which are given in Table 5. NI SignalExpress requires the project file to be saved which will keep the current parameters set the same unless a change is necessary.

Table 5. NI SignalExpress Parameter Settings

Item	Value	
Strain Gage Factor*	Bi-axial	1.99
	Three-directional	1.2
Gage Resistance*	350 Ω	
Vex Source	External	
Vex Value	10 V	
Strain Configuration	Quarter Bridge I	
Acquisition Mode	Continuous Samples	
Samples to Read	200k	
Sampling Rate	20 kHz	

*Values depend on specific strain gauges.

Once the values in Table 5 are verified, location for strain and pressure files to be recorded is changed depending on the type of test run is conducted in the DAQmx Acquire window. Raw data collected is written in text file format by NI SignalExpress, and the option to create continuous samples is selected in any case the recording

surpasses 200k samples. This is to ensure previously recorded files are not overwritten and data is lost. The recorded files are stored locally in the processor, and an external drive is used to extract files for further processing.

3. Rupture Disk Assembly

The Zook rupture disk is first removed from its individualized packaging which includes the installation instructions that specify the maximum recommended torque values of the holder and shock test assembly. The disk is then placed on the inlet flange of the holder in line with the alignment pin ensuring the directional flow arrow is indicating the proper way. The outlet flange is then carefully positioned on top of the rupture disk with the alignment pin secured in its corresponding opening. The holder is then fastened by four high strength capscrews using a torque wrench at a maximum recommended torque of 43 Nm (32 Ft-lbs). Figure 11 displays the rupture disk assembly installed on the shock test rig (STR) according to manufacturer's specifications.



Figure 11. Rupture Disk Assembly on the Shock Test Rig

Lastly, the rupture disk assembly is then installed on the STR with companion flanges using Durlon 8500 type gaskets in between for a proper seal and tighten the provided 193 Grade B7 studs and A194 Grade 2H nuts at the recommended torque of

79.9 Nm (59 Ft-lbs). Table 6 is provided by the manufacture specifications for the rupture disk assembly and companion flange torque values.

Table 6. Shock Test Rig Assembly Specifications and Recommended Torque Values. Adapted from [23].

Assembly Type	Nominal Diameter of Bolt	Thread Pitch	Thread per inch	Max Recommended Torque
Rupture Disk	9.5 mm (3/8 in)	1.058 mm	24	43 Nm (32 Ft-lbs)
Shock Test Rig	15.8 mm (5/8 in)	2.309 mm	11	64.9 Nm (88 Ft-lbs)

4. Shock Loading System

Once the rupture disk assembly and companion flanges are installed, the STR is then lowered underwater to conduct a leak test. This is done by pressurizing the CASS to 150 psi, which is read on the pressure gauges attached to the compressed air tank, at 10 psi increments while constantly checking for air bubbles anywhere on the submerged STR. If there was a constant flow of air bubbles, then it was necessary to depressurize the system by closing off the compressed air tank and purging the air contained between the STR and tank valve. Figure 12 displays the valves used connected to the compressed air tank that control the air flow. After retrieving the STR above water, the threads, where the air bubbles were escaping, are tightened and another leak test is then performed. This is to ensure the pressure reading at the time of the rupture disk bursts is fairly accurate and consistent.



Figure 12. Compressed Air Supply System Control Valves

5. Sample and Sensor Placement

The anechoic tank has six I-beams that run parallel to the directed shock wave from the loading source and supports six removable plywood pieces that serve as a safety tank cover. The sample test rig is submerged exactly 1.98 m (78 in) below the beams using a vinyl-covered steel wire anchored by a hold bar on the beams. Pressure sensors are then lowered forward of the CTR depending on the standoff distance of the test.

Three pressure sensors are used in a triangular formation with the first pressure sensor (P1) closest to the STR, and the second pressure sensor (P2) along with the third pressure sensor (P3) positioned at the same radial distance from the shock loading as the test sample. This configuration is to take note of the maximum pressure from P1 and to consider the radial shock wave of the loading source. Figure 13 shows the pressure sensor diagram for a shock load testing.

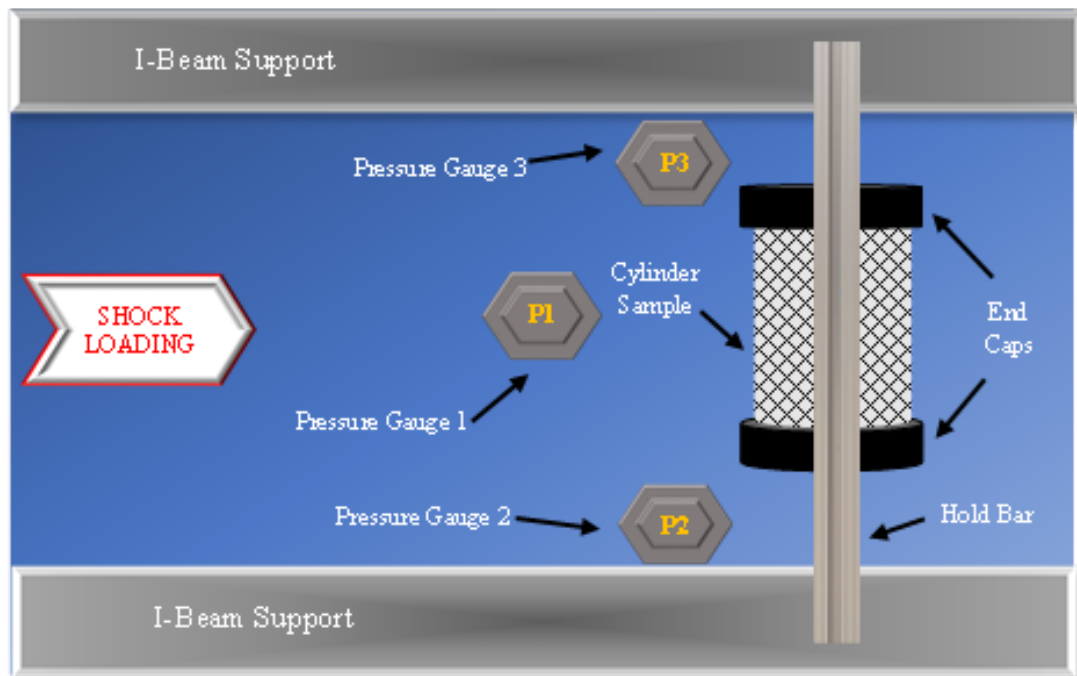


Figure 13. Pressure Sensor Diagram for Shock Load Testing Top View

IV. RESULTS AND ANALYSIS

CFC and PLA composite cylinders are fabricated, submerged, and tested under directed shock loading using a CASPUR system. This chapter will discuss the pressure loading and dynamic responses of two different cases for these composite cylinders. The arrangement of experiments conducted is to allow multiple test runs on the same cylinder as a controlled test sample. Unfortunately, this type of testing method has presented a flaw where microfractures may have occurred during the initial shock loading tests and weaken the fibers on the surface or internally. To manage this concern, a visual and physical examination of the outer surface and inner diameter is conducted prior to the next test run as well as underwater video footage is recorded for this purpose.

Early trial samples were used to assess the tolerance of the composites at several stand-off distances with water and/or air filled within. Meaning that 100% water level is tested at the furthest possible stand-off distance, if a fracture or rupture is not detected, then the water level is lowered to 50% and tested again at the same stand-off distance. If no fracture or rupture occurs after the test run with 0% water level, then the CTR is moved closer to the shock source. With that preliminary data collected, a starting stand-off distance is established for CFC and PLA cylinders at 0.45 m (1.47 ft) and 0.75 m (2.46 ft), respectively.

The naming convention for the cylindrical samples are as follows: the single number in parenthesis indicates a single-wall cylinder structure, and a pair of numbers indicates a double-wall structure. Where the first number is the outer cylinder, and the latter is the inner cylinder. The water levels specify the amount of water internal to the structure for the single-wall cylinders and within the annulus for the double-wall cylinders.

A. TOTAL PRESSURE LOADING ANALYSIS

Three pressure sensors are configured in the same triangular formation throughout the experimental process as shown in Figure 13. The largest pressure reading for each test run is P1, compared to P2 and P3, primarily because of the shorter distance from the

shock loading. Additionally, P2 and P3 pressures are averaged given that these sensors are positioned at the same radial distance from the shock source portrayed in Figure 14. However, due to the limited spacing between the I-beams in the y-direction, the stand-off distance of P2 and P3 are positioned as close to the radial distance as physically possible.

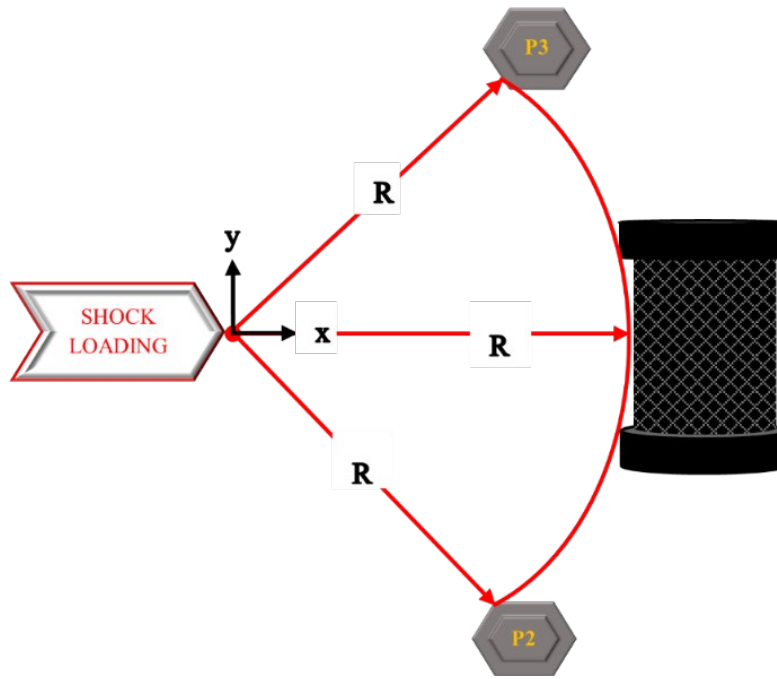


Figure 14. Schematic of P2 and P3 Pressure Sensors from Load Source

The maximum pressure loadings as a function of the stand-off distances with mean and standard deviation measurements are presented in Figure 15. Pressure data outliers are retracted from the distribution plot for one of two reasons – the sensors lost connection which zeroed out the reading, or the DAQ did not record in time that resulted in the latter end of the shock loading. Nonetheless, the shock loading profile is consistent with the spatial and temporal distribution of a typical blast wave [17, 24]. This means that the closer the sensors are to the detonation point, the higher the pressure loading becomes which, in turn, confirms the reliability of the CASPUR system as the shock loading source for this study. A tabulated summary of mean peak pressure loadings with respect to stand-off distance is given in Table 7.

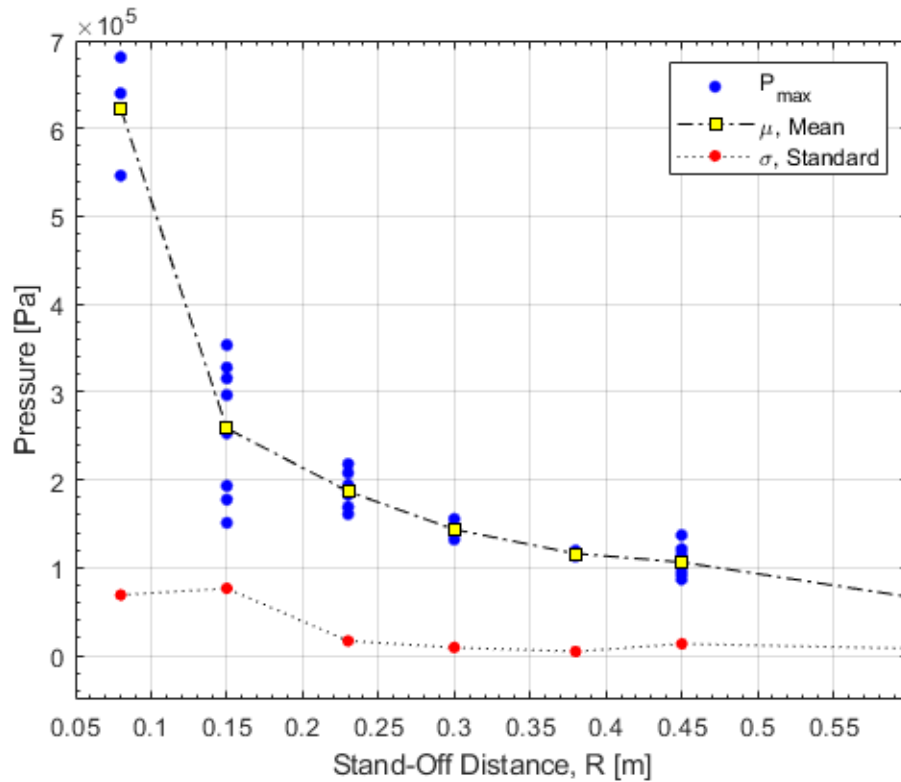


Figure 15. Peak Pressure Distribution Plot with Mean and Standard Deviation Metrics

In addition, the number of petals, which is noted as each of the quadrant on the rupture disk, would rupture with only one or two at a time; however, it does not have an impact on the delivery of the shock load to the sensors or cylindrical structures since it is rated to burst at precisely 2.06 MPa (300 psi) with some tolerance.

Pressure profiles of each test run will be discussed later in this chapter in Section B and Section C along with strain analysis for CFC cylinders and PLA cylinder, respectively. Figure 16 displays an example of a rupture disk post-test run with one petal opened installed on the STR.

Table 7. Summary of Mean Peak Pressure Loadings with respect to Stand-Off Distance

Stand-Off Distance* [cm]	Mean Peak Pressure [kPa]	Mean Peak Pressure [psi]
7.5	622.37	90.26
15	258.60	37.51
23	186.88	27.10
30	143.57	20.82
38	116.17	16.84
45	106.31	15.42
60	66.92	9.70
75	66.87	9.69

*Stand-Off distance is based on the radial distance of the pressure sensors from the loading source.

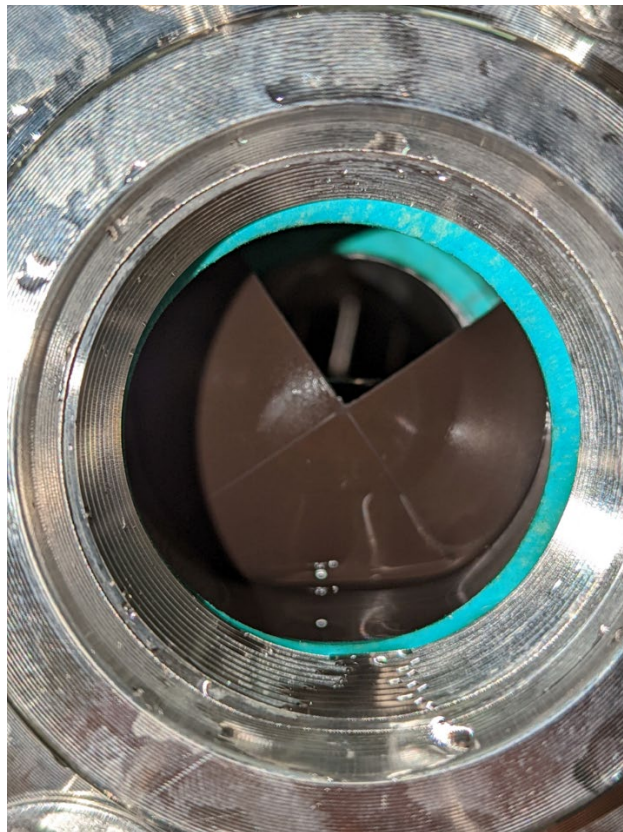


Figure 16. Zook Rupture Disk Post-test Run with One Petal Opened

An essential point to note is the physics of the shock wave propagation, where there is a transmitted wave and a reflected wave. A transmitted wave is the initial pressure loading detected, and a reflected wave is the pressure that is redirected back towards the water after contact with a structure or surface [25]. Figure 17 displays an example of a shock wave propagation for a free field and near water-air interface with the same peak pressure, then a separation at the arrival of the reflected wave. This reaction is based on the density of the structure or surface as well as the fluid medium on the opposite side of the structure or surface. In this present work, the pressure profiles will be presented in the manner of 0% and 50% water levels compared with 100% water levels, correspondingly.

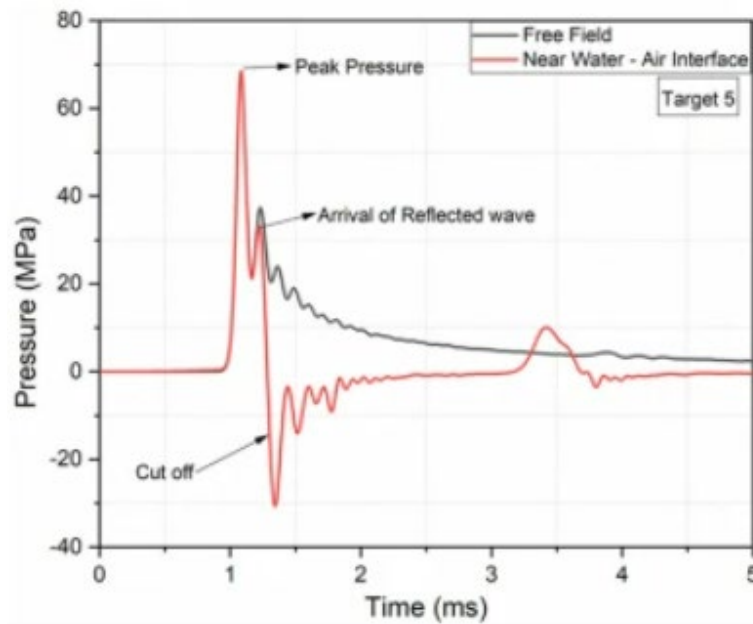


Figure 17. Pressure Profile Comparison of Free Field and Near Water – Air Interface. Source: [25].

As a reference model, Figure 18 displays a comparison of the shock wave propagation of a double-layer steel shell with water filled in between the layers, represented on the left, and air filled represented on the right. This comparison perfectly exhibits a transmitted and reflected wave for water filled medium as well as a rarefaction

wave for an air filled medium. The transmitted wave is seen, on the left, move through the outer sphere and into the water medium, while the reflected wave is the outline of the shock that is redirected back towards the water. In contrast, a rarefaction wave seen on the right, is when the wave being redirected back towards the water is much larger than the transmitted wave that goes through the outer layer. This is because of the change in impedance between the surrounding water and the air medium in between the layers [26].

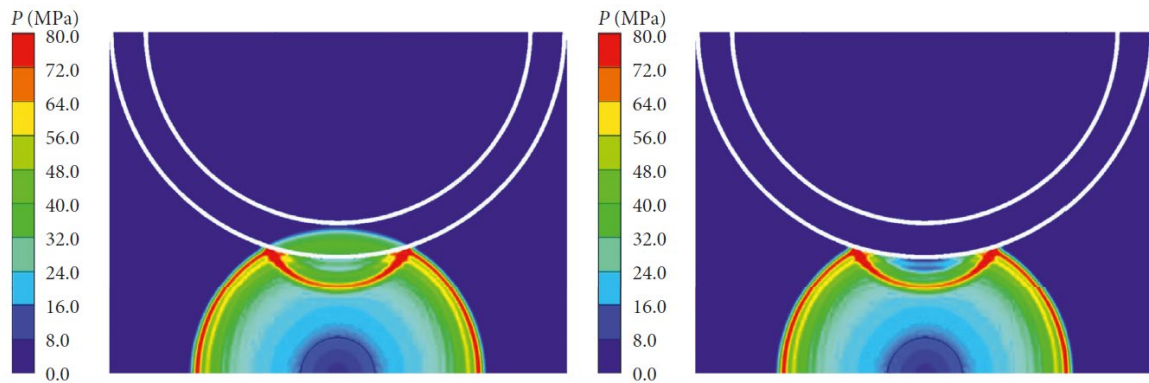


Figure 18. Shock Wave Propagation Comparison of a Double-Layer Sphere Filled with Water (left) and Air (right) in Between the Layers.
Source: [26].

B. CARBON FIBER COMPOSITE

1. Overview

The CFC cylinders used in the data collection are created with two layers of dry carbon fiber and epoxy resin mixture. One sample was wrapped with shrink tape before curing and the other without. The cylinder that cured without shrink tape had affected the outer surface by creating multiple stress concentrations in between the fibers. The cylinder that was wrapped in shrink tape prior to curing resulted in a much smoother outer surface. However, since the winding process is unpredictable, some fibers were laid unevenly that created cavities underneath the shrink tape throughout the sample. Table 8 provides the calculated internal fluid volume for single-wall and double-wall cylinders.

Table 8. Internal Water Volume for CFC Cylinders

Sample Configuration	Water Level [%]	Water Volume [mL]	Water Volume [fl. oz]
Single	0	0	0
Single	50	1,795.42	60.71
Single	100	3,590.84	121.42
Double	50	1,163.35	39.33
Double	100	2,326.70	78.67

2. CFC Pressure Analysis

CFC cylinders have a starting stand-off distance at 0.45 m (1.47 ft) where the structure does not present any visual failure after loading. In reference to Figure 14, the linear distance in the x-direction from the load source is annotated in the legend of the pressure profile plots to help understand the linear spacing of the pressure sensors.

These pressure time histories prove strongly that there is uniformity of the shock wave propagation with P2 and P3 readings almost recording the same data points even if placed at two separate ends of the cylinder. Figure 19 shows the pressure profile plots for samples CFC(1) and CFC(2) at 0.45 m (1.47 ft) with 0% water level and 100% water level, respectively. The maximum pressures, $P_{\max}$, coincided perfectly in these test runs, which is the goal but rarely happens at the same exact pressure reading due to the $\pm 5\%$ burst tolerance of each rupture disk.

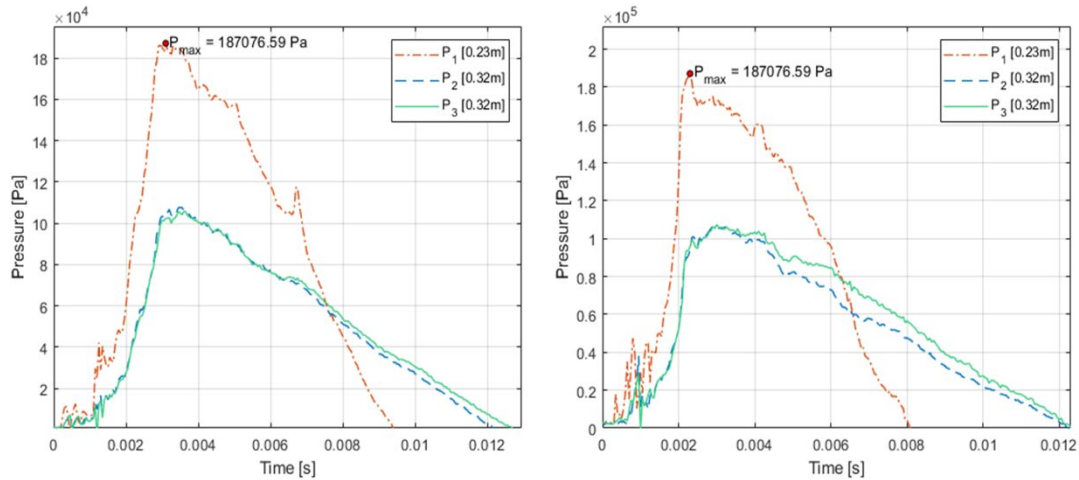


Figure 19. Pressure Profiles for CFC(1) and CFC(2) Cylinder Samples with 0% and 100% Water Levels at 0.45 m Stand-Off

In the case of CFC(1) sample with 0% water level, there is a noticeable reflection wave peak for P_1 that occurs at approximately 6.7 milliseconds. This is because the impedance of air is much lower than of water causing a rarefaction wave, where the shock wave bounces back from the structure causing cavitation near the outer shell [26]. Comparing to the slight increase in pressure for CFC(2) at around 4 milliseconds, which may be caused by a secondary bubble from the STR instead of an instantaneous reflection wave peak. The reflected wave peak is prominent on P_1 because of the placement being perpendicular with reference to the cylindrical sample and in line with the shock wave propagation at a shorter stand-off distance.

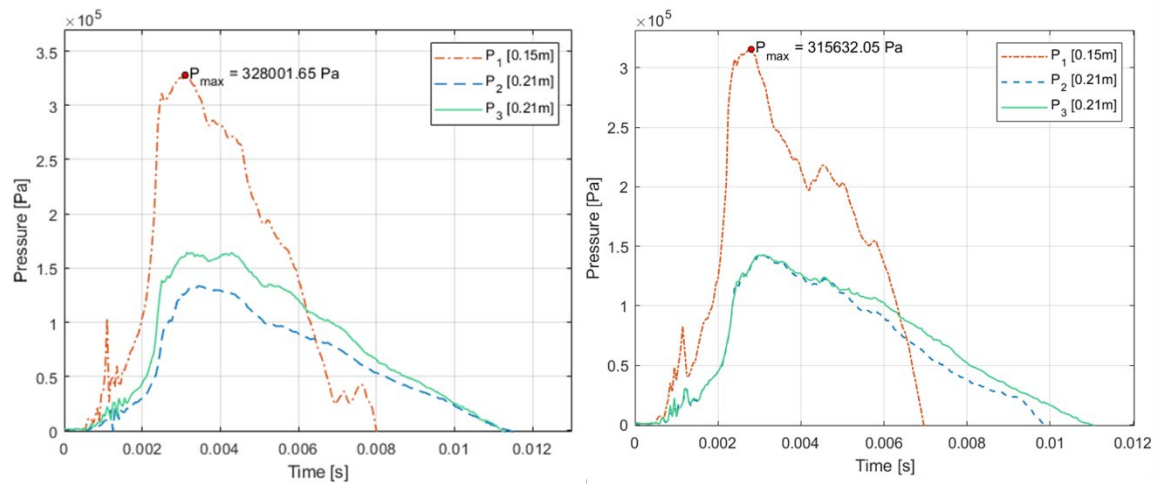


Figure 20. Pressure Profiles for CFC(3/4) Cylinder Sample with 50% and 100% Water Levels at 0.30 m Stand-Off

CFC(3/4) being a double-wall cylinder displays a mildly different pressure profile as the partially filled annulus does not show the reflection wave until much later, approximately 6.7 milliseconds, as shown in Figure 20. While the fully filled annulus presents a clear reflection wave response around 4.5 milliseconds. Depending on if the annulus is partially filled or fully filled, the shock wave will either be transmitted through the annulus completely or may separate between the air or water mediums. Since the density of composite materials are very similar to water, at about $1,000 \text{ kg/m}^3$ (62.4 lb/ft^3), the shock wave is transmitted through the outer cylinder then eventually reaches the inner cylinder.

Now to evaluate the pressure profiles at a closer stand-off distance of 0.15 m (0.49 ft) between a partial and fully filled annulus. Figure 21 shows the pressure comparison for CFC(3/4) sample for 50% and 100% water levels as well.

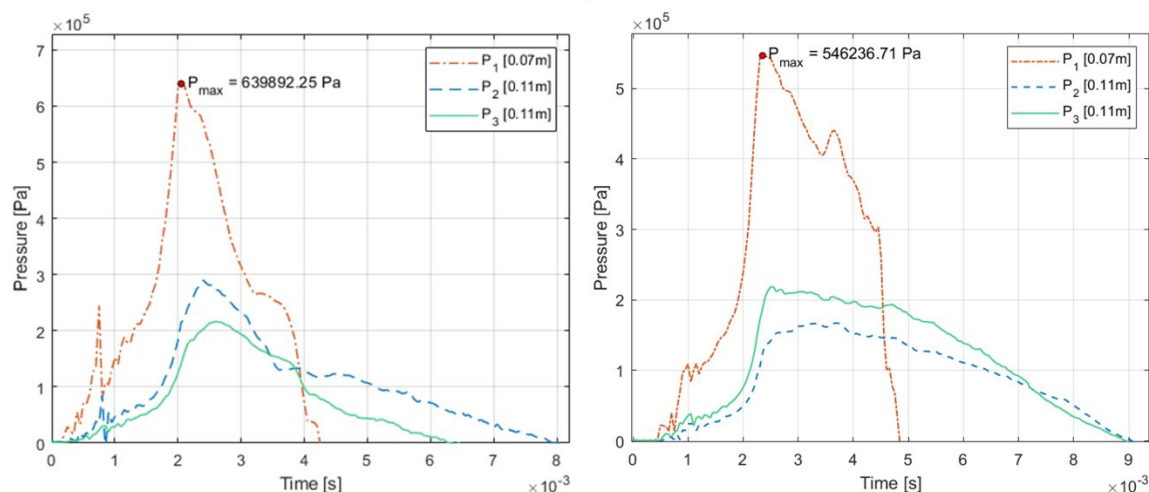


Figure 21. Pressure Profiles for CFC(3/4) Cylinder Sample with 50% and 100% Water Levels at 0.15 m Stand-Off

At the distance of 0.15 m (0.49 ft) the pressure reading displays a less polished graph mainly because following the initial burst of the rupture disk are pockets of air that form air bubbles. Where some of the air encapsulates the pressure sensors and at times cavitate leaving the magnitudes for P_2 and P_3 unequal in recorded pressures. Moreover, there is a wide variance in the peak pressures as well as the amount of time the pressure is reached at maximum and back down to zero.

3. CFC Strain Analysis

Dynamic response for two cases is considered in the order of single-wall cylinders then advancing to double-wall cylinders. Refer to Figure 5 in Chapter II, “Experimental Set-Up,” which outlines the locations of the strain gauge rosettes for all cylinders, if needed.

a. Single-Wall Cylinder

Sample CFC(1) was tested at 0.45 m (1.47 ft) with 0% water level as the initial run, and later tested at 0.21 m (0.68 ft) stand-off distance with the same water level. Figure 22 displays the strain responses of CFC(1) sample at 0.45 m (1.47 ft) stand-off distance for the front, top, posterior, and bottom positions labeled as ϵ_1 , ϵ_2 , ϵ_3 , and ϵ_4 , with respect to the axial and hoop directions. Although, ϵ_{x4} and ϵ_{y3} strain data were

excluded due to a loose wire connection post-shock loading which resulted in unreliable strain readings.

To note, the increase in magnitude of ϵ_{x2} and ϵ_{y2} do not indicate a fracture, but quite possibly a minor deformation because this sample did not show any fractures when inspected and remained structurally sound. Therefore, a following test run is conducted at a closer stand-off distance.

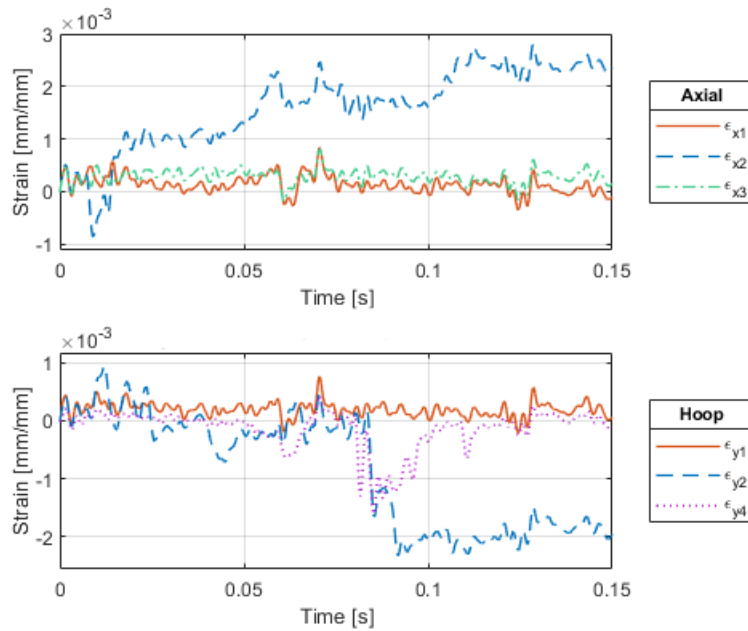


Figure 22. Strain Plots for CFC(1) Single-Wall Cylinder with 0% Water Level at 0.45 m Stand-Off

As expected, the sample fractured at the closer distance being that the air internal of the cylinder was affected by the transmitted wave from the shock loading which caused cavitation as the rarefaction wave occurred on the surface of the cylinder. Figure 23 presents the strain responses of the fractured CFC(1) sample at 0.21 m (0.68 ft) stand-off distance, and Figure 24 outlines the visible fractures on the CFC(1) cylinder in bronze coloring.

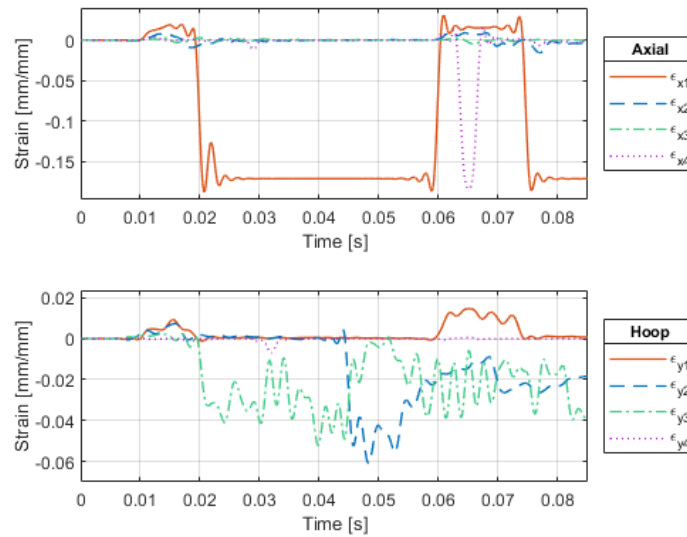
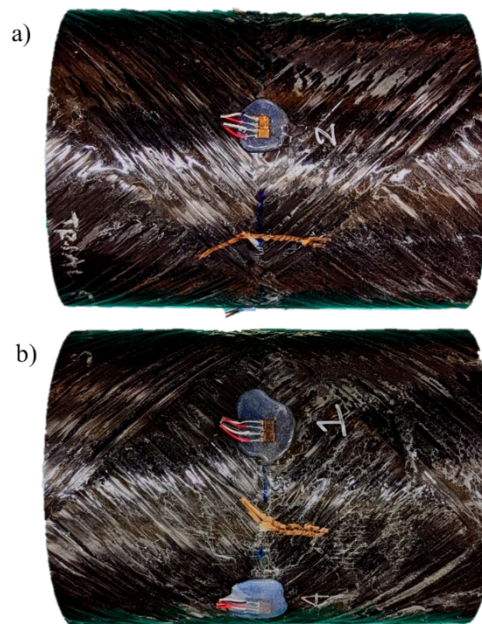


Figure 23. Strain Plots for CFC(1) Single-Wall Cylinder with 0% Water Level at 0.21 m Stand-Off Distance



a) Top image displays the top strain gauge rosette with fracture highlighted. b) Bottom image displays the front and bottom strain gauge rosettes with fracture highlighted.

Figure 24. Fractured CFC(1) Single-Wall Cylinder with Splintered Areas Highlighted

The following set of test runs are conducted with CFC(2) composite sample. Figures 25–28 presents the front, top, posterior, and bottom strain responses for CFC(2) single-walled cylinder sample at 0.45 m (1.47 ft) with 0%, 50% and 100% water levels. To note, for the 50% water level sample, ε_{y1} was removed in the plot due to a loose connection caused by the shock loading. Also, ε_{y3} and ε_{y4} , detached from the wire connection when the final RTV coating was in the process of drying overnight. Therefore, only ε_{x3} and ε_{x4} are available for this sample.

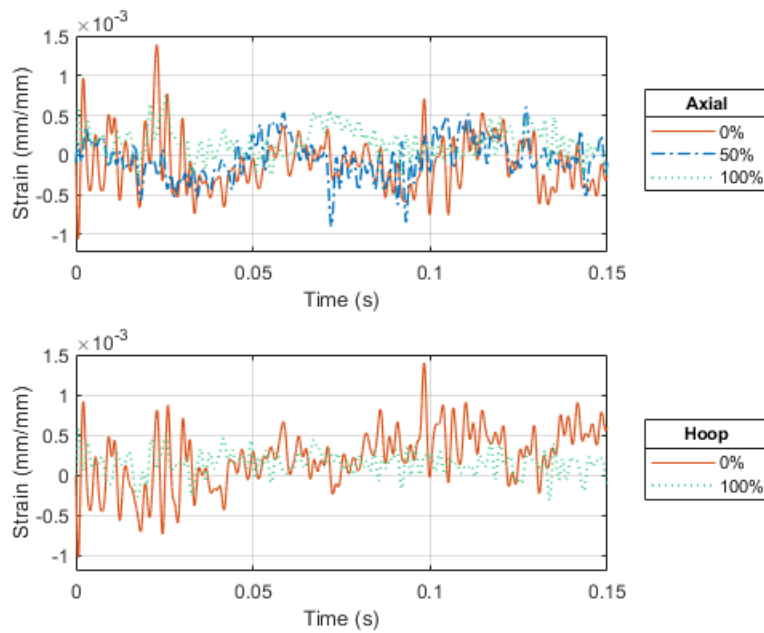


Figure 25. Front Strain Comparison of CFC(2) Single-Wall Sample for Three Water Levels at 0.45 m Stand-Off

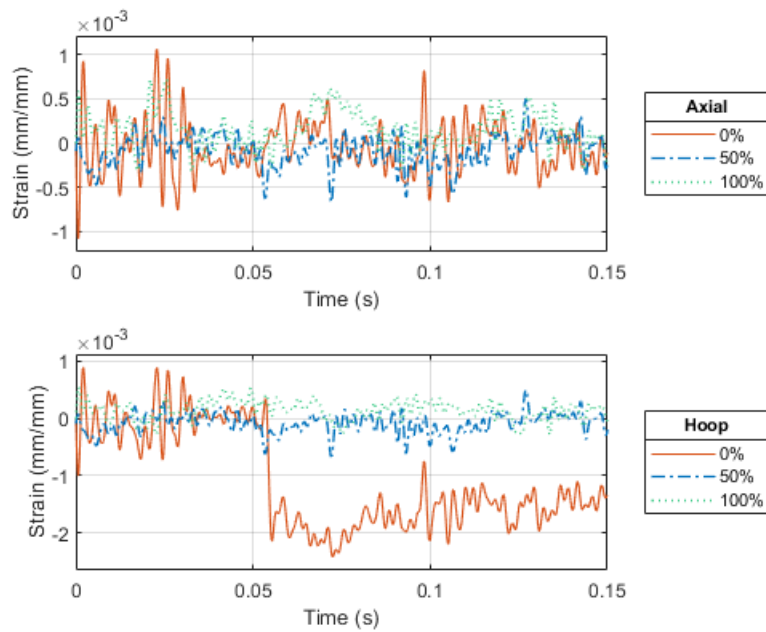


Figure 26. Top Strain Comparison of CFC(2) Single-Wall Cylinder for Three Water Levels at 0.45 m Stand-Off

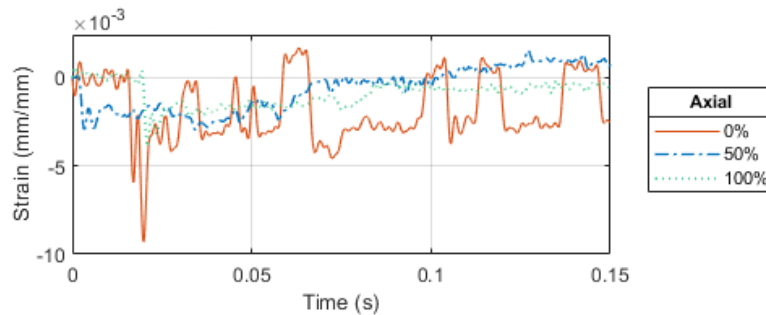


Figure 27. Posterior Strain Comparison of CFC(2) Single-Wall Cylinder for Three Water Levels at 0.45 m Stand-Off

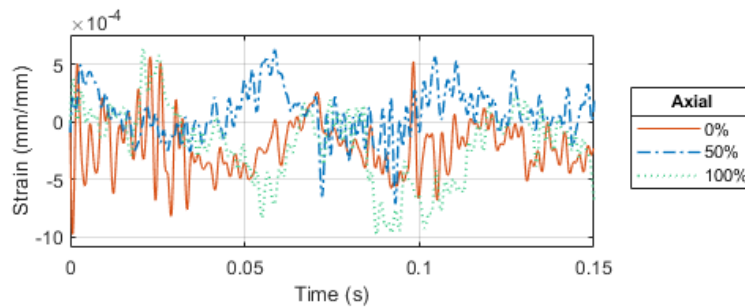


Figure 28. Bottom Strain Comparison of CFC(2) Single-Wall Cylinder for Three Water Levels at 0.45 m Stand-Off

Because the CFC(2) sample showed no fractures or splintering during this set of test runs, the cylindrical response was at, or below, micro-strain levels. Also, to note that the 0% water level cylinder had a larger strain reading in almost all points, which signifies more movement throughout the cylinder from the shock loading that may lead to a possible structural failure.

b. Double-wall Cylinders

CFC double-wall cylinders are tested with a 15.2 cm (6 in) and 8.9 cm (3.5 in) diameter samples. The water levels specify the amount of water filled within the annulus of the structure, and the inner cylinder is strictly filled with air.

CFC(3/4) is analyzed at 100% and 50% water levels only and 0% was not considered due to the similarity of the single-wall cylinder with air internal of the cylinder since the interaction of the inner and outer cylinders was considered minimal without water in-between. All strain gauge rosettes are attached on the outer surface of the CFC cylinders. Where S1 is located at the front side and S2 is on the posterior side of the outer cylinder, while S3 and S4 are attached in the same manner but for the inner cylinder. The strain responses are presented in the order of stand-off distances starting at 0.45 m (1.47 ft), 0.30 m (0.98 ft), and 0.15 m (0.49 ft). Figures 29–32 display 50% and 100% water levels for the double-wall cylinder structure for comparison.

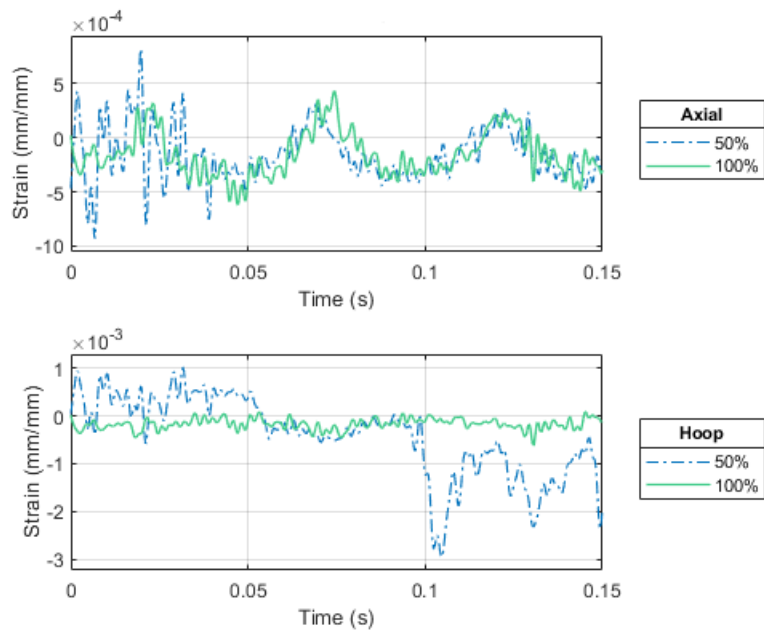


Figure 29. Front Strain Comparison of CFC(3/4) Outer Cylinder for Two Water Levels at 0.45 m Stand-Off

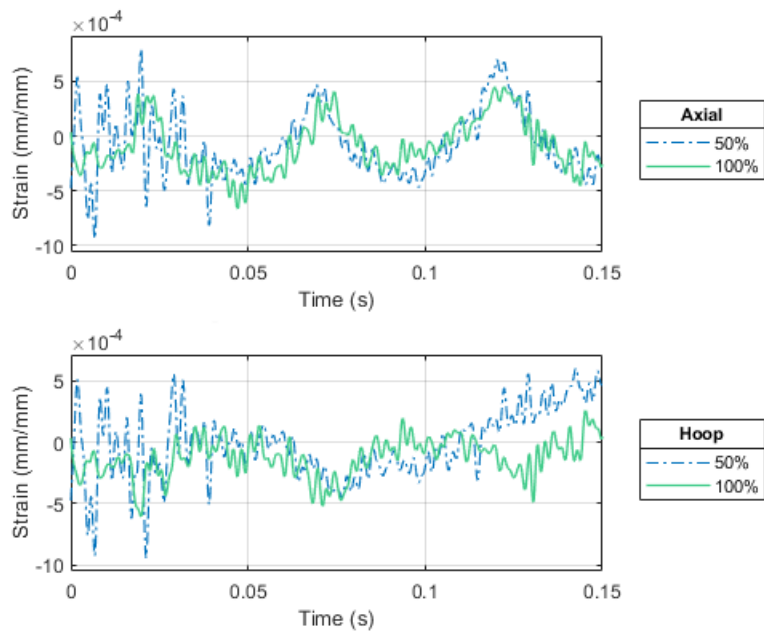


Figure 30. Posterior Strain Comparison of CFC(3/4) Outer Cylinder for Two Water Levels at 0.45 m Stand-Off

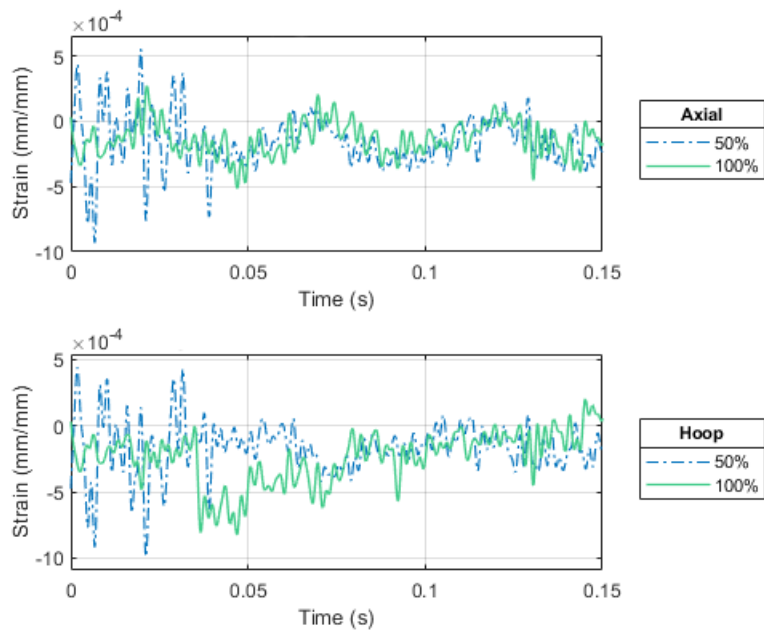


Figure 31. Front Strain Comparison of CFC(3/4) Inner Cylinder for Two Water Levels at 0.45 m Stand-Off

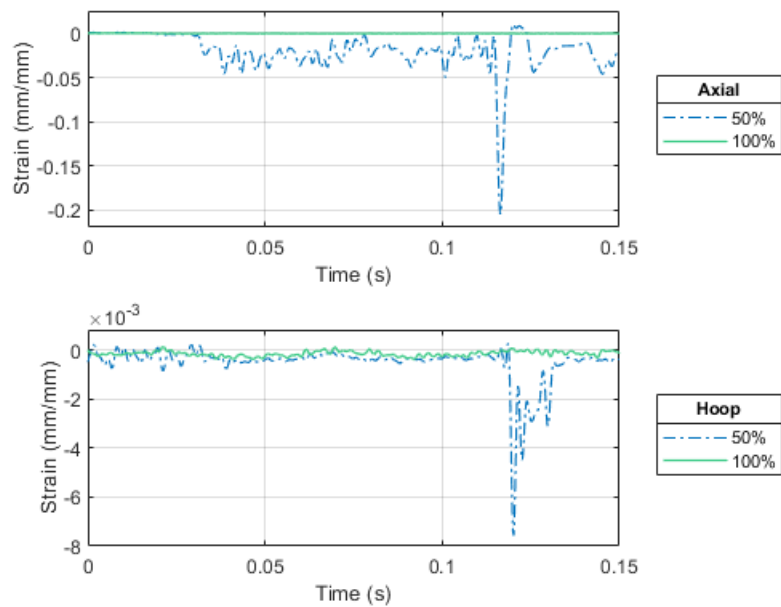


Figure 32. Posterior Strain Comparison of CFC(3/4) Inner Cylinder for Two Water Levels at 0.45 m Stand-Off

In comparison between a partially filled and fully filled annulus, the partially filled cylinder displayed higher responses meaning larger movement compared to a fully loaded annulus; partly because of the shock wave interacting with the internal medium and causing a rarefaction wave or a transmitted wave. In addition, the front side strains for both water levels show an in-step response for the axial directions meaning that the cylinder moves in the same frequency regardless of the internal fluid.

Now to assess the strain response at a closer stand-off distance, Figures 33–36 show the strain responses of sample CFC(3/4) at 0.30 m (0.98 ft) stand-off distance with 50% and 100% water levels for comparison.

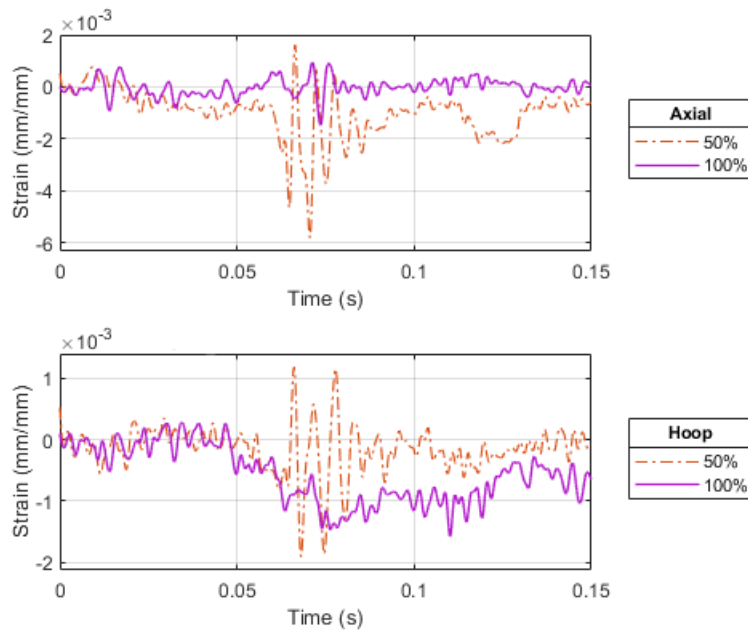


Figure 33. Front Strain Comparison of CFC(3/4) Outer Cylinder for Two Water Levels at 0.30 m Stand-Off

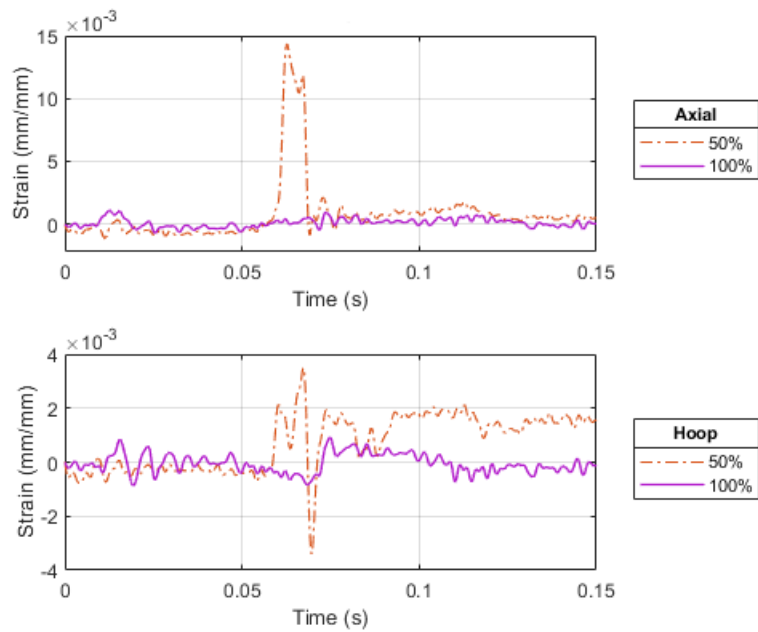


Figure 34. Posterior Strain Comparison of CFC(3/4) Outer Cylinder for Two Water Levels at 0.30 m Stand-Off

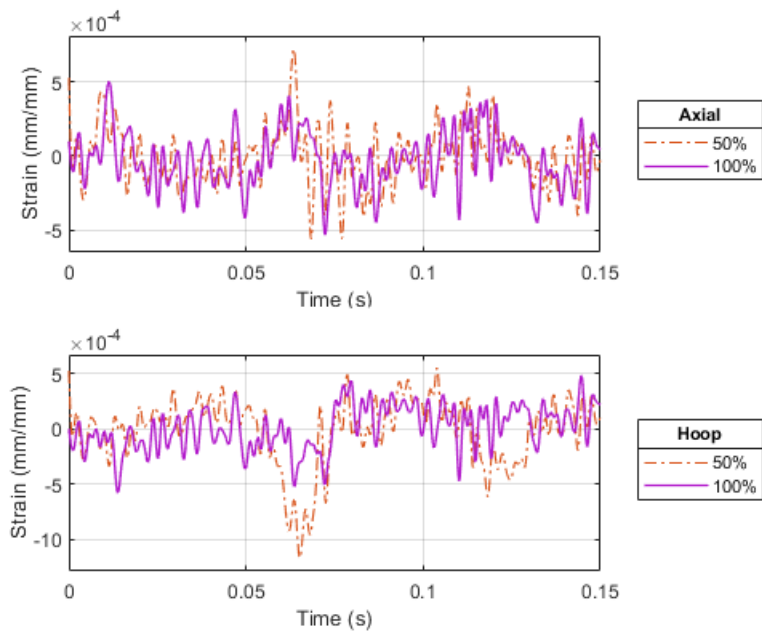


Figure 35. Front Strain Comparison of CFC(3/4) Inner Cylinder for Two Water Levels at 0.30 m Stand-Off

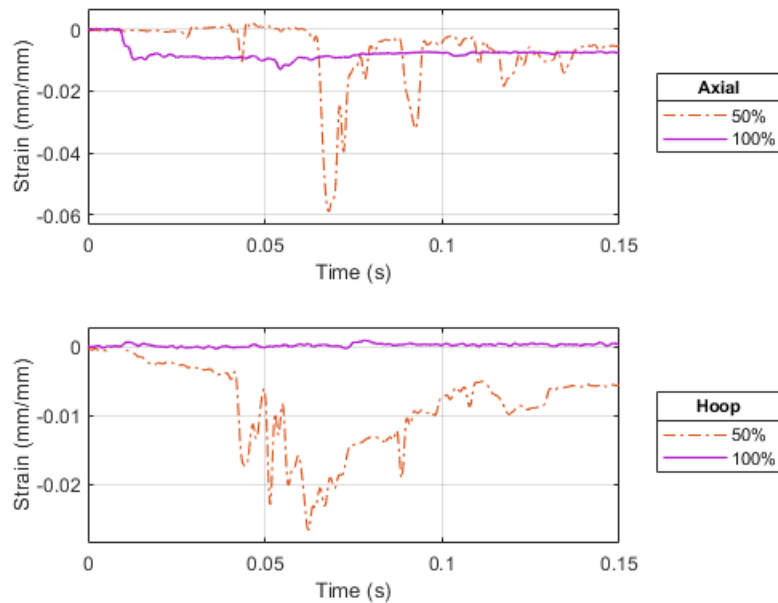


Figure 36. Posterior Strain Comparison of CFC(3/4) Inner Cylinder for Two Water Levels at 0.30 m Stand-Off

An interesting response was taken from the outer cylinder of the partially filled structure as it displays the shock propagation through the structure in the hoop and axial direction. As well as the inner cylinders displaying the shock propagation between the front and posterior side, and to add that the inner cylinder showed no fracture or splintering even after a higher than usual compressive strain. In addition, the 50% water level inner cylinder, as shown in Figures 35–36, is a possible response of cavitation due to the high magnitude in the negative direction which is indicative of a compressive strain. However, further investigation is needed to verify cavitation occurring in a double-wall cylinder.

More importantly, the dynamic response of the 50% water level test run that resulted in a structure failure at 0.15 m (0.49 ft) for the CFC(3/4) cylinder. Figure 37 exhibits the stain responses for the fractured double-wall cylinder, and Figure 38 shows the fractured outer cylinder.

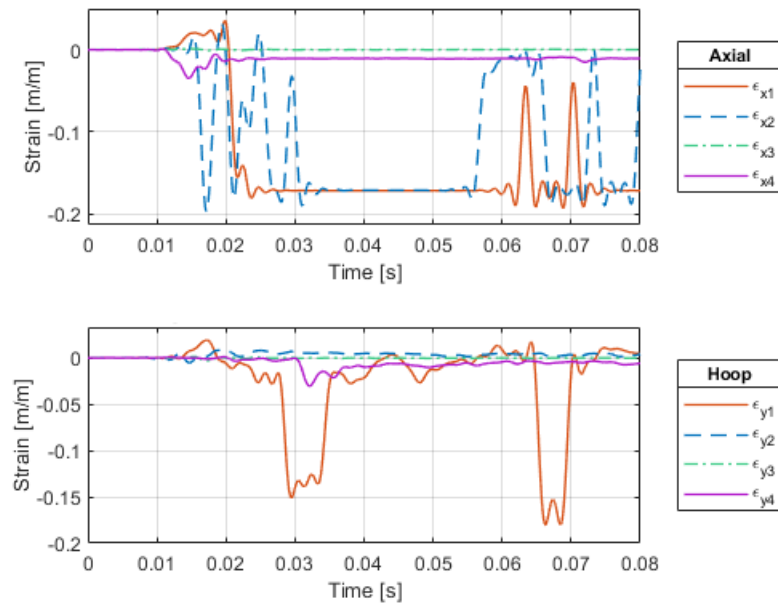
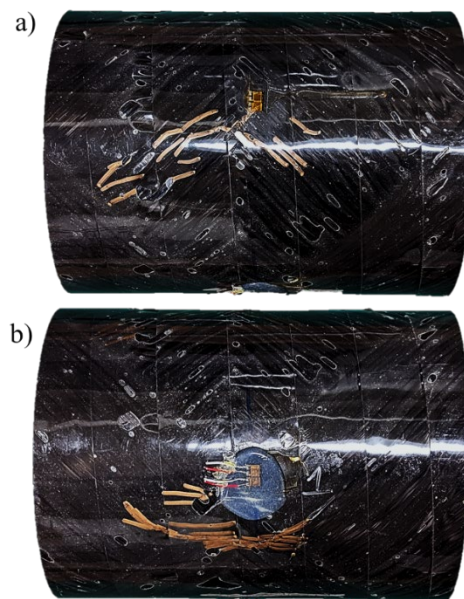


Figure 37. Strain Plots for CFC(3/4) Double-Wall Cylinder with 50% Water Level at 0.15 m Stand-Off



a) Top image displays the top side with fracture highlighted. b) Bottom image displays the front strain gauge rosette with fracture highlighted in bronze color.

Figure 38. Fractured Outer Wall on Sample CFC(3/4) Double-Wall Cylinder with Splintered Areas Highlighted

Fractured CFC cylinders were effected mostly in the front and/or top sides of the structure, describing a local failure, and no other failure was detected in a post-fracture visual inspection. Moreover, only samples with water levels less than 100% showed failure strain responses, which is the determining factor of a rarefaction wave creating a cavitation bubble on the surface of the cylinder. Hence, the air compressing around the surface of the cylinder is enough pressure to fracture the composite material. Lastly, the 45° winding angle reinforces the structural integrity of the cylinder by allowing the woven pattern to support each fiber in the hoop and axial directions.

C. POLYLACTIC ACID COMPOSITE

1. Overview

All PLA cylinders are created using the same print settings as previously mentioned, and the one difference is the filament color used which are PLA Silver Metallic, PLA Green, and PLA Blue. The cylindrical structures consist of a 15.2 cm (6 in) diameter for the single-wall cylinders, and the double-wall cylinder has a 15.2 cm (6 in) outer diameter with a 12.7 cm (5 in) inner diameter. The internal fluid volumes are calculated for both single and double wall cylinders given in Table 9.

Table 9. Internal Water Volume for PLA Cylinders

Sample Configuration	Water Level [%]	Water Volume [mL]	Water Volume [fl. oz]
Single	0	0	0
Single	50	1,795.42	60.71
Single	100	3,590.84	121.42
Double	50	556.58	18.82
Double	100	1,113.16	37.64

With the limited number of rupture disks on hand, only one test run for each stand-off distance at 0.75 m (2.46 ft), 0.60 m (1.97 ft), and 0.45 m (1.47 ft) was performed for each cylindrical configuration.

2. PLA Pressure Analysis

Based on the preliminary data, single-wall PLA cylinders with 0% water level had a maximum shock load tolerance beyond 0.75 m (2.46 ft) stand-off distance without showing structural failure. Therefore, only 100% water levels for both configurations were tested from this stage forward while using the 0% water level test strain data as a valuable comparison. As mentioned earlier, the linear distance in the x-direction from the load source is annotated in the legend of the pressure profile plots to help understand the linear spacing of the pressure sensors.

Figure 39 displays the pressure profile comparison for PLA(1) and PLA(2) single-wall cylinders at 0.75 m (2.46 ft) with 0% water level and 100% water level, respectively. The maximum pressure for PLA(1) presents a steep peak indicating a rapid and significant change in pressure which agrees with the instantaneous rupture of the PLA(1) cylinder. As stated, PLA cylinders did not survive a 0% water level test run at the 0.75 m (2.46 ft) stand-off which is the reason why samples PLA(2) and PLA(3/4) will only be tested at 100% water levels.

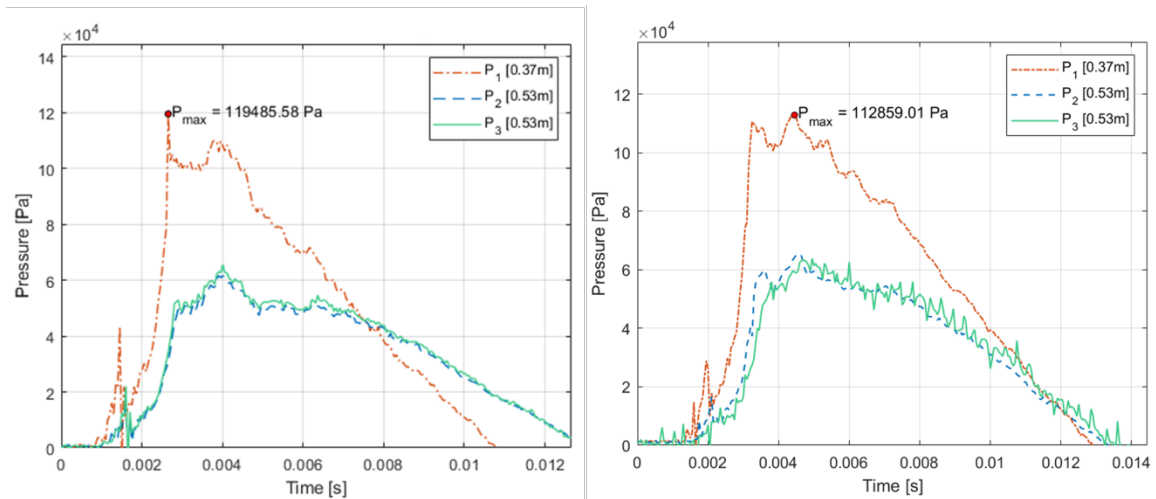


Figure 39. Pressure Profiles for PLA(1) and PLA(2) Cylinder Samples with 0% and 100% Water Levels at 0.75 m Stand-Off

Figure 40 compares PLA(2) single-wall and PLA(3/4) double-wall cylinders to determine if the air inside the inner cylinder affects the shock wave propagation. To note, PLA(3/4) double-wall sample ruptured on this test run and yet showed no major difference in the pressure profile. Therefore, if the annulus is filled at 100% water level, then the pressure from the ruptured cylinder does not affect the surrounding areas.

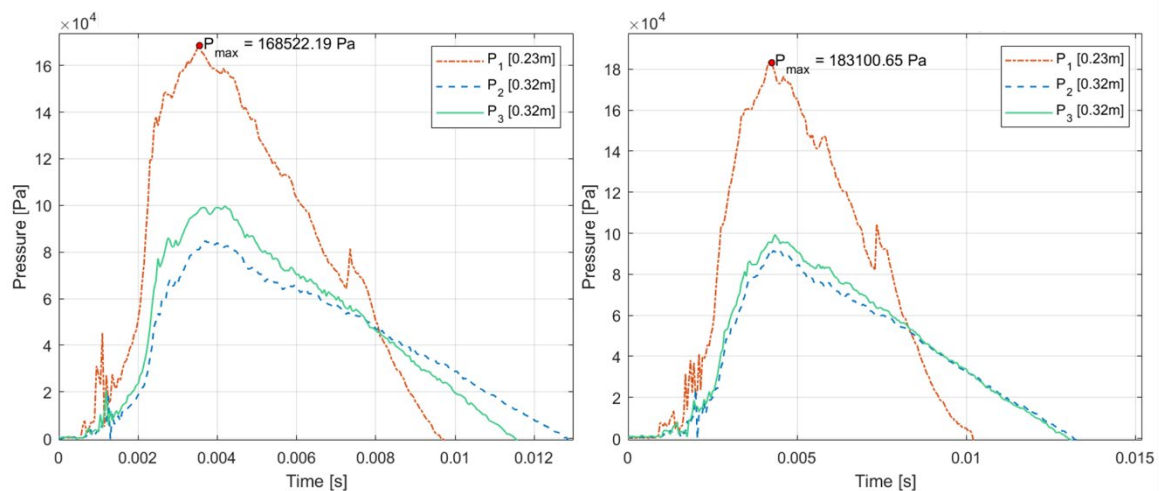


Figure 40. Pressure Profiles for PLA(2) Single-Wall Cylinder and PLA(3/4) Double-wall Cylinder Samples at 0.45 m Stand-Off

3. PLA Strain Analysis

Dynamic responses of two cases will be discussed in this sub-section which considers various stand-off distances for PLA cylinders. Refer to Figure 5 in Chapter II, “Experimental Set-Up,” for the strain gauge positioning, if needed.

a. Single-Wall Cylinders

Figure 41 presents the strain for PLA(1) cylinder which shows a clear fractured response by the pure magnitude of the strain. Also, much of the shock load was absorbed by the front strain gauge rosette which shows the highest magnitude compared to the top, posterior, and bottom locations. Figure 42 displays the fractured areas of PLA(1) cylinder sample.

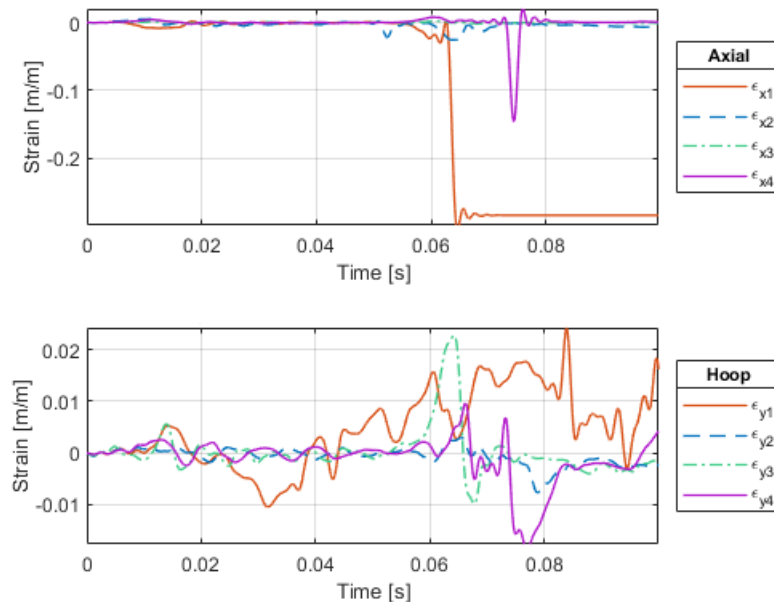
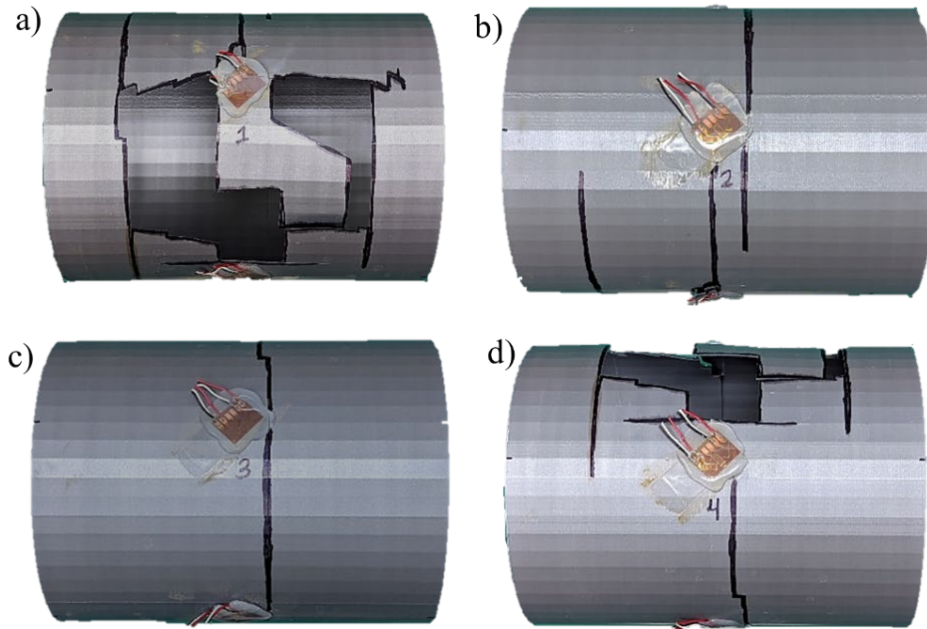


Figure 41. Fractured Strain Response of PLA(1) Single-Wall Cylinder with 0% Water Level at 0.75 m Stand-Off



a) Front side b) Top side c) Posterior side d) Bottom side

Figure 42. PLA(1) Single-Wall Cylinder Sample with Ruptured Areas Outlined

Now let's compare the strain response of a similar PLA cylinder, but with 100% water level shown in Figures 43–46.

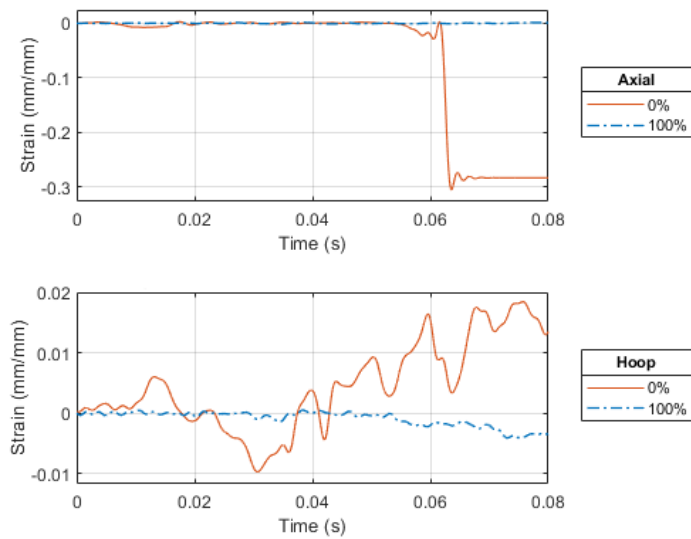


Figure 43. Front Strain Comparison of Single-Wall PLA Cylinders for Two Water Levels at 0.75 m Stand-Off

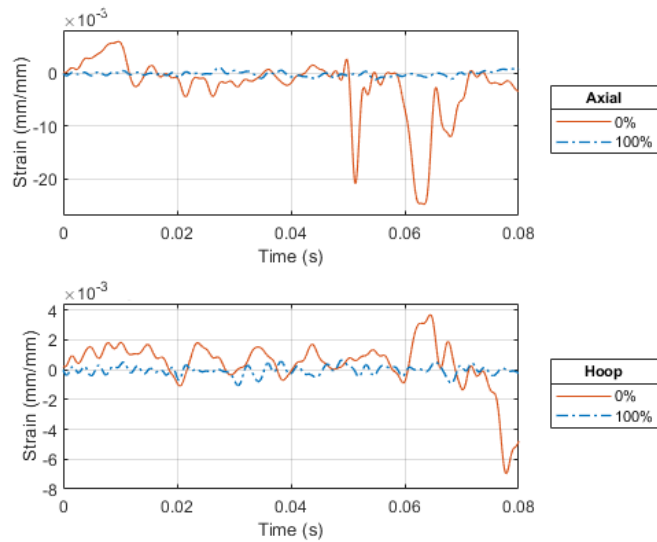


Figure 44. Top Strain Comparison of Single-Wall PLA Cylinders for Two Water Levels at 0.75 m Stand-Off

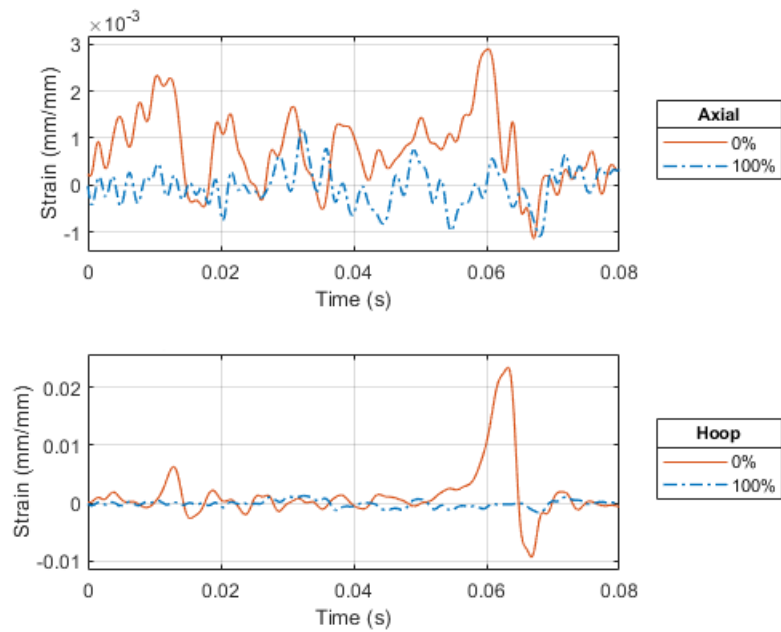


Figure 45. Posterior Strain Comparison of Single-Wall PLA Cylinders for Two Water Levels at 0.75 m Stand-Off

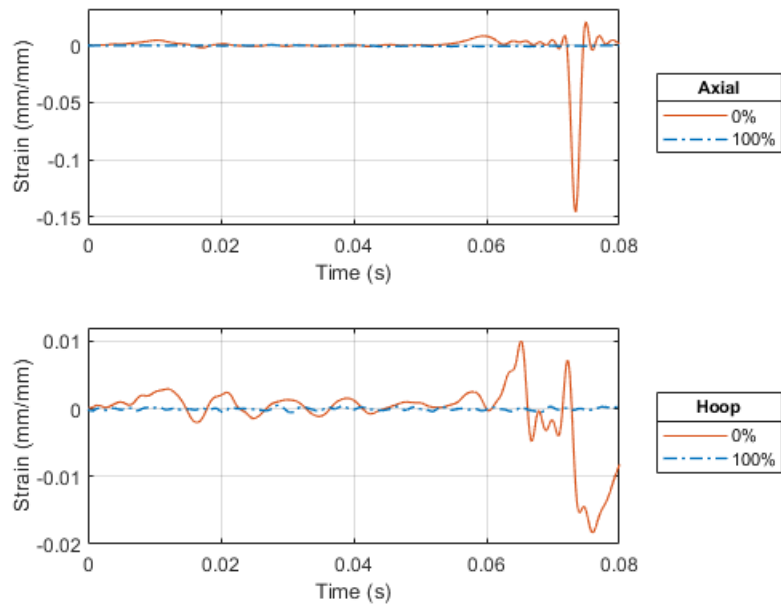


Figure 46. Bottom Strain Comparison of Single-Wall PLA Cylinders for Two Water Levels at 0.75 m Stand-Off

It is important to note that the strain response of the 100% water level structure is much less than the 0% water level because of the added support that the water internal to the cylinder is providing the outer layer. Now to evaluate that assumption, sample PLA(2) is tested at distances closer to the shock loading and comparing the strain responses in Figures 47–50.

As expected, the strain response at 0.60 m (1.97 ft) is much larger than of 0.75 m (2.46 ft) because of the higher pressure wave; moreover, the strain response captured the movement of the shock wave as it shows a gradual increase then decrease as the wave passes through. That response is more pronounced in the front and top side of the cylinder as well as the bottom side. Since the cylinder is filled with only water, there is no impedance change, which then allows the shock wave to transmit through the outer surface and into the water medium instead of redirecting the shock wave away from the structure.

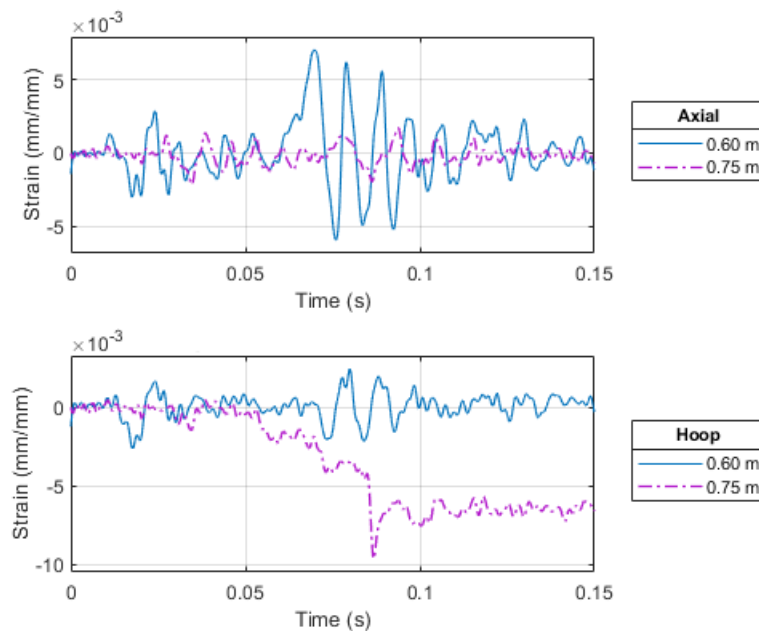


Figure 47. Front Strain Comparison of PLA(2) for Two Stand-Off Distances with 100% Water Level

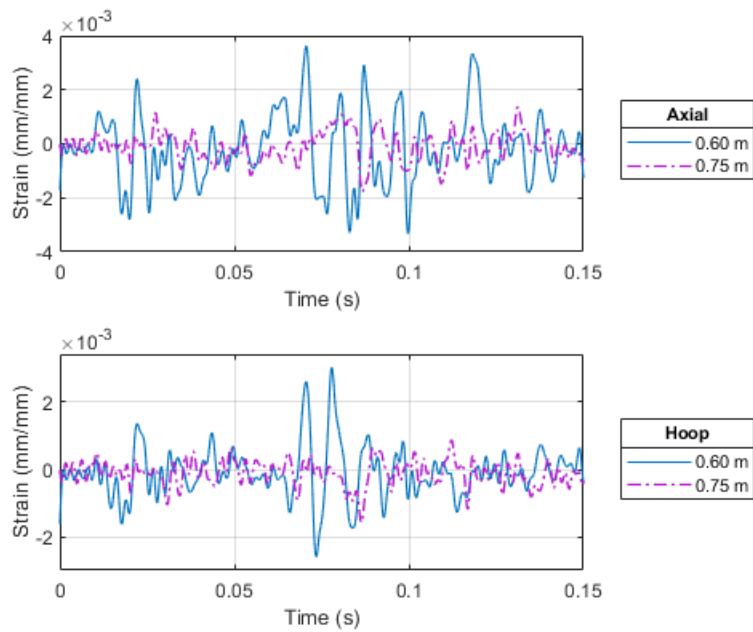


Figure 48. Top Strain Comparison of PLA(2) for Two Stand-Off Distances with 100% Water Level

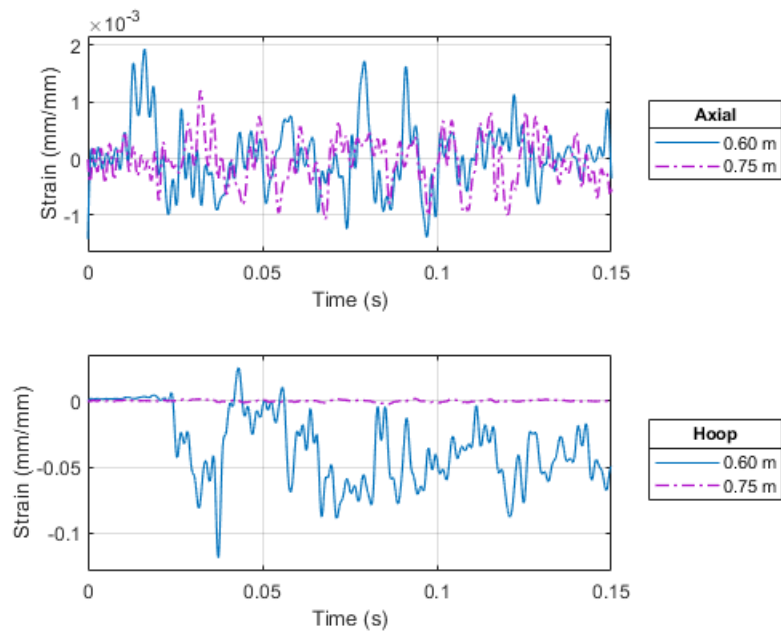


Figure 49. Posterior Strain Comparison of PLA(2) for Two Stand-Off Distances with 100% Water Level

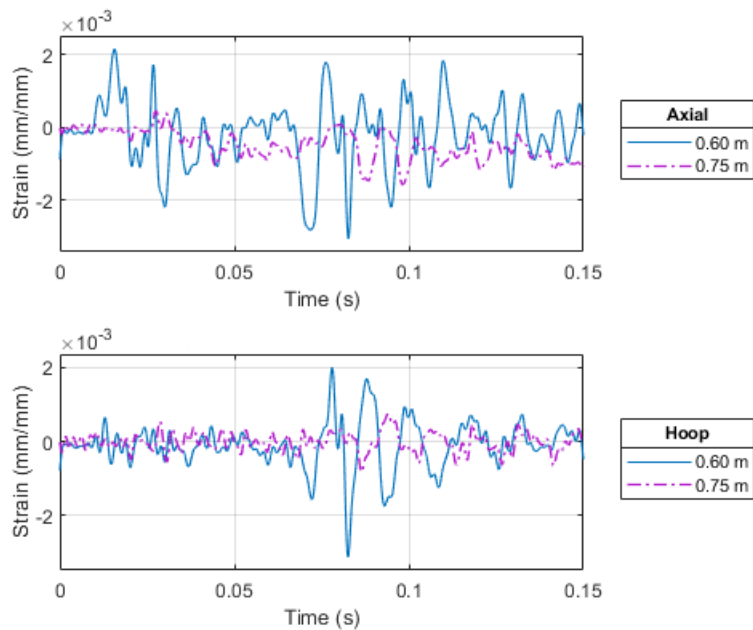


Figure 50. Bottom Strain Comparison of PLA(2) for Two Stand-Off Distances with 100% Water Level

To complete the full testing sequence, PLA(2) is then moved to the closest stand-off distance where a PLA cylinder is guaranteed to rupture at 0.45 m (1.47 ft). Figure 51 presents the strain plot of PLA(2) at 0.45 m (1.47 ft) with 100% water level, where the fractured strain response can be seen as the steep rise and fall of the plot line for the top and front sides in the axial direction.

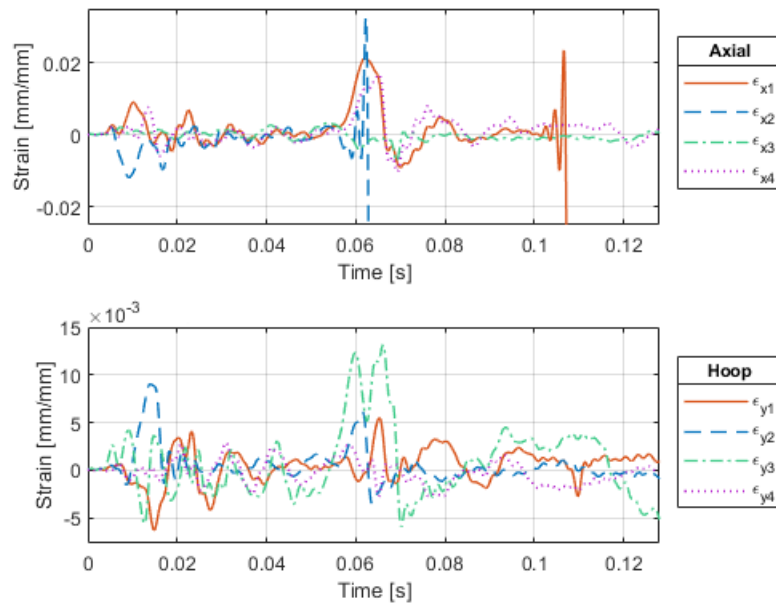


Figure 51. Fractured Strain Response of PLA(2) Single-Wall Cylinder with 100% Water Level at 0.45 m Stand-Off

Figure 52 displays the ruptured PLA(2) sample from the front side to the bottom side with the fractured areas outlined. To note, the posterior side of the cylinder showed the largest damage possibly due to the shock wave propagation moving at a rapid speed which caused enough strain to fracture in the direction of the shock wave.

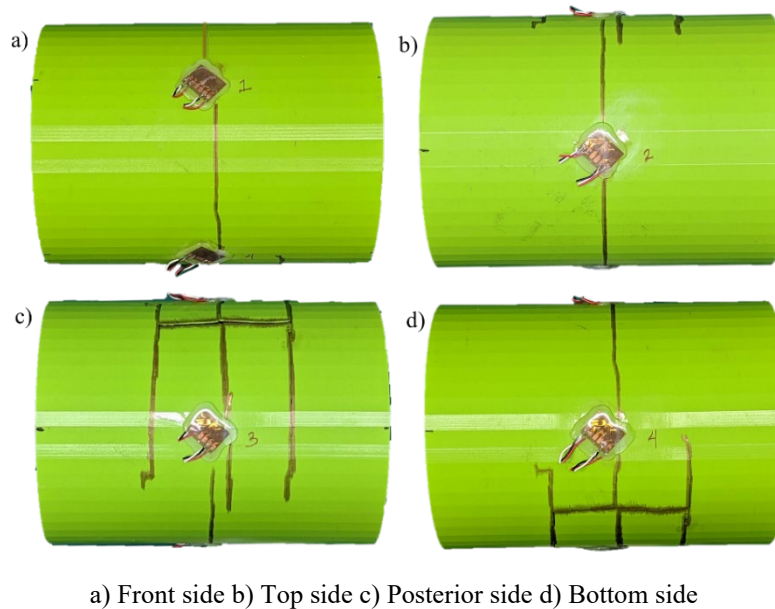


Figure 52. PLA(2) Single-Wall Cylinder Sample with Ruptured Areas Outlined

PLA(3/4) samples were tested at 0.75 m (2.46 ft), 0.60 m (1.97 ft), and 0.45 m (1.47 ft) as a double-wall cylindrical structure. Unfortunately, the strain data at 0.75 m (2.46 ft) stand-off distance was not recorded correctly and is not a viable source for comparison. However, the following test runs were successful and strain data is displayed in Figures 53–56.

In Figure 54, notice the steep response for the 0.45 m (1.47 ft) stand-off distance, which is the moment a fracture occurs in the posterior side of the outer cylinder. The front hoop strain for the inner cylinder, in Figure 55, displayed unreliable data due to a lost connection post-shock loading and therefore excluded in the plot. Figure 57 displays the outer (left) and inner (right) cylinders for PLA(3/4) sample with the fractured areas outlined.

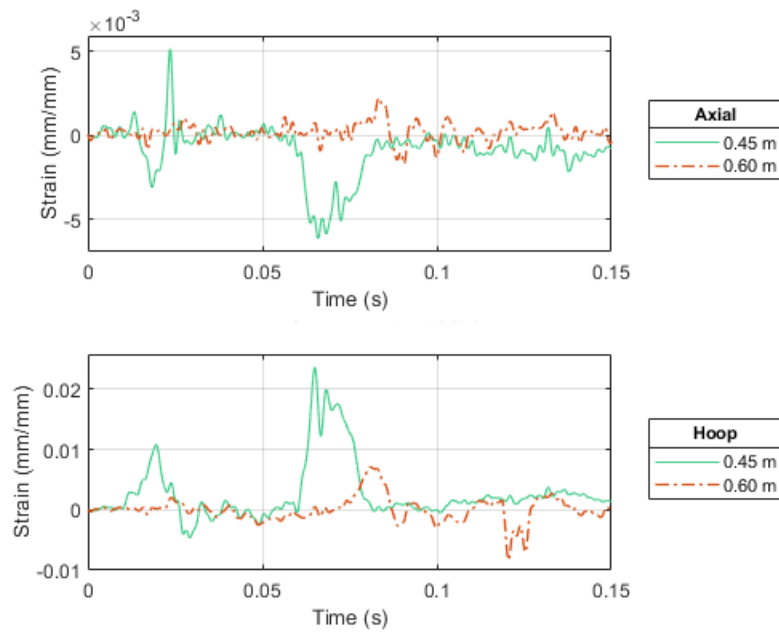


Figure 53. Front Strain Comparison of PLA(3/4) Outer Cylinder with 100% Water Level at Two Stand-Off Distances

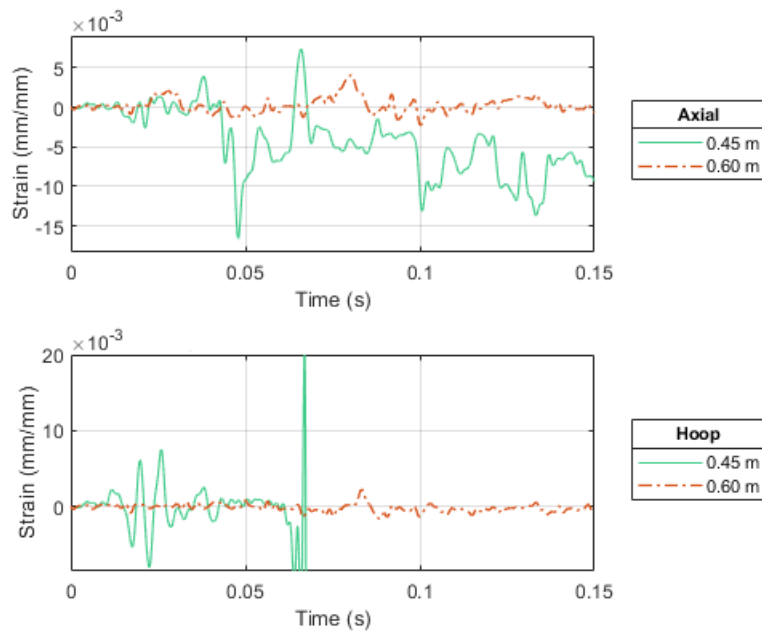


Figure 54. Posterior Strain Comparison of PLA(3/4) Outer Cylinder with 100% Water Level at Two Stand-Off Distances

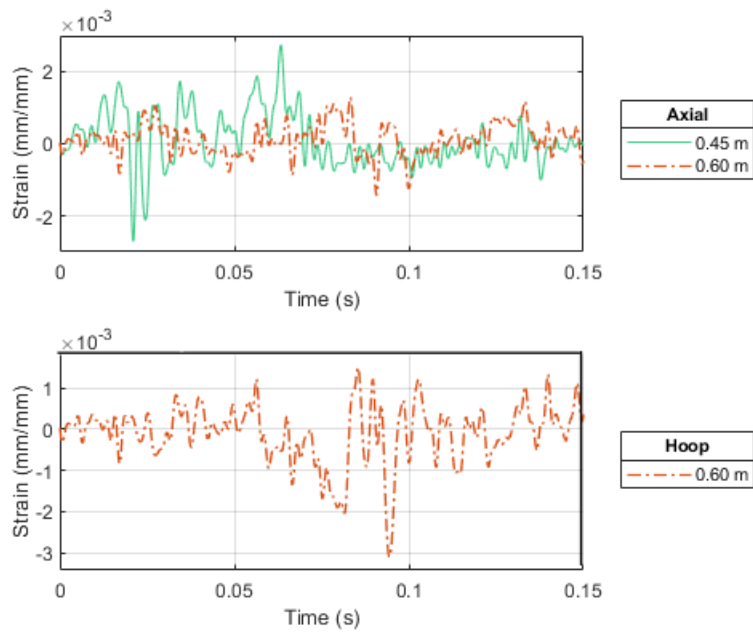


Figure 55. Front Strain Comparison of PLA(3/4) Inner Cylinder with 100% Water Level at Two Stand-Off Distances

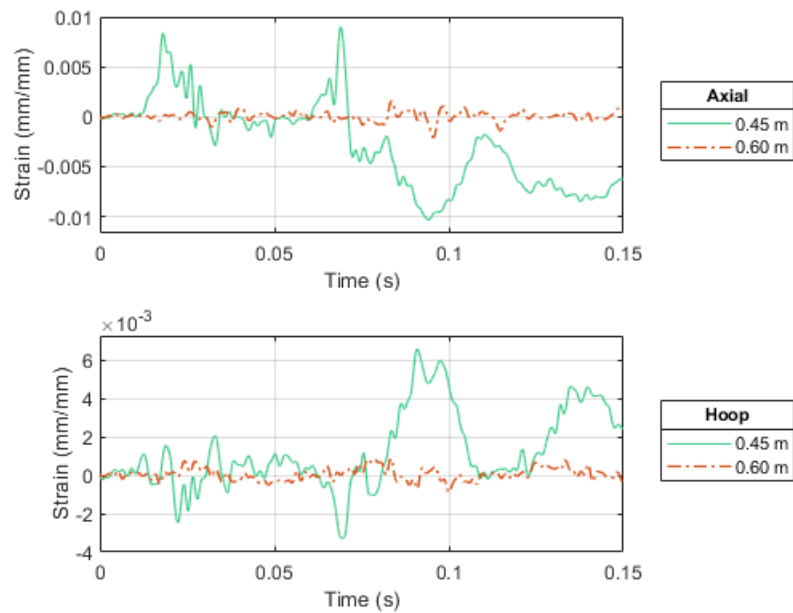
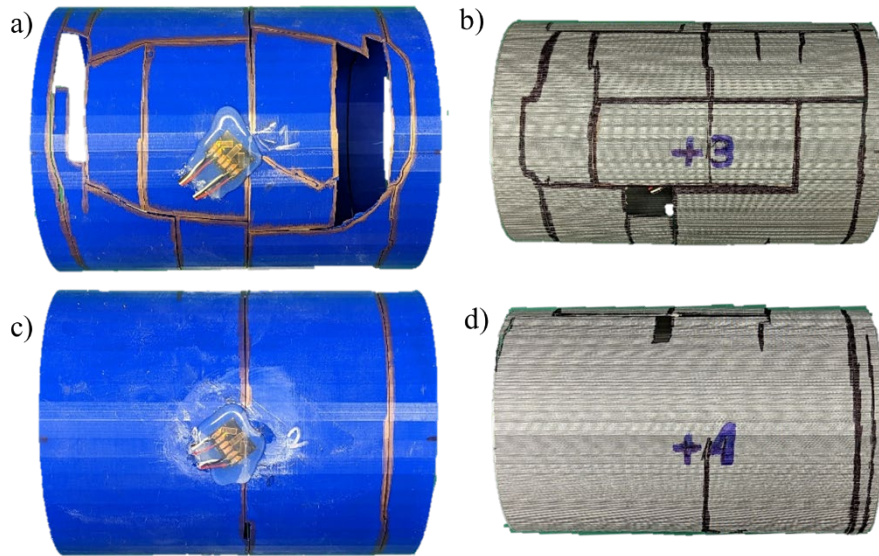


Figure 56. Posterior Strain Comparison of PLA(3/4) Inner Cylinder with 100% Water Level at Two Stand-Off Distances



Samples on the left side labeled a and c are the front and posterior sides of the outer cylinder, and samples on the right side labeled b and d are the front and posterior sides of the inner cylinder.

Figure 57. Ruptured PLA(3/4) Double-wall Sample with Fractured Areas Outlined

PLA cylinders are rather simple to create and almost readily available with enough filament on hand. Although, based on this experimental data, it is proven that the material does not withstand underwater shock loading. Moreover, the printing method of the 3D printer is an important factor to the structural integrity of the cylinder since there is little to no change in direction of the layers. This creates stress concentrations in between the layers and a point of failure when an external force is involved. The thickness of the cylinder is also a factor in the structure failing. All in all, the PLA cylinders would require more structural support, robustness, and interlocked layers to survive an underwater explosion.

V. CONCLUSIONS

The objective of this research was to analyze the dynamic response of composite cylinders subjected to underwater shock loading. Carbon fiber and polylactic acid composite materials were constructed and tested separately as single-wall and double-wall cylindrical structures. A support structure was designed to have the ability to submerge the samples and investigate different water levels within the cylinders.

For CFC cylinders, it was determined that any amount of air filled internally is affected by the shock loading through a rarefaction wave. In contrast, CFC cylinders with 100% water level showed a much higher tolerance to the shock loading which is credited to the winding process where each fiber is interlocked with a $\pm 45^\circ$ winding layer.

Additionally, PLA cylinders were found to be more sensitive to shock loading for both single-wall and double-wall configurations as it displays a global failure when the initial fracture occurs. This is found to be the result of the print layering method of the 3D printer. Furthermore, the implosion or cavitation that occurs when a 0% water level PLA cylinder ruptures affects the pressure in the surrounding areas compared to a 100% water level PLA sample.

Lastly, the data found in this study supports the present and future of composite vessel design, and the knowledge of composite material behavior will further expand the application throughout various communities.

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VI. RECOMMENDATIONS

A. EXPERIMENTAL IMPROVEMENTS

Watertight integrity is one of the many issues encountered in this research. To battle that issue, rubber compound was used instead of RTV coating. The rubber compound is more workable when used inside the grooves in between the end cap and cylinder sample edges. Creating PLA samples are more consistent for testing purposes and utilizing a transparent filament, compared to a solid-colored filament, would be more beneficial in representing the accuracy of the water levels internally. Additionally, the PLA printing time is another concern because of the total duration, so to save on time the idea of printing two cylinders is available.

Another issue this research faced are the end caps, or structural supports, fracturing at the mounting point which hindered the use of the rigid CTR. Thus, a redesigned end cap with a more robust mounting brackets is required for a rigid body testing environment. In the topic of fractures, this study consisted of a rapid expansion of gasses that affects a structure to be examined; hence, the use of a high-speed camera is valuable to this analysis to capture the instantaneous timing of the shock wave in contact with the structure and environment.

Lastly, the recommendation of a reusable shock loading mechanism that does not limit the number of experimental test runs which could be performed. This is to ensure the data recorded is not solely counting on one test run. Also, it will allow repeatable strain data by conducting an identical test run multiple times with the same structure configuration, stand-off distance and water levels.

The few improvements mentioned, are only a starting point to enhancing the experimental procedures and analysis of cylindrical structures under shock loading. The outlook for composite materials is not only promising but highly advantageous.

B. FUTURE WORK

This research conducted is simply a baseline to the understanding of composite material behavior; moreover, the following are opportunities for future work to continue the study of composites such as multi-layer cylindrical structures. The importance of analyzing a multi-layer cylinder is to expand the design of ship hulls, submarines, and submerged piping systems. With numerous capabilities and the idea of a fallback layer in any case of structural damage should occur.

Damaged composites are another topic of interest for future work because this current work is concentrated only on the strain response when the shock loading is deployed, but not what happens after the fracture takes place. A post-fracture analysis helps close the gap between the shock load strain response and the material behavior on a microscopic level.

Another study brings the focus to rigid boundary conditions, to compare the difference between a free-moving structure and a fixed structure when shock loading is involved. This comparison is beneficial with regards to exploring support structures options for data collection systems. Lastly, understanding the pressure loading outside of the structure is important, but recording the internal pressure during a shock wave would be very appealing to the cyber systems community with knowing how the internals are impacted by a pressure wave.

APPENDIX. TABULATED EXPERIMENTAL DATA

Date	X1	Y1	X2	Y2	X3	Y3	Max Pressure (Pa)	P2 & P3 Max Average Pressure (Pa)	Environment	Standoff Distance	Sample	Material	Single/Double Cylinder	Outer Diameter	Inner Diameter	Inside (W/A)	Failure (Y/N)	Failure Location	Water Level (%)
22-Apr-22	45	0	75	-10	75	10	44,832.50	44,524.92	Rigid	75 cm	T6(2)	CFRC	Single	15.2 cm	N/A	Water	N	N/A	100
22-Apr-22	45	0	75	-10	75	10	46,941.64	40,492.55	Rigid	75 cm	T6(2)	CFRC	Single	15.2 cm	N/A	Water	N	N/A	100
29-Apr-22	45	0	60	-10	60	10	86,947.78	71,850.53	Rigid	60 cm	T2(1)	CFRC	Single	15.2 cm	N/A	Water	N	N/A	100
12-May-22	45	0	60	-10	60	10	29,254.72	20,208.53	Suspended	60 cm	T2(1)	CFRC	Single	15.2 cm	N/A	Air	N	N/A	0
12-May-22	15	0	30	-10	30	10	516,487.39	319,245.05	Suspended	30 cm	T2(1)	CFRC	Single	15.2 cm	N/A	Air	Y	Front and Top	50
12-May-22	30	0	45	-10	45	10	155,589.89	86,920.23	Suspended	45 cm	T5(2)	CFRC	Single	15.2 cm	N/A	Air	N	N/A	0
20-May-22	23	0	32	-12.7	32	12.7	187,076.59	106,646.94	Suspended	45 cm	CFC(1)	CFRC	Single	15.2 cm	N/A	Air	N	N/A	0
20-May-22	15	0	21	-12.7	21	12.7	296,635.88	124,737.95	Suspended	21 cm	CFC(1)	CFRC	Single	15.2 cm	N/A	Air	Y	Front and Bottom	0
26-May-22	15	0	21	-12.7	21	5	353,624.39	132,216.95	Suspended	30 cm	T2(2)	CFRC	Single	15.2 cm	N/A	Water	N	N/A	100
26-May-22	7.5	0	11	-12.7	11	12.7	680,976.99	151,139.97	Suspended	15 cm	T2(2)	CFRC	Single	15.2 cm	N/A	Water	Y	Front and Bottom	100
26-May-22	23	0	32	-12.7	32	5	207,839.84	56,432.45	Suspended	45 cm	T5(2)/3.5(2)	CFRC	Double	15.2 cm	8.9 cm	Water	N	N/A	100
03-Jun-22	23	0	32	-12.7	32	12.7	189,727.22	100,558.01	Suspended	45 cm	CFC(3/4)	CFRC	Double	15.2 cm	8.9 cm	Water/Air	N	N/A	100
21-Jun-22	23	0	32	-12.7	32	12.7	194,144.93	110,856.75	Suspended	45 cm	CFC(3/4)	CFRC	Double	15.2 cm	8.9 cm	Water/Air	N	N/A	100
22-Jun-22	23	0	32	-12.7	32	12.7	218,000.58	108,327.55	Suspended	45 cm	CFC(3/4)	CFRC	Double	15.2 cm	8.9 cm	Water/Air	N	N/A	50
22-Jun-22	15	0	21	-12.7	21	12.7	315,632.05	143,374.90	Suspended	30 cm	CFC(3/4)	CFRC	Double	15.2 cm	8.9 cm	Water/Air	N	N/A	100
23-Jun-22	15	0	21	-12.7	21	12.7	328,001.65	149,194.42	Suspended	30 cm	CFC(3/4)	CFRC	Double	15.2 cm	8.9 cm	Water/Air	N	N/A	50
23-Jun-22	7.5	0	11	-12.7	11	12.7	546,236.71	193,232.98	Suspended	15 cm	CFC(3/4)	CFRC	Double	15.2 cm	8.9 cm	Water/Air	N	N/A	100
29-Jul-22	23	0	32	-12.7	32	12.7	161,012.08	113,922.76	Suspended	45 cm	CFC(2)	CFRC	Single	15.2 cm	N/A	Water/Air	N	N/A	50
01-Aug-22	7.5	0	11	-12.7	11	12.7	639,892.25	253,065.63	Suspended	15 cm	CFC(3/4)	CFRC	Double	15.2 cm	8.9 cm	Water/Air	Y	Front and Top	50
10-Aug-22	23	0	32	-12.7	32	12.7	168,963.96	119,252.23	Suspended	45 cm	CFC(2)	CFRC	Single	15.2 cm	N/A	Air	N	N/A	0
22-Aug-22	23	0	32	-12.7	32	12.7	187,076.59	121,175.15	Suspended	45 cm	CFC(2)	CFRC	Single	15.2 cm	N/A	Water	N	N/A	100
24-Aug-22	23	0	32	-12.7	32	12.7	190,168.99	137,158.24	Suspended	45 cm	PLA-1	PLA	Single	15.2 cm	N/A	Air	Y	Center Mass	0
7-Sep-22	37.5	0	53	-28	53	28	119,485.58	69,086.98	Suspended	75 cm	PLA(1)	PLA	Single	15.2 cm	N/A	Air	Y	Front and Hoop	0
6-Oct-22	37.5	0	53	-28	53	28	112,859.01	64,669.55	Suspended	75 cm	PLA(2)	PLA	Single	15.2 cm	N/A	Water	N	N/A	100
12-Oct-22	45	0	51	-28	51	28	93,862.84	70,740.43	Suspended	60 cm	PLA(2)	PLA	Single	15.2 cm	N/A	Water	N	N/A	100
12-Oct-22	23	0	32	-12.7	32	12.7	168,522.19	92,344.46	Suspended	45 cm	PLA(2)	PLA	Single	15.2 cm	N/A	Water	Y	Center Mass	100
14-Oct-22	37.5	0	53	-28	53	28	17,436.40	2,539.99	Suspended	75 cm	PLA(3/4)	PLA	Double	15.2 cm	12.7 cm	Water/Air	N	N/A	100
17-Oct-22	45	0	51	-28	51	28	100,931.18	73,057.49	Suspended	60 cm	PLA(3/4)	PLA	Double	15.2 cm	12.7 cm	Water/Air	N	N/A	100
18-Oct-22	23	0	32	-28	32	28	183,100.65	95,505.59	Suspended	45 cm	PLA(3/4)	PLA	Double	15.2 cm	12.7 cm	Water/Air	Y	Center Mass	100
24-Oct-22	45	0	51	-28	51	28	24,504.75	3,796.29	Suspended	60 cm	PLA(6)/PLA(7)	PLA	Double	15.2 cm	12.7 cm	Water/Air	Y	Top	50

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