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DYNAMIC BEHAVIOR OF COMPOSITE STRUCTURES SUBJECTED TO
AGGRESSIVE MARINE ENVIRONMENTS: AN EXPERIMENTAL AND
COMPUTATIONAL INVESTIGATION

BY

CARLOS RAFAEL JAVIER MELLA

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

MECHANICAL ENGINEERING AND APPLIED MECHANICS

UNIVERSITY OF RHODE ISLAND

2019

DOCTOR OF PHILOSOPHY DISSERTATION

OF

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2019

ABSTRACT

Four studies were completed to investigate the dynamic behavior of composite structures after exposure to marine environments, with a fifth study which deals with the energy absorption effects of foam materials in underwater implosion. These studies evaluated the following: In-air blast response of composite plates after prolonged exposure to saline water; The in-air blast response of composite plates after prolonged exposure to ultraviolet radiation; Hydrostatic and blast initiated implosion of composite cylinders after exposure to saline water; Underwater blast response of fully submerged composite plates after exposure to saline water; Hydrostatic initiated implosion of metallic cylinders with foam fillers. Two high-speed cameras were used to record the deformation of the structures in real time, where a third camera was used to record the explosive gas bubble when applicable. For air blast experiments, three piezoelectric pressure sensors were used to record the transient pressure data, whereas for underwater applications, tourmaline pressure transducers were utilized to record the dynamic pressure. Three-dimensional Digital Image Correlation was employed to obtain full field displacements, strains, and velocities during dynamic loading. Numerical simulations were included to compliment the experiments and obtain further understanding not achievable with experimental data. The air blast response of composites was modeled using the LS-DYNA code with a material model capable of including damage in tension, tensile shear, and compression. The underwater explosives response of composite plates was a Coupled Eulerian-Lagrange model created using the DYSMAS software.

The completion of these studies concluded that: Exposure to saline water decreases the blast performance of composites. Furthermore, the removal of moisture shows that there is permanent material degradation after exposure to saline water; Ultraviolet radiation exposure increases the stiffness of composite materials and decreases the failure strains in tension and shear; exposing hollow cylindrical composites to saline water decreases the critical collapse pressure in hydrostatic implosion, and the overall energy released during implosion is lower for weathered composites when compared to virgin structures; the underwater blast performance of saline water exposed plates is governed by the standoff distance of the explosive as well as the hydrostatic pressure of the fluid; and foam materials can mitigate the energy associated with implosion when placed inside of cylindrical structures.

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PREFACE

This dissertation is submitted for the degree of Doctor of Philosophy in Mechanical Engineering and Applied Mechanics at the University of Rhode Island. This work is presented in a manuscript format that consists of five chapters.

Chapter 1 deals with the blast response of carbon fiber reinforced composites which have been exposed to saline water for prolonged time periods. Moreover, plates exposed to saline water were placed in a desiccator to remove the absorbed moisture. Removing the absorbed water reduces the residual stresses and strains induced by swelling, which allows for the investigation of the permanent material degradation induced by water absorption.

Chapter 2 details the blast response of composite materials after exposure to ultraviolet radiation. In this chapter, composite materials were utilized to investigate the mechanisms of failure that are typical of glass fiber, and carbon fiber, and how these change with exposure to ultraviolet radiation exposure.

Chapter 3 builds on previous knowledge on the hydrostatic and blast initiated implosion of filament-wound carbon fiber composite cylinders in underwater environments. In this study, composite cylinders were exposed to saline water which changes the material properties of composites. The study investigates the hydrostatic and blast initiated implosion of such environmentally weathered composite tubes.

The completion of Chapter 4 builds on Chapter 1, where flat composite plates were exposed to saline water for prolonged periods of time. In this chapter, the composite plates were subjected to explosive loads in a fully submerged underwater environment. Furthermore, the pressure of the surrounding fluid was varied to alter the interaction

between the gas bubble induced by the explosives and the composite structures. Such loadings induce different mechanisms of failure on the weathered composite structures.

Chapter 5 is unrelated to the first four chapters, where metallic structures are utilized rather than composite structures. This chapter was completed to understand the energy emitted during the underwater collapse of aluminum structures, and how this energy can be mitigated by the use of closed cell foams placed inside of the implodable volumes.

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Chapter 1 Blast Response of Hydrothermally Degraded Carbon Fiber / Epoxy Composite Plates

by

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ABSTRACT

An experimental study was conducted to evaluate the in-air blast response of unidirectional carbon fiber / epoxy plates after prolonged exposure to saline water. The plates were submerged in a water bath at 65°C containing 3.5% NaCl content for 800 hours. This simulates approximately 10 years of operating conditions in accordance to Fick's law of diffusion coupled with Arrhenius's Equation and a reference ocean temperature of 17°C. Composite plates were also exposed to saline water for 800 hours and then placed in a desiccator for 1600 hours to remove the moisture and investigate the permanent damage caused by water absorption. After saline water exposure, the plates were fully clamped on all edges and subjected to a concentrated and controlled air blast using a shock tube apparatus. Three-Dimensional Digital Image Correlation was coupled with high-speed photography to obtain full-field displacements of the composite plates during blast loading. Furthermore, three Piezoelectric pressure transducers were mounted on the shock tube apparatus and utilized to measure the pressure history of the shockwave. Quasi-static tests were performed to obtain the tensile and shear material properties of the composites for virgin specimens and specimens exposed to saline water. Compression After Impact experiments were conducted to evaluate the residual strength of the plates after being subjected to shock loading. After 800 hours of exposure to the salt water solution, the plates reached moisture saturation. The diffusion of water into the matrix showed a decrease in tensile modulus, shear modulus, failure stresses and strains in tension and shear, as well as higher out of plane displacements when subjected to shock loading when compared to virgin specimens. Plates which were exposed to the saline water bath for 800 hours and

afterwards desiccated showed higher out of plane displacements when subjected to shock loading than virgin structures. However, the desiccated plates showed lower out of plane displacements from shock loading when compared to fully saturated plates (800 hours of exposure).

1. INTRODUCTION

A series of experiments was conducted to study the blast response of environmentally degraded carbon fiber / epoxy composite plates. The plates were exposed to a 65°C temperature saline water bath, containing 3.5% NaCl, for 800 hours, which is equivalent to 10 years of service life according to Arrhenius' equation and a reference temperature of 17°C. Composite plates were also exposed to the saline water bath for 800 hours and then placed in a desiccator for 1600 hours to investigate the effect of swelling due to moisture absorption. The plates were then subjected to a concentrated and controlled shockwave generated by a shock tube. Three-Dimensional Digital Image Correlation (DIC) was coupled with high-speed photography to obtain full field deformation data throughout the blast event. This work aims to understand the material degradation and potential premature failure in composite materials that are exposed to aggressive marine environments. Failure to account for such degradation in the design of composite structures for marine applications can lead to catastrophic results.

The material properties of fiber reinforced composites are known to decrease when exposed to moisture [1]. The diffusion of water into the matrix of composites can be described by Fick's second law of diffusion [2,3] which is dependent on the diffusing substance, temperature, pressure, concentration of the diffusing substance, and the

physical parameters of the composite, such as resin type, fiber volume fraction, void content, and fillers [4-6]. To conduct diffusion experiments in a reasonable time frame, accelerated life testing methods are employed by using water baths at elevated temperatures which drives the diffusion of water into the polymer matrix of composites at faster rates [7-12].

The accelerated life testing methods have shown that material properties of composites degrade over time, such as stiffness, fatigue life, creep behavior, delamination strength, and resistance to impact, shock, and blast loads [13-17]. Several studies have aimed to find a correlation between the accelerated life testing time in a laboratory environment to real life working conditions by performing diffusion studies to obtain an acceleration factor. In such studies, the diffusion of water is recorded by measuring the weight gain in composites under different temperatures. Once the temperature dependence of the diffusion coefficient is known, an activation energy is obtained. Arrhenius's equation is then used to relate the laboratory water bath temperatures to real life working temperatures [18].

The current study deals with the blast response of unidirectional fiber reinforced composite materials after prolonged exposure to saline water. Moreover, the study investigates the permanent damage in composites caused by water absorption by removing the moisture and subjecting such panels to blast loading. The findings show that exposure to saline water causes substantial loss in stiffness and blast loading performance. Furthermore, the experimental results show that removing the water from composite materials allow some increase in blast loading performance when compared

to fully saturated plates, though the composites suffer permanent degradation from saline water absorption.

2. EXPERIMENTAL SETUP

A total of three in-air blast loading experimental cases were investigated in this study. Each case was repeated twice, totaling in six experiments. The plates were exposed to the saline water bath for 0 hours and 800 hours, with an additional set of plates being exposed to the saline water bath for 800 hours and then placed in a desiccator for 1600 hours to remove the moisture in the composite plates. Table 1.1 summarizes the experimental cases and their details.

Table 1.1. Experimental details. The remainder of the text will utilize the notation given to address each specific saline water exposure time and fiber orientation as shown

Case	Exposure Time (hr)	Year Equivalent (yr)	Fiber Orientation
c_0	0	0	[+45°, -45°]s
c_800	800	10	[+45°, -45°]s
c_D	800 (Desiccated)	10	[+45°, -45°]s

2.1. Material

The composite plates consisted of four plies of unidirectional carbon fabric oriented in a [+45°, -45°]s layup. The fabric used was Tenax HTS40 F13 24K 1600tex from Toho Tenax Inc. (Rockwood, TN). The fibers have a 1% polyurethane-based sizing finish for compatibility with the resin/hardener used. The resin/hardener mixture was a 100/30 weight ratio of the RIMR135/RIMH137 epoxy from Momentive Performance Materials Inc. (Waterford, NY). The plates were manufactured at TPI Composites Inc. (Warren, RI) by using the Vacuum Assisted Resin Transfer Molding (VARTM) process. The process was performed on a smooth, heated Teflon top table. Once the resin was

infused into the fabric, the plates were allowed to dry and harden on the table at 70°C for 24 hours. Afterwards, curing was completed by placing the plates in an oven at 70°C for 10 hours. All specimens were cut from a single sizeable composite sheet to minimize variations in the manufacturing process. The plates had a 1% void content, measured in accordance to ASTM Standard D2734 [19], and a 60% fiber volume content. The final thickness of the plates was 1.25 mm.

2.2. Weathering Facility

Two water tanks were used to expose the composite plates to saline water, shown in Figure 1.1. The volumetrically smaller tank was placed inside of the larger tank. Both tanks were filled with deionized water, with the smaller tank having 3.5% NaCl content. The water in the larger tank was heated by four immersion heaters and maintained at a constant temperature of 65°C. The larger tank was maintained free of NaCl to avoid corrosion of the heaters. The immersion heaters used are Polyscience LX Immersion Circulators (Cole Parmer, Vernon Hills, IL). The temperature of 65°C was selected as to not reach the glass transition temperature of the composite materials, measured to be 82°C in accordance to ASTM Standard D7028 – 07 [20]. Before placing the composite materials in the elevated temperature saline water bath, the specimens were placed in a desiccator for seven days to remove accumulated moisture from the environment. The composite materials were then submerged in the saline water bath for 800 hours. All experiments were conducted the same day the specimens were removed from the accelerated weathering facility to avoid loss of moisture.

One of the contributing factors for the loss in performance of composite materials that have been exposed to marine environments is residual stresses and strains from

swelling due to water absorption. Therefore, a separate set of specimens were exposed to the saline water bath for 800 hours and then placed in a desiccator for 1600 hours for the removal of moisture to investigate the permanent damage caused by water absorption, but do not have such swelling and residual stresses present.

Figure 1.1. Accelerated weathering facility setup

2.3. Material Characterization Procedure

Quasi-static tensile and in-plane shear properties were obtained using an Instron 5585 and following ASTM Standards D3039 [21] and D3518 [22], respectively. A random speckle pattern was painted on one face of the specimens to employ 2D DIC and obtain full field strain data. The images were captured by a Prosilica camera model GC2450 from Allied Vision Technologies GmbH (Stadtroda, Germany). The tensile and shear experiments were used to quantify the effective material properties for virgin specimens, as well as the properties of composites exposed to the saline water bath.

2.4. Shock Tube Facility

A shock tube apparatus was used to subject the composite plates to a transverse shockwave. The shock tube is 8 m in length and is composed of four separate sections:

driver section, driven section, converging conical section, and a 38 mm diameter muzzle. A schematic of the shock tube can be seen in Figure 1.2.

Figure 1.2. Shock tube facility showing key aspects of the experimental setup. The shock tube muzzle is confined in a steel chamber with acrylic windows for DIC imaging. The composite specimen is placed flush to the shock tube muzzle end

A Mylar diaphragm separates the driver section from the driven section. The driver section is pressurized using helium gas until the diaphragm ruptures, which causes a propagation of pressure down the shock tube and become a planar shockwave. The pressure of the shockwave is captured by three piezoelectric pressure transducers which are mounted flush to the shock tube muzzle. The pressure transducers are Piezoelectric PCB102A by PCB Piezotronics Inc. (Depew, NY). When the shock wave impinges on the specimen, the shock is compressed and reflected back into the shock tube muzzle, which is the loading that the specimens experience. The composite plates were placed flush to the shock tube muzzle and clamped on all edges. The clamping fixture consisted of two steel plates with a central square cavity of 178 mm by 178 mm in dimension, giving an unsupported area of 31684 mm^2 . The steel plates were bolted together with 16 screws, with each screw having an applied torque of $20 \text{ N}\cdot\text{m}$ to maintain a consistent clamping force for all experiments. Two Photron FastCam SA1 cameras by Photron

USA (San Diego, CA) were used to obtain stereo images of the blast event. Two Super Sun-Gun SSG-400 from Frezzi Energy Systems Inc. (Hawthorne, NJ); were used to illuminate the specimens during the experiments.

2.5. Digital Image Correlation

DIC is an optical technique which provides full-field displacement measurements on the specimen surface. During blast loading, two cameras are used for capturing the three dimensional response of the plates. The cameras were calibrated and synchronized prior to the completion of the experiments by using a grid of dots with known relative locations. The calibration grid was displaced in all degrees of freedom while recording the images. The coordinate locations of the dots allow for a correspondence of the coordinate system for each camera. Utilizing the calibration obtained, a software performs the DIC technique on image pairs of the blast event from the two cameras. A high contrast random speckle pattern was applied to the composite plates by coating the specimen with white paint on one face, and randomly placing black dots approximately 2 mm in diameter throughout the coated area. The Photron FastCam SA1 cameras were set to record at 20,000 frames per second. The analyses of the high-speed images were performed using the commercially available VIC-3D 7 software by Correlated Solutions, Inc. (Columbia, SC). The VIC-3D software matches common pixel subsets of the random speckle pattern between a reference undeformed image and the deformed images.

3. EXPERIMENTAL RESULTS

To correlate the elevated temperature of 65°C in the weathering facility to real service temperatures, a mass diffusion study was performed for different water bath temperatures. Once the correlation between the laboratory exposure time was correlated to real life working temperatures, blast experiments were conducted on carbon fiber plates after 0 hours and 800 hours of exposure to the 65°C saline water bath. A separate set of specimens were exposed to the saline water bath for 800 hours and then placed in a desiccator for 1600 hours to remove the moisture from the plates. After blast loading, Compression After Impact (CAI) experiments were performed on all composite plates to evaluate the residual strength.

3.1. Diffusion Study

The diffusion study was carried out on coupons of the composite material with dimensions of 51 mm x 51 mm for both fiber orientations. For the diffusion study, the assumptions are that the diffusion of the salt water solution into the epoxy matrix obeys Fick's law of diffusion, the diffusion coefficient is constant throughout the composite specimen, the temperature and pressure of the diffusion substance is constant, the plate is initially free of water, and that the diffusion is one dimensional. Since the assumptions are reasonably close to the experimental setup, Fick's second law of diffusion can be expressed by [3]

$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{\left[\frac{-D(2n+1)^2 \pi^2 t}{4h^2} \right]} \quad \text{Equation 1.1}$$

where M_t is the total diffusion substance absorbed by the plate at time t , M_∞ is the saturation mass, D is the diffusion coefficient, and h is the thickness of the specimens.

To obtain the diffusion coefficient, Equation 1.1 can be further simplified by taking the time in which the plates have reached 50% of the saturation mass, given by

$$D = 0.049 \frac{h^2}{t_{50}} \quad \text{Equation 1.2}$$

where t_{50} is the time it takes for the plate to reach 50% of the saturation mass. The dependence of reaction rate to temperature is governed by Arrhenius equation [23], and can be used to model the temperature variation of diffusion coefficients, such that

$$D = D_o e^{-\frac{E_a}{RT}} \quad \text{Equation 1.3}$$

where D_o is an arbitrary constant, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature. The diffusion study was carried out for temperatures of 5°C, 25°C, 45°C, and 65°C to obtain the activation energy of composite plates. The percent mass change as a function of time is shown in Figure 1.3 (a), whereas the relationship between temperature and the diffusion coefficient is shown in Figure 1.3 (b).

Figure 1.3. (a) Mass diffusion trend for different temperatures (b) Relationship between diffusivity and temperature

To obtain a relationship between the elevated temperature and normal service temperature, an acceleration factor is used. The acceleration factor is defined as the ratio

between the diffusion rate of normal working conditions and the diffusion coefficient of the higher laboratory temperature.

$$AF = \frac{D_o e^{\frac{E_a}{RT_2}}}{D_o e^{\frac{E_a}{RT_1}}} = e^{\frac{E_a}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)} \quad \text{Equation 1.4}$$

Since the elevated temperature of the water bath was maintained at 65°C and the average temperature of the ocean is ~17°C, the submergence time of 800 hours in the 65°C water bath is equivalent to 10 years of normal service time. Exposing composite materials to saline water causes the composites to swell [2]. The swelling from water absorption introduces residual stresses in the composite materials, which shows as a decrease in mechanical properties. To investigate the permanent damage caused by water absorption, the residual stresses are removed by placing the composite specimens in a desiccator for 1600 hours. Previous studies [24] showed that removing the moisture in composite materials does not revert the material property deterioration, therefore this phenomenon is further studied in terms of the blast response of composite plates. The trend of mass loss is shown in Figure 1.4.

Figure 1.4. Mass lost for specimens exposed to saline water until saturation and placed in a desiccator for the removal of moisture

Similar to the mass gain, the loss in mass has an exponential trend. The composite coupons had an original mass of 17.5401 grams prior to saline water exposure, where the dashed line in Figure 1.4 is the percent difference between the saturated mass and the initial mass. After a total of 800 hours of exposure to the saline water bath, the composites had reached a total mass of 17.6968 grams (0.9% mass increase). The composite coupons were then placed in a desiccator for 1600 hours, in which time the specimens had a mass of 17.5164 grams, a total of 1.01% mass loss when compared to the saturated specimens. Furthermore, the desiccated specimens had 0.135% less mass than the original virgin specimens, which shows that the composite material lost material, likely due to hydrolization causing mass loss [2, 25, 26].

3.2. Material Characterization

Quasi-static material characterization experiments were completed following ASTM standards D3039 [21] and D3518 [22] to obtain tensile and shear properties for all exposure times. The quasi-static material properties of the composite materials are shown in Table 1.2 , given as the average of five tests.

Table 1.2. Quasi-static material characterization results

Weathering Case	0 Hours	800 Hours	800 Hours (Desiccated)
$E_{1,2}$ (GPa)	78.40±1.80	78.00±2.10	78.13±2.18
G_{12} (GPa)	7.38±0.19	5.32±0.24	5.52±0.14
ν_{12}	0.039±0.01	0.040±0.01	0.040±0.01
Failure Normal Strain (%)	1.46±0.09	1.38±0.09	1.41±0.09
Failure Shear Stress (MPa)	45.30±1.20	41.30±1.90	45.80±2.70
Failure Shear Strain (%)	4.92±0.79	7.25±0.25	5.34±0.83

The change in the tensile modulus $E_{1,2}$ is negligible after 800 hours of exposure to saline water since fiber dominated properties are generally unaffected by saline water

exposure [24]. In terms of shear properties, the shear modulus G_{12} decreased by 20% after 800 hours of exposure to saline water. Specimens placed in a desiccator after 800 hours of exposure showed a 4% increase in shear modulus when compared to specimens exposed to the saline water bath for 800 hours and no desiccation. Furthermore, the failure shear stress increased by 11% compared to the specimens exposed to the saline bath for 800 hours. However, the material properties did not revert back to the initial values, therefore there is permanent damage caused by water absorption that cannot be attributed to residual stresses and strains due to swelling from water saturation.

3.3. Shock Loading

The pressure profile generated by the shockwave is shown in Figure 1.5 for the carbon fiber plates exposed to saline water for 0 hours, 800 hours desiccated plates. The pressure curve shown corresponds to the pressure transducer closest to the muzzle end.

Figure 1.5. Shockwave pressure over time for plates with saline water exposure times of 0 hours, 800 hours, and desiccated plates after 800 hours of exposure

For consistency, the time in which the reflected shock wave is registered by the pressure sensor is taken to be at $t = 0$ ms. The average reflected pressure was 1.85 ± 0.06

MPa, giving a similar initial load in all experiments. When the shockwave impinges on the specimen, the transverse load causes the plate to deflect away from the shock tube. As separation increases between the plate and the shock tube muzzle, the pressure of the shockwave decays exponentially. Once the maximum out of plane displacement is reached, the plate begins to deflect back towards the shock tube. As the plate moves back toward the shock tube, the loading pressure increases, seen after 1.00 ms. The magnitude of the second pressure increase depends on the distance between the plate and the shock tube, which is related to the stiffness of the plate and the damage induced by the shockwave. To further understand the damage potential of the shockwave, the total impulse imparted on the plates was calculated, taken from 0 ms until the pressure fully decays. The impulse is obtained using Equation 1.5

$$I = \int_0^t P(t) * A dt \quad \text{Equation 1.5}$$

where $P(t)$ is the shockwave pressure, and A is the loading area. The energy transferred to the plates from the shockwave can be stored in the form of elastic strain energy, or dissipated in the form of fracture, therefore plates with higher permanent deformation and higher displacements will yield lower impulse curves. Similar results have been seen in previous studies on blast loading [27]. The impulse calculated is not the true impulse imparted on the composite plates, rather it is a quantification of comparative stiffness changes as well as damage induced in composite plates. The impulse for the carbon fiber plates are shown in Figure 1.6.

Figure 1.6. Impulse imparted on composite plates after 0 hours and 800 hours of saline water exposure as well as plates exposed to saline water for 800 hours and desiccated for 1600 hours

The total impulse imparted on the c_0, c_800 and c_D plates were 3.85 N*s, 3.20 N*s and 3.20 N*s, respectively. The impulse imparted on the carbon fiber plates exposed to saline water for 800 hours was lower than virgin structures, implying that the impulse provided by the shock wave caused a higher degree of damage for weathered plates. Moreover, there is no appreciable difference between plates exposed to saline water for 800 hours and moisture-free plates which were exposed to the saline water for 800 hours. Composite materials that have been exposed to saline water and then desiccated exhibit similar responses as composites which were not desiccated.

3.4. DIC Results

The high speed images coupled with 3D DIC yielded full field deformation data for the composite plates. The center point out of plane displacements were extracted from the DIC results and plotted as a function of time, shown in Figure 1.7. When the shockwave loads the plates, the specimens deform out of plane. Once the maximum out of plane displacement is reached, the specimen deflects back towards the shock tube.

However, damage around the clamped boundary of the specimens maintain the plates with a permanent convex shape throughout the blast event.

Figure 1.7. Centerpoint out of plane displacements for plates exposure to the saline water bath for 0 hours, 800 hours, and desiccated plates

Virgin specimens reached a maximum centerpoint out of plane displacement of 12.80 mm. Specimens exposed to saline water had a maximum out of plane displacement of 14.70 mm, 16% higher than virgin specimens. Plates exposed to saline water for 800 hours and then placed in a desiccator for 1600 hours showed a maximum out of plane displacement of 13.90 mm, 7% lower than c_800 plates. The quasi-static experiments showed that desiccated plates had higher in-plane shear modulus (4% higher) than plates exposed to the saline water bath for 800 hours and no desiccation, as well as higher failure shear stress, therefore desiccating fully saturated composite materials can restore stiffness lost due to water absorption. However, the desiccated plates had a maximum out of plane displacement which was 8.5% higher than the virgin specimens.

To understand the extent of damage caused by the shockwave, the kinetic energy of the plates was calculated. Since the displacements are not uniform throughout the plate

(displacements and velocities are higher at the centerpoint than at the boundaries), it is useful to represent the kinetic energy as an average taken throughout the plate. Moreover, rather than considering the entire mass of the plate, the density of the plate is utilized, giving an average kinetic energy density

$$KE_{density} = \frac{1}{2} \rho_{composite} \left[\left(\frac{dU}{dt} \right)^2 + \left(\frac{dV}{dt} \right)^2 + \left(\frac{dW}{dt} \right)^2 \right] \quad \text{Equation 1.6}$$

where $\rho_{composite}$ is the density of the composite plates. The kinetic energy density for the plates is shown in Figure 1.8.

Figure 1.8. Kinetic energy density averaged throughout the plate for composites plates given for saline water exposure times of 0 hours, 800 hours, and desiccated specimens

When the shockwave impinges on the specimen, the energy of the shockwave is transferred onto the composite plates, which causes an increase in velocity (in the x , y , and z directions) on the plate. At this instance, there is no permanent deformation throughout the plate. shown by the full field strain data. The energy transferred to the composite plates by the shock wave is higher for the plates that have been exposed to the saline water bath for 800 hours as when compared to virgin specimens, seen at 0.30 ms. The loss in stiffness causes the plates to deform at a faster rate when compared to the virgin specimens, giving rise to higher kinetic energy. Furthermore, the mass of the

composites increases with exposure to saline water, therefore these plates carry higher kinetic energy as opposed to virgin structures. When the deformation of the plates reaches the clamped boundary after 0.30 ms, the rate of change in displacement decreases, seen as a decrease in kinetic energy (the out of plane displacement continues to increase until 0.60 ms). Energy is dissipated by the boundary in the form of damage caused to the composite plate, as well as a restriction in displacement caused by the clamping fixture. When the maximum out of plane displacement is reached, the kinetic energy decreases to zero. The second peak in the kinetic energy density plot is associated with the remaining elastic energy not spent in permanent deformation of the plate or dissipated by the boundary, therefore it is expected for the secondary peak to be larger in the case of no exposure to the saline water bath as opposed to plates exposed to the saline water bath for 800 hours. Furthermore, there is an increase in kinetic energy density at 1.4 ms for virgin specimens, which is associated with the elastic energy stored in the plate, causing small amplitude vibrations. This behavior is not present in the plates exposed to saline water, likely due to a higher degree of energy spent deforming these plates when compared to virgin structures. The desiccated plates appear to behave similar to plates not exposed to saline water in terms of the initial kinetic energy density peak (5% difference). The second and third peaks associated with the elastic strain energy stored in the plates are also similar between the desiccated plates and plates not exposed to salt water, though there appears to be some appreciable difference.

When the shock wave impinges on the composite plates, a flexural wave is generated in the positive out of plane direction. Moreover, a flexural wave in the negative out of

plane direction is generated, seen in Figure 1.9 (a) given as out of plane velocity contours. The equation for the velocity of the flexural wave is given by [28]

$$C_f = \sqrt[4]{\frac{S}{\rho h}} \sqrt{\omega} \quad \text{Equation 1.7}$$

where C_f is the velocity of the flexural mode, h is the thickness of the composite, ρ is the density, and ω is the frequency of the flexural wave. The value S is given by

$$S = D_{11}I_x^4 + 4D_{16}I_x^3I_y + 2(D_{12} + 2D_{66})I_x^2I_y^2 + 4D_{26}I_xI_y^3 + D_{22}I_y^4 \quad \text{Equation 1.8}$$

where D_{ij} are values of the bending stiffness matrix given by classical laminate theory. As the plates deflect out of plane, the flexural wave propagates through the surface of the composite specimen. The flexural wave does not propagate uniformly due to the anisotropic nature of the plates, therefore the velocity of the transverse wave is higher along the fiber direction of the outer ply of the composite, most noticeable after 0.25 ms. When the negative wave reaches the boundary of the composite, it reflects back towards the center with a positive magnitude. Similarly, when the positive wave reaches the boundary, it reflects back as a negative wave. Since the wave propagation velocity is uniform in all directions, waves of different magnitudes and directions meet throughout the composite plate, therefore for analysis purposes, only the incident waves will be considered. A line along the direction of the fiber where the transverse wave propagation is highest was selected, and the velocity along the length of the line are shown for different time instances in Figure 1.9 (b) for the c_0 plates.

(a)

(b)

Figure 1.9. (a) Full field out of plane velocity contours for the c_0 plates (b) DIC transverse incident wave for c_0 plates

The first line shows when an increase in out of plane velocity is registered by the high speed photography. At the next time instance of 0.10 ms, the out of plane velocity has a maximum out of plane velocity of 30 m/s about the center of the plate 60 mm away from the center in both positive and negative directions, there is a negative velocity magnitude. After 0.15 ms, the wave about the center of the plate plateaus, which separates into two waves traveling in opposite directions, seen after 20 ms. After 0.30 ms, the wave has a constant velocity of ~ 20 m/s, with a peak velocity of 23 m/s seen at ~ 65 mm from the center of the plate. To obtain the velocity of the transverse wave, the peak velocity was taken at each frame. The distance traveled between frames was divided by the time, and averaged to obtain an average transverse wave velocity. The highest transverse wave velocity is seen in the c_0 plates, with an average velocity of

435 m/s. Since the speed of a transverse wave is dependent on the stiffness and thickness of the plates [29], the velocity of the flexural wave of the c_800 plates is 8% lower than the c_0 plates. Furthermore, the flexural wave speed of the c_D plates is 5% lower than the c_0 plates.

3.5. Compression After Impact (CAI)

Quasi-static CAI experiments were performed on specimens after being subjected to shock loading in accordance to ASTM Standard D7137 [30] to measure and compare the compressive residual strength properties of virgin and environmentally degraded composite plates. The CAI method utilizes a flat, rectangular composite plate which is subjected to compressive loading using a stabilization fixture, shown in Figure 1.10 (a). The dimensions of the specimen were 152 mm x 102 mm with a thickness of 1.25 mm, which were centrally cut out of the original shock-loaded composites. The compressive load was applied to the top platen of the fixture using an Instron 5585. The load applied versus the change in displacement of the Instron head is shown in Figure 1.10 (b) for the composite plates. Since there is damage in the composite specimens, the strains in the plates are not uniform, therefore Figure 1.10 (b) does not represent the stress-strain behavior of the plates that is required for obtaining the effective modulus of the specimens. Rather, the Ultimate Compressive Residual Strength of the composite plates after shock loading. The full field strains of the composite plates were obtained using 3D DIC, and were extracted at the two marked locations shown in Figure 1.10 (a). The strain locations are located 25 mm from the top right and left corners, in the vertical and horizontal directions.

Figure 1.10. (a) Compression After Impact fixture for measuring residual strength of shock loaded composite plates. The dimensions of the cut-out are shown, as well as the location of the strain measurements. (b) Load versus Instron head displacement for environmentally weathered composite plates

The ultimate compressive residual strength decreases with increasing exposure to the saline water, with a 9% decrease after 800 hours of exposure for desiccated specimens, the ultimate compressive residual strength is 4% lower than virgin specimens (5% higher than saturated plates). The effective modulus of the composite plates after shock loading is given by

$$E_{CAI} = \frac{(P_{3000} - P_{1000})}{(\varepsilon_{3000} - \varepsilon_{1000}) * A} \quad \text{Equation 1.9}$$

where ε_{3000} is 3000 microstrains, ε_{1000} is 1000 microstrains, P_{3000} is the load corresponding to 3000 microstrains, P_{1000} is the load corresponding to 1000

microstrains, and A is the cross-sectional area of the plates. The effective moduli for the composite plates are tabulated in Table 1.3.

Table 1.3. Compression After Impact effective modulus given for composite materials subjected to shock loading after exposure to saline water for 0, 800, and desiccated plates

Weathering Case	Ultimate Compressive Residual Strength (MPa)	Effective Compressive Modulus (GPa)
c_0	60	9.04
c_800	52	5.78
c_D	53	5.84

Unlike the ultimate strength, the effective modulus decreases substantially after exposure to saline water. The effective modulus decreased by 36% after 800 hours of exposure. Placing saturated plates in the desiccator for 1600 hours did not increase the effective modulus by an appreciable amount, giving a value of 35% lower than virgin specimens. The quasi-static properties showed that the failure tensile stress does not change with exposure to saline water (fiber dominated property), and the failure shear stress decreases by 8% after 800 hours of saline water exposure. Therefore, the ultimate strength of composites is not greatly altered by exposure to saline water. However, the effective modulus is altered considerably, which can result in premature catastrophic failure. It should be noted that the effective modulus, as well as the ultimate strength are a function of several factors, such as specimen geometry, fiber layup, damage type, damage size, damage location, boundary conditions and material properties, therefore the differences in ultimate strength and effective modulus do not indicate lower properties due to a higher degree of damage for weathered plates; the differences can be due merely to a decrease in material property, without a substantial increase in damage.

4. CONCLUSIONS

The blast response of fiber reinforced composite plates after prolonged exposure to saline water was studied experimentally. The following conclusions can be drawn based on the findings of this study:

- Mass saturation was reached in composite materials after 800 hours of exposure to the saline water bath when the temperature was maintained at 65°C. Exposing composite materials to the saline water bath for 800 hours and afterwards being placed in a desiccator showed that the mass decreases past the original mass of the composite material, showing that composites lose material when exposed to saline water.
- The quasi-static material properties of the composite materials decreased with exposure to saline water. Weathering the plates to the saturation point showed a substantial decrease in shear modulus when compared to virgin specimens. However, fiber dominated properties such as tensile modulus and failure tensile strain did not change. Placing specimens in a desiccator for 1600 hours after being exposed to saline water for 800 hours showed that the material properties did not revert back to the original values given by virgin specimens. However, removing moisture from saturated plates cause an increase in material properties.
- Composite plates exposed to saline water for 800 hours had a maximum out of plane displacement 16% higher than virgin specimens. Plates exposed to saline water for 800 hours and then placed in a desiccator for 1600 hours had a maximum out of plane displacement which was 8% higher than virgin specimens. However, when compared to plates exposed to fully saturated plates, the out of plane displacement

of desiccated plates was 7% lower. Therefore, composite materials can partially regain stiffness when moisture is removed.

- Compression After Impact experiments showed a minimal loss in ultimate compressive residual strength for plates exposed to saline water. The ultimate compressive residual strength of plates exposed to saline water for 800 hours was 4% lower than virgin specimens. Furthermore, the effective modulus decreased by 35% for such plates. Moisture free plates which had been exposed to saline water for 800 hours did not show an increase in effective modulus when compared fully saturated plates.
- Overall, exposing composite plates to saline water decreased the material properties, blast resistance capabilities, and residual strength after blast loading. Removing moisture from fully saturated plates showed an increase in material properties, as well as blast performance, which shows that removing residual stresses due to swelling from water absorption can increase the material properties of composite plates, although there is permanent damage caused to composites from water absorption.

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Chapter 2 Effect of Prolonged Ultraviolet Radiation Exposure on the Blast Response of Fiber Reinforced Composite Plates

By

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ABSTRACT

An experimental study with corresponding numerical simulations was conducted to evaluate the blast response of composite plates after prolonged exposure to ultraviolet radiation. Two composite materials were used in this study, namely, carbon fiber / epoxy and glass fiber / vinyl ester. The composite materials consisted of four unidirectional fiber plies oriented in a $[\pm 45^\circ]_s$ layup. The plates were placed in a QUV Accelerated Weathering Tester for 500 hours of exposure on each face, totaling 1000 hours of ultraviolet radiation exposure, equivalent to 2.5 MJ/m^2 of energy. The QUV Accelerated Weathering Tester was equipped with eight UVA-340 lamps to provide real service life exposure conditions. Material characterization experiments were performed on virgin specimens, as well as specimens exposed to ultraviolet radiation for 1000 hours to determine its effect on the mechanical properties of the composites. Blast experiments were conducted on the composite plates to investigate the dynamic response before and after exposure to ultraviolet radiation. The plates were clamped on all edges and subjected to an air blast using a shock tube apparatus. Three-Dimensional Digital Image Correlation was coupled with high-speed photography to obtain full-field displacements of the specimens during blast loading. Furthermore, three Piezoelectric pressure transducers were mounted on the shock tube apparatus and utilized to measure the pressure history of the shock wave loading. The quasi-static material characterization showed that the tensile modulus E_I had minimal change after exposure to ultraviolet radiation for 1000 hours. However, matrix dominated properties such as the in-plane shear modulus G_{I2} increased after exposure to ultraviolet light for both the carbon and glass fiber composites, which resulted in lower out of plane displacements during blast

loading. For the carbon fiber plates, the forced vibration frequency induced by the transverse blast load was higher in plates exposed to ultraviolet radiation when compared to virgin specimens. However, for the glass fiber plates exposed to ultraviolet radiation, the forced vibration frequency decreased when compared to virgin specimens. Finally, the finite element simulations were in good agreement with the experimental results. The simulations revealed that the glass fiber plates exposed to ultraviolet radiation had higher failure strains at the boundary than virgin specimens, despite having higher stiffness. A parametric study in which higher loading was simulated also showed that the glass fiber plates experienced more damage after 1000 hours of ultraviolet radiation exposure.

1. INTRODUCTION

The blast response of fiber reinforced composite plates with prolonged exposure to ultraviolet (UV) radiation was studied experimentally and computationally. Carbon fiber / epoxy and glass fiber / vinyl ester composite plates were exposed to UV radiation for 500 hours on each face of the plates, for a total of 1000 hours, equivalent to 2.5 MJ/m² of energy. The plates were then subjected to blast loading using a shock tube facility. During experiments, three-dimensional digital image correlation technique (DIC) coupled with high-speed photography was used to record and evaluate the full field deformation data. In addition, Finite Element Modeling (FEM) was performed using the LS-DYNA code to simulate the structural response of the plates subject to shock loading.

The motivation for this work stems from the concern of damage to marine structures during their service life. Composite materials are utilized for the construction of marine structures due to their high strength to weight ratios, low thermal, magnetic and acoustic signatures, and resistance to corrosion. However, the mechanical properties of composites are known to change when exposed to UV light for prolonged time periods. Marine structures can also be subjected to shock, blast, and impact loading during their service life, therefore, material property change from UV radiation exposure needs to be accounted for in the design of such structures. Failure to account for the change in material properties can potentially yield unwanted structural responses and catastrophic failure.

When exposed to UV light, the polymer matrix in composite materials undergoes chemical changes due to the breaking of covalent bonds, which causes chain scission [1] and crosslinking of the polymer chains [2]. Crosslinking and chain scission operate in a competing manner during UV exposure. In the early stages crosslinking dominates, in which case the matrix becomes stiffer, and soon after chain scission takes over, resulting in increased microcracking and surface deterioration [3]. Therefore, the magnitude of degradation in composite materials is directly related to the irradiance of the UV light [4], as well as the total exposure time [5, 6]. Since the chemical changes occur in the matrix material rather than the fibers, the matrix dominated properties are affected the most by UV radiation [7]. Studies have shown that exposure to UV radiation can cause the tensile modulus to decrease in composite materials [8], while others have concluded that there is an increase in tensile modulus and tensile failure stress when exposed to UV radiation [9,10]. Previous work done on the mechanical behavior of

composite materials, with exposure to UV radiation; do not include their performance under dynamic blast loads, therefore, the need for this study.

Composite materials have been studied both experimentally and computationally under dynamic loading [11], with some studies concentrating on the damage of composite materials subjected to impact loading at low velocities [12, 13], while others have focused on obtaining the high strain rate behavior of composite materials using a Split Hopkinson Pressure Bar [14]. Recently, studies have experimentally evaluated and computationally modeled the dynamic failure of sandwich composites subjected to underwater explosions [15]. Other studies on the blast response of composites subjected to underwater explosions were completed, where experimental results were correlated to computational models using the LS-DYNA Software [16, 17]. However, these studies have not included the dynamic behavior of composites after prolonged exposure to UV radiation.

The findings from this study show under quasi-static conditions fiber-dominated properties are marginally affected after exposure to UV radiation. However, matrix dominated properties were altered significantly after exposure to UV radiation, leading to lower out of plane displacements during blast loading

2. EXPERIMENTAL SETUP

Experiments were conducted for carbon fiber plates and glass fiber plates. The plates were exposed to 1000 hours of UV radiation, with a control case for each material in which no exposure was provided. Each experimental case was repeated three times,

totaling twelve experiments. Table 2.1 summarizes the experimental cases and their details.

Table 2.1. Experimental configurations given in terms of material type, exposure time, density, thickness, and fiber layup

Case	Material	Exposure Time (Hour)	Density (kg/m ³)	Thickness (mm)	Fiber Layup
c0	Carbon Fiber /Epoxy	0	1420	1.25	[±45°]s
c1000	Carbon Fiber /Epoxy	1000	1410	1.25	[±45°]s
g0	Glass Fiber /Vinyl Ester	0	2100	1.40	[±45°]s
g1000	Glass Fiber /Vinyl Ester	1000	2090	1.40	[±45°]s

2.1. Materials

The composite plates utilized in the study consist of four plies of unidirectional fabric oriented in a [±45°]s layup. For the carbon fiber plates, the fabric used was Tenax HTS40 F13 24K 1600tex carbon fibers (1% polyurethane-based sizing finish) from Toho Tenax Inc. (Rockwood, TN). The resin/hardener mixture was a 100/30 weight ratio of the RIMR135/RIMH137 epoxy from Momentive Performance Materials Inc. (Waterford, NY). For the glass fiber plates, the fabric material used was Saertex X-E-988g/m² - 1270mm (Silane sizing) from Saertex (Saerbeck, Germany). The resin/hardener used was a 10/1 weight mixture, where the resin was CoREZYN Modified Vinyl Ester resin MVR8015A by Interplastic Corporation (St. Paul, MN), and the hardener was Organic Peroxide Type D UN3105 by United Initiators Inc (Helena, AR).

The plates were manufactured by the Vacuum Assisted Resin Transfer Molding (VARTM) at TPI Composites Inc. (Warren, RI). The resin mixtures for the carbon fiber and glass fiber plates were drawn into the fabric at a constant pressure of 730 mmHg.

The process was completed on a smooth, heated Teflon top table. All plates were allowed to dry and harden on the heated table at 70°C for 24 hours. For the carbon fiber plates, once hardened, curing was completed by placing the plates in an oven at 70°C for 10 hours. For the glass fiber plates, curing was completed by placing the plates in an oven at 60°C for 2 hours. All specimens for both material types were cut from a single composite sheet to minimize variations in the manufacturing process. The plates had a 1% void content, measured in accordance to ASTM Standard D2734 [18], and a 60% fiber volume content. The carbon fiber and glass fiber plates had a thickness of 1.25 mm and 1.40 mm, respectively.

2.2. Material Characterization Procedure

Quasi-static tensile and in-plane shear properties were obtained using an Instron 5585 by Instron (Norwood, MA) and following ASTM Standards D3039 [19] and D3518 [20], respectively. To follow the ASTM Standard D3039, the $[\pm 45^\circ]$ s plates were cut at an angle to obtain $[0^\circ, 90^\circ]$ s fiber orientation specimens. A random speckle pattern was painted on one face of the specimens to employ 2D DIC and obtain full field strain data. The images were captured by a Prosilica camera model GC2450 from Allied Vision Technologies GmbH (Stadtroda, Germany). The tensile and shear experiments were used to quantify the effective material properties, as well as to support the computational models. The strain rate sensitivity of carbon and glass fiber composites, though not negligible, is sufficiently small [21]. Therefore, the quasi-static characterization is used in the dynamic simulations.

2.3. UV Radiation Exposure

The composite materials were exposed to UV radiation using a QUV Accelerated Weathering Tester, by Q-Lab Corporation (Westlake, OH), by following ASTM Standard D 4329 – 99 [22]. The schematic of the QUV Accelerated Weathering Tester is shown in Figure 2.1.

Figure 2.1. Schematic of the QUV Accelerated Weathering Tester used to expose the composite plates to UV radiation for 1000 hours

The QUV tester is equipped with eight UVA-340 lamps, which simulates sunlight in the wavelength region from 365 nm down to the solar cut-off of 295 nm. During UV exposure, the temperature of the chamber was maintained at a constant 60°C. Prior to exposing the composite plates to UV radiation, the specimens were placed in a desiccator for seven days to remove any moisture. The composite materials were exposed to UV radiation for 500 hours on one face, and an additional 500 hours on the other face, totaling 1000 hours of exposure.

2.4. Shock Tube Facility

A shock tube apparatus was used to generate a controlled and concentrated shock wave to provide a transverse dynamic load on the composite plates. The shock tube is 8

m in length and is composed of four separate sections: driver section, driven section, converging conical section, and a 38 mm diameter muzzle. A schematic of the shock tube can be seen in Figure 2.2.

Figure 2.2. Shock tube facility showing key features of the experimental setup. The shock tube muzzle is confined in a steel chamber with acrylic windows for DIC imaging. The composite specimen is placed flush to the shock tube muzzle end

To generate the shock wave, a Mylar diaphragm is used to separate the driver section from the driven section. The driver section is pressurized using helium gas until the diaphragm ruptures. The sudden change in pressure and density between the two sections generates a high speed pressure wave, which propagates down the length of the shock tube and develops into a planar shock front. When the shock wave impinges on the specimen, the shock is compressed and reflected back into the shock tube muzzle. The reflected shock wave pressure is the loading that the specimens experience. The pressure of the shock is captured by three piezoelectric pressure transducers, which are mounted flush to the shock tube muzzle. The Pressure transducers are Piezoelectric PCB102A, by PCB Piezotronics Inc. (Depew, NY). The composite plates were clamped on all edges, and a random speckle pattern was painted on the back face for 3D DIC. The clamping fixture consisted of two steel plates with a central square cavity of 152

mm by 152 mm in dimension. The steel plates were bolted together with 36 screws, each screw having an applied torque of 20 N*m to maintain a consistent clamping force for all experiments. The plates were placed flushed against the shock tube muzzle. Two Photron FastCam SA1 cameras, by Photron USA (San Diego, CA) were used to obtain stereo images of the blast event. Two Super Sun-Gun SSG-400 from Frezzi Energy Systems Inc. (Hawthorne, NJ) were used to illuminate the specimens during the experiments.

2.5. Digital Image Correlation

DIC is a well established optical technique for obtaining full field displacement measurements on the specimen surface. For 3D DIC, two cameras are required for capturing the three dimensional response of the plates. The cameras were calibrated and synchronized prior to the completion of the experiments by using a grid of dots with known relative locations. The grid was placed where the plates are located during the experiments. The calibration grid was displaced in all degrees of freedom while recording the images. The coordinate locations of the dots allow for a correspondence of the coordinate system for each camera. The DIC is then performed on the image pairs that are recorded during the shock event. A high contrast random speckle pattern was applied to the composite plates by coating the specimen with white paint on one face, and randomly placing black dots approximately 2 mm in diameter throughout the coated area. The Photron FastCam SA1 cameras were set to record at 25,000 frames per second. The analyses of the high-speed images were performed using the commercially available VIC-3D 7 software from Correlated Solutions, Inc. (Columbia, SC). The VIC-

3D software matches common pixel subsets of the random speckle pattern between a reference undeformed image and the deformed images.

2.6. Finite Element Simulation

The Finite Element Modeling (FEM) was performed using the LS-DYNA code available from the Livermore Software Technology Corporation (Livermore, CA). All simulations were performed with LS-DYNA release 6.1.1 in double precision mode. The composite plates consist of four through thickness elements (1 through the thickness element per ply), modeled as fully integrated solid elements. The model element sizing was 1.27 mm by 1.27 mm for the in plane dimension. For the carbon fiber and glass fiber plates, the thickness dimension of each element was 0.31 mm and 0.35 mm, respectively. The boundary nodes of the plates were restricted in all degrees of freedom to simulate the fully clamped boundary condition. The material card utilized was the Mat_Composite_Damage (Mat_022). This material definition is orthotropic, and includes failure criteria of longitudinal and transverse failure in tension and compression, as well as in-plane shear failure. The pressure profile obtained experimentally was applied directly to the simulations. During the initial loading, there is a uniform pressure distribution over the central circular area, corresponding to the inner diameter of the shock tube. However, as the specimen deforms, a gap forms between the shock tube and the specimen. This results in an expanded loading area over the face of the plate, accompanied by a decrease in load magnitude. The decrease in load on the face of the specimen is assumed to be in a stepwise mode as shown in Figure 2.3. A similar approach has been taken by the authors in previous work [23].

Figure 2.3. The stepwise decay in pressure assumed in the FEM simulations during shock loading. The inner circle is 19 mm in radius, with subsequent circles having a thickness of 2.54 mm for a total outer radius of 26.62 mm

3. EXPERIMENTAL RESULTS

3.1. Mass Change

To monitor the mass change of the composite materials from exposure to UV radiation, five coupons were cut to 50 mm by 50 mm and exposed to UV radiation following ASTM standard D 4329 – 99 [22]. The mass was measured with an AG204 Analytical Balance from Mettler Toledo (Columbus, OH). The mass change of the composite materials was monitored every hour for the initial 12 hours of exposure, where the specimens were turned over after every measurement. After the initial 12 hours of exposure, the mass was monitored and recorded every 24 hours throughout the 1000 hours of UV radiation exposure. The mass change of the composite materials as a function of exposure time is shown in Figure 2.4.

Figure 2.4. Mass change induced by UV radiation as a function of exposure time for both the carbon fiber and glass fiber plates

The trend shown is an average of five coupons exposed to UV radiation. For both the carbon fiber and glass fiber composites, there is a rapid decrease in the mass within the first 24 hours of exposure. It is postulated that the initial decrease in mass is likely due to the removal of moisture not removed by the desiccator. However, it is possible that the mass loss is due to other chemical processes. After the rapid decrease in mass, the specimens continued to lose mass in a semi-linear fashion. This decrease in mass is due to the ionization of molecules in the polymer matrix, which causes chemical reactions and breakage of the polymer chains. Overall, the glass fiber and carbon fiber composites lost a total of 0.63% and 0.47% of the original mass, respectively.

3.2. Quasi-Static Experiments

The specimens used for the quasi-static experiments were from the same batch of materials used for the blast experiments. Table 2.2 shows the effective elastic moduli, Poisson's ratio, in-plane shear moduli, and failure stresses and strains. The results for the effective material properties in Table 2.2 are calculated from five tests per case.

Table 2.2. Effective quasi-static material properties for the carbon fiber and glass fiber composites

Weathering Case	g0	g1000	c0	c1000
E_I (GPa)	20.03±0.54	21.04±0.72	78.40±1.80	79.90±2.50
G_{I2} (GPa)	6.03±0.48	7.13±0.55	7.38±0.19	8.91±0.53
ν_{I2}	0.03±0.01	0.05±0.01	0.04±0.01	0.05±0.02
Failure Normal Stress (GPa)	0.53±0.02	0.44±0.03	0.70±0.03	0.76±0.10
Failure Normal Strain (%)	2.49±0.38	2.37±0.07	1.46±0.09	0.90±0.15
Failure Shear Stress (MPa)	31.50±1.50	30.60±1.80	45.31±1.22	53.85±1.48
Failure Shear Strain (%)	2.62±0.21	2.24±0.16	4.98±0.79	2.34±0.50

There is a negligible increase in the tensile modulus E_I after 1000 hours of exposure to UV radiation in the carbon fiber specimens. For the glass fiber plates, the change in tensile modulus is 5%, which is within experimental error. Since UV radiation does not affect the fibers, fiber-dominated properties will remain relatively unchanged [6]. However, there is an 18% increase in shear modulus for the glass fiber composites, and a 20% in shear modulus for the carbon fiber plates. The failure tensile and shear strains decreased after 1000 hours of exposure to UV radiation in both the glass fiber and carbon fiber specimens due to embrittlement. Previous work [1] has shown that most of the material changes occur on the outer plies of composites, since these are directly exposed to UV light. For the material property calculations, it is assumed that the UV exposed specimens had isotropic properties through the thickness. This assumption is reasonable to make since the plates are thin.

3.3. Shock Loading

The pressure profiles generated by the shock tube are shown in Figure 2.5 (a) for the glass fiber plates, and Figure 2.5 (b) for the carbon fiber plates. The pressure curves shown correspond to the pressure transducer closest to the muzzle end.

Figure 2.5. Shock wave pressure profile depicting the incident pressure, reflected pressure, and subsequent pressure curve for (a) glass fiber and (b) carbon fiber experiments

For consistency, the time in which the reflected shock wave is registered is taken to be $t = 0$ ms. The reflected pressure was 1.2 MPa for all experiments, consistently providing the same initial loading. When the shock wave impinges on the specimen, the plate begins to deform out of plane. As the plate is deflecting away from the shock tube, the pressure profile decays exponentially. However, when the maximum displacement is reached, the plate reverses direction and deflects towards the shock tube. As the plate moves back toward the shock tube, the loading pressure increases. This behavior continues as the plate vibrates, seen as oscillations in the pressure curve. To fully understand the loading applied, the total impulse imparted on the plates was calculated, taken from time 0 ms until the pressure fully decays. The impulse is obtained using Equation 2.1

$$I = \int_{t_i}^{t_f} P(t) * A dt \quad \text{Equation 2.1}$$

where $P(t)$ is the shock wave pressure, A is the loading area, t_i is the time when the shock wave impinges on the specimen, and t_f is the time in which the shock wave pressure decays to zero. Since the incident and the peak reflected pressures are the same for all

plates, ideally the impulse will be similar. However, the interaction between the shock wave and the structures will depend on the plate stiffness and damage induced, which yields different pressure curves after the initial peak pressure.

The impulse imparted on the specimen can be stored as elastic energy in the plate, or spent in permanent deformation. Therefore, specimens with higher permanent deformation will yield lower impulse. Similar results have been seen in previous studies on blast loading [24]. The impulse for the glass fiber plates are shown in Figure 2.6 (a), Figure 2.6 (b) for the carbon fiber plates.

Figure 2.6. Total impulse for the (a) glass fiber plates (b) carbon fiber plates

The total impulse imparted on the g0 and g1000 plates was 3.90 N*s and 3.50 N*s, respectively. A similar trend is seen for the carbon fiber plates, where the total impulse imparted on the c0 and c1000 plates was 4.50 N*s and 4.00 N*s, respectively. The impulse for the plates exposed to UV radiation (g1000 and c1000) have lower impulse when compared to the respective virgin specimens (g0 and c0). This implies that the impulse provided by shock wave caused a higher degree of damage for plates exposed to UV radiation.

3.4. DIC Results

The high speed images coupled with 3D DIC yielded full field deformation data. The out of plane displacements at the centerpoint of the specimens were extracted and plotted as a function of time, shown in Figure 2.7 (a) for the glass fiber plates, and Figure 2.7 (b) for the carbon fiber plates. When the shock wave impinges on the specimen, the composite plate deflects out of plane. Once the maximum displacement is reached, the specimen deflects back towards the shock tube. However, damage induced at the boundaries of the plate prevents the plates from reaching the original position ($W = 0$ mm).

Figure 2.7. Out of plane displacement induced by the shock loading. The displacements were measured at the center point of the plates for the (a) glass fiber plates and (b) carbon fiber plates

The maximum out of plane displacement for the g0 plates was 12.58 mm, occurring at 0.68 ms. In comparison, the g1000 plates had a maximum out of plane displacement of 11.82 mm, occurring at 0.65 ms. The 6% difference in maximum out of plane displacement between the g0 and g1000 plates is due to the difference in plate stiffness. A similar trend is seen in the carbon fiber plates, where the c1000 plates had a 16% lower out of plane displacement when compared to the c0 plates.

The frequency of vibration can be readily obtained by performing an FFT analysis. For the FFT analysis, a Mode I vibration was assumed, therefore the average out of plane displacements for the entire plate was used. The FFT results are shown in Figure 2.8 (a) and Figure 2.8 (b) for the glass fiber and carbon fiber plates, respectively.

Figure 2.8. FFT analysis of plate deformation giving vibration frequencies for (a) glass fiber plates and (b) carbon fiber plates

To better understand the vibration of the plates, the natural frequencies of vibration were obtained. The Helius Composite Software, by Autodesk, Inc. (San Rafael, CA) was used for the calculation of the natural frequencies. The natural and forced frequencies induced by shock loading for all plates are shown in Table 2.3.

Table 2.3. Natural and forced frequencies for the virgin and UV exposed carbon fiber and glass fiber

Exposure Case	Natural Frequency (Hz)	Forced Frequency (Hz)
g0	270	980
g1000	290	840
c0	460	1170
c1000	470	1270

The g1000 plates had higher tensile and shear stiffness than the g0 plates, resulting in a higher natural frequency. However, the forced vibration frequency is lower for the g1000 plates. It is postulated that the g1000 plates lost stiffness during the blast loading from the accumulation of damage as the plates vibrated. Higher damage was expected in the g1000 plates relative to the g0 plates since the failure stress and strains in tension and shear are lower for g1000 plates.

The c1000 plates experienced an increase in tensile and shear failure stresses, resulting in lower damage and higher vibration frequency when compared to the c0 plates. It should be noted that the stiffening effects seen in the c1000 plates are not always beneficial; structures are designed to have certain tensile, shear, and flexural stiffness, therefore stiffening effects in these situations can be detrimental.

4. FINITE ELEMENT SIMULATION RESULTS

4.1. Model Validation

To validate the models, the centerpoint out of plane displacements were extracted from the finite element analysis and compared with the experimental results.

Figure 2.9. Finite element simulation results given in terms of out of plane displacements. The results are compared with the experimental data for (a) c0 plates, (b) c1000 plates (c) g0 plates, (d) g1000 plates

The comparison between simulated and experimental data for the carbon fiber plates is shown in Figure 2.9 (a) for the c0 plates, and Figure 2.9 (b) for the c1000 plates. The finite element simulations were able to accurately predict the peak displacement, as well the time in which it occurs. Moreover, the simulations predicted the permanent convex deformation induced by damage at the boundaries. The comparison between experiment and simulation for the g0 and g1000 plates are shown in Figure 2.9 (c) and Figure 2.9 (d), respectively. Similar to the carbon fiber plates, the simulations for the g0 and g1000 plates reasonably captured the maximum out of plane displacement, as well as the time

in which it occurs. The simulations are well within an acceptable range in terms of maximum out of plane displacement for all experiments.

The numerical results are more suited for analyzing the strain states along the boundary of the plates since DIC does not provide displacements and strains at the boundary. In the present case, the in-plane strains ϵ_{xx} (horizontal) are very similar to the ϵ_{yy} (vertical) strains due to symmetry, therefore only the ϵ_{yy} strains are presented. Figure 2.10 (a) shows a line on the surface of the plate, from the center point to the edge (0 to $L/2$) where the maximum ϵ_{yy} strains were extracted. The strains are presented such that each value is the maximum strain experienced at the respective point through the duration of the simulation. This manner of presentation removes the time dependence from the strain measurement and captures the highest strain in each element through time. Figure 2.10 (b) and Figure 2.10 (c) show the maximum ϵ_{yy} strains extracted from the centerline of the plate for the glass fiber and carbon fiber plates, respectively. The strain locations are normalized with respect to the total length of the plate (L^*/L). The maximum strain at the edge of the plate for the g0 and g1000 specimens were 13%, much larger than the tensile failure strains given by the quasi-static experiments. This indicates that failure occurs at the boundary of the plates. A similar behavior is seen in the carbon fiber plates, with maximum strains of 16% for the c0 plates and 14% for the c1000 plates. It should be noted that the large strains shown include failure due to interfibrillar cracks, matrix and fiber failure, and ply delamination.

Figure 2.10. In-plane strains extracted from the face where the shock loading is applied (a) The dashed line indicates the location from which the maximum ϵ_{yy} strains are extracted (b) in plane strains in glass fiber plates (c) in plane strains in carbon fiber plates

The through thickness strain distribution for the glass fiber and carbon fiber plates is extracted from the dashed line shown in Figure 2.11 (a). The strain locations are normalized with respect to the total thickness of the plate, with the origin (normalized location 0) being the center of the plate through the thickness.

Figure 2.11. Through thickness variation in the maximum ϵ_{yy} strains starting from the shock loaded face (a) The dashed line indicates the location from which the strains are extracted (b) through thickness strains in the glass fiber plates (c) through thickness strains in the carbon fiber plates

The through the thickness ϵ_{yy} strains for the glass and carbon fiber plates are shown in Figure 2.11 (b) and Figure 2.11 (c), respectively. The 0.5 value on the normalized thickness position scale is the face which is exposed to shock loading. Since the g1000 plates had lower failure tensile and shear stresses and strains when compared to the g0 plates, the through the thickness strains are higher, except for when the strains are closer to the shock blast exposed face. This indicates that the g1000 plates had higher damage than the g0 plates at the boundary. The c1000 plates had higher failure tensile and shear stresses than the c0 case, therefore the strains are lower for the c1000 strains through the thickness.

4.2. Simulated Plate Response Under Higher Applied Shock Loading

The composite materials became brittle after exposure to UV radiation due to micro-crack formation on the outer plies of the composite material. To explore the behavior of the plates under higher loading, the magnitude of the pressure load was increased by 10% and was input to the finite element models. The out of plane displacement for both the glass fiber and carbon fiber plates are shown in Figure 2.12 (a) and Figure 2.12 (b), respectively.

Figure 2.12. Centerpoint out of plane displacements for (a) glass fiber plates and (b) carbon fiber plates subjected to 10% higher shock loading

For the glass fiber plates, the initial peak displacement is reached at 0.60 ms. The difference in maximum displacement between the g0 and g1000 plates negligible. After the initial peak displacement, the out of plane displacement continues to increase for the g1000 plates, whereas the g0 plates undergoes plate vibrations. The continued increase in out of plane displacement for the g1000 arises from accumulated failure at the boundaries. In terms of the carbon fiber plates, the c0 plates experienced higher out of plane displacement than the c1000 plates. Despite the failure strains in tension and shear being 33% and 53% lower for the c1000 plates, the corresponding failure stresses were

higher, Therefore, the c1000 did not suffer higher quantity of accumulated damage at the boundaries.

4.3. Effect of Thickness of Plates on Shock Response

Previous work has shown that UV radiation does not fully penetrate composite materials, therefore the material property change occurs on the outer plies directly exposed to UV radiation [1]. As the thickness of the plates increase, the inner plies will receive less UV radiation. In this study, the plates had a total of four plies, with both faces exposed to UV radiation for 500 hours. Since the thickness of the plies are small, it is reasonable to assume that all plies underwent material change from UV radiation exposure. To understand the effects of UV radiation on thick composites, plates of 16 plies were numerically simulated (total of 5 mm thickness). The two outermost plies were modeled with altered properties by UV radiation, whereas the remaining inner plies were modeled with unexposed properties. The midpoint out of plane displacement history for the glass fiber and carbon fiber plates are shown in Figure 2.13 (a) and Figure 2.13 (b), respectively.

Figure 2.13. Centerpoint out of plane displacements for the 16-ply plates, the two outermost plies modeled with altered properties and the inner plies modeled with unexposed properties, (a) glass fiber plates (b) carbon fiber plates

The displacement peaks match between the g0 and g1000 plates. An FFT analysis showed that the vibration frequency of the plates was similar between weathered and virgin plates, however the amplitude of vibration was larger for the virgin structures. A similar trend is seen in the carbon fiber plates, where there is no difference in vibration frequency, and the amplitude for the c0 plates is higher than the c1000 plates. This indicates that the stiffening effects of the outer plies due to UV radiation exposure has an effect on the dynamic response of thick composite plates, though potentially negligible.

5. CONCLUSIONS

The blast response of fiber reinforced composite plates after prolonged exposure to UV radiation was studied experimentally and computationally. The following conclusions can be drawn based on the findings of this study:

- The mass of the carbon fiber and glass fiber plates decreased with exposure to UV radiation. Within the first 24 hours, the mass decreased rapidly. The mass continued

to decrease throughout the 1000 hours of exposure and did not stabilize, therefore material property change will continue to occur after 1000 hours.

- The tensile modulus for the carbon fiber and glass materials remained relatively unchanged after exposure to UV radiation. However, the shear modulus for the two materials increased. The failure strains in tension and shear decreased for both the carbon fiber and glass fiber plates after UV exposure. Furthermore, the failure stress in tension and shear decreased for the glass fiber plates, and increased for the carbon fiber plates.
- When subjected to blast loading, plates exposed to 1000 hours of UV radiation experienced lower centerpoint out of plane displacements. The lower out of plane displacements are attributed to the higher shear modulus. The plate vibrations induced by the shock loading were higher in c1000 plates when compared to the c0 plates due to the increase in shear modulus of the c1000 plates. The g1000 plates had lower plate vibration frequency when compared to the g0 plates due to the accumulation of damage at the plate boundary.
- The finite element simulations were able to capture the blast response of the UV exposed carbon and glass fiber composite plates. The simulations accurately predicted the maximum peak displacements, as well as peak displacement time.
- The numerical models showed that the glass fiber plates exposed to UV radiation for 1000 hours experienced higher strains along the boundary than virgin specimens. This behavior occurred since the UV exposed glass fiber plates became brittle, with lower failure stresses and strains in tension and shear. The simulations showed that

the UV exposed carbon fiber specimens had lower strains at the boundaries as since the UV exposed carbon fiber plates had higher failure stress in tension and shear.

- Upon increasing the blast loading by 10% in the numerical simulations, there was an increase in the maximum out of plane displacement for the glass and carbon fiber plates when compared to the original loading. Glass fiber plates exposed to UV light for 1000 hours had similar initial out of plane displacements as virgin plates, however damage accumulation at the boundary caused the displacement to continue to increase, whereas virgin specimens vibrated out of plane. The higher damage accumulation seen in the glass fiber plates exposed to UV radiation is expected since the failure tensile and shear stresses and strains are lower.
- Thicker composite plates modeled with outer plies as UV altered lamina had similar dynamic response than virgin structures. The partially degraded plates had higher vibration amplitudes, though the difference in vibration frequencies were negligible.
- Exposure to UV radiation can have a wide range of effects on composite materials. The materials can become stiffer and produce higher vibrations from blast loading. However, materials can also become brittle and fail catastrophically when subjected to blast loading.

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Chapter 3 Hydrostatic and Blast Initiated Implosion of Environmentally Degraded Carbon-Epoxy Composite Cylinders

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ABSTRACT

The underwater collapse mechanics of environmentally degraded filament-wound Carbon-Epoxy composite tubes were investigated in this study. The composite tubes were submerged in an elevated temperature saline water solution for 35 and 70 days. The temperature of the saline bath was held at 65°C, in which case the 35 and 70 days duration simulates 3.8 and 7.6 years of service life in accordance with Arrhenius' equation and a reference temperature of 17°C. Experiments were performed underwater in a pressure vessel designed to simulate a free-field environment by maintaining constant hydrostatic pressure throughout the collapse event. Two cases of implosion were studied: implosion initiated by increasing the hydrostatic pressure in the vessel until the critical collapse pressure was reached; and by detonating an explosive charge while the composite structure was subjected to 80% of its critical collapse pressure. Three-Dimensional Digital Image Correlation was coupled with high-speed photography to obtain the full-field displacements and velocities of the composite tubes during collapse. Moreover, the pressure fields created during the structural collapse were recorded with tourmaline pressure transducers and coupled with the full-field deformations to analyze the collapse mechanics. Mass saturation was reached during the first 35 days of submergence in the saline water bath. For the implosion initiated by hydrostatic pressure, the composite tubes submerged in the saline water bath displayed different behavior in comparison to the tubes with no exposure. The critical collapse pressure decreased by 20% after 35 days of exposure to the elevated temperature water bath when compared to the non-weathered tubes, and 24% after 70 days of exposure to the elevated temperature water bath when compared to the non-weathered tubes. The

full-field data showed that the weathered structures collapsed with higher center-point velocities, which arise from substantial cracking and damage accumulation during the collapse event, as well as lower structural stiffness. The aged composite tubes had a lower overpressure pulse due to an increase in damage. For the blast initiated implosions, the reduced structural stiffness resulted in a quicker instability event. Lastly, further weathering after saturation led to a decrease in structural strength and performance.

KEYWORDS

Accelerated weathering; Implosion; Service life; Composites; Shock

1. INTRODUCTION

The underwater collapse mechanics of environmentally degraded filament-wound Carbon-Epoxy (CE) composite tubes are presented in this study. The experiments were performed in a pressure vessel designed to simulate a free-field environment by maintaining a constant hydrostatic pressure. For hydrostatic initiated implosions, the hydrostatic pressure in the tank was gradually increased until instability in the structure was reached. For the blast initiated implosions, an explosive was detonated in the near-field of the composites to cause instability and subsequent implosion. In recent years, the marine community has demonstrated increased interest in composite materials due to their high strength to weight ratio, their potential for lower operating depths, reduced magnetic, acoustic, and thermal signatures, and noise dampening capabilities [1]. One of the leading concerns in the application of composite materials for underwater structures is the degradation of mechanical properties from water absorption [2].

Structures with air-filled volumes can implode underwater due to high pressures. This risk is magnified when the material properties degrade from prolonged exposure to saline water. Furthermore, composite marine structures can be subjected to underwater shock and blast loading, which can lead to instability and implosion under subcritical hydrostatic pressures [3]. If the degradation of material properties is not accounted for in marine applications, the failure of structures can be catastrophic.

The process of water diffusion into an epoxy matrix has been studied extensively, with the standard procedure being a Fickian model based on Fick's second law of diffusion [4]. Studies have aimed to understand the mechanical behavior of composites subjected to material degradation from water absorption and concluded that the increase in mass from water absorption leads to residual internal stresses due to swelling, fiber/matrix debonding, and delamination of the materials [5, 6]. Accelerated life testing methods aim to mimic the effect of prolonged exposure in a reasonable timeframe. For these testing methods, composite materials are submerged in water baths at elevated temperatures to increase the rate of water diffusion into the matrix of the composite [7-10]. Arrhenius' equation has been utilized to calculate the activation energy by obtaining the diffusion coefficient of composites at various temperatures [11]. Once the activation energy is known, an Acceleration Factor (AF) can be determined, which relates the elevated temperature in the accelerated life test to normal service temperatures.

The implosion of filament-wound CE tubes has been studied to experimentally determine the critical collapse pressure and the collapse mode, with some studies utilizing Digital Image Correlation (DIC) to examine the implosion process [12, 13].

The response of metallic structures subjected to Underwater Explosive (UNDEX) has been studied [14, 15] with some work recently done on the blast initiated implosion of composite cylinders [16]. However, no experimental work exists on the hydrostatic or shock-initiated implosion of CE composite tubes after prolonged exposure to marine environments.

This work aims to understand the hydrostatic and shock-initiated implosion mechanics of CE tubes after prolonged exposure to saline water. High-speed photography coupled with 3D DIC is used to record the implosion event and understand the collapse mechanics by obtaining full field deformation data. The local pressure field generated during implosion was studied to understand the energy released during collapse. In addition, the underwater shock and bubble pulses generated by an UNDEX were examined. For hydrostatic initiated implosions, the collapse pressure dropped drastically after exposure to the saline water bath. In the case of UNDEX initiated implosion, the weathered specimens experienced a more catastrophic collapse at earlier times as opposed to virgin structures. Therefore, it is crucial that material degradation be taken into account when designing composite structures for underwater applications.

2. EXPERIMENTAL SETUP

A total of six experimental implosion cases were investigated in this study. Each case was repeated twice, totaling twelve experiments. Three cases pertain to the hydrostatic initiated implosion and three for blast initiated implosion. Experiments were conducted for three different duration of saline water exposure for both instability initiation methods: no weathering (0 days of submersion in a water bath), weathering to

full saturation (35 days of submersion in a water bath), and weathering pass full saturation (70 days of submersion in a water bath). The temperature of the water bath was held at a constant 65°C. Table 3.1 summarizes the experimental cases and their details.

Table 3.1. Details of experiments performed. The temperature of the water bath was a constant 65°C for all exposure times

Cases	Collapse Initiation	Standoff Distance (mm)	Weathering Time (Days at 65°C)	Equivalent Service Time (Years at 17°C)	Critical Pressure (MPa)	Pre-Pressure (% P_{cr})
H0	Hydrostatic	N.A.	0	0	1.17 ± 0.04	N.A
H35	Hydrostatic	N.A.	35	3.8	0.93 ± 0.05	N.A
H70	Hydrostatic	N.A.	70	7.6	0.90 ± 0.06	N.A
U0	UNDEX	102	0	0	1.17 ± 0.07	80
U35	UNDEX	102	35	3.8	0.93 ± 0.08	80
U70	UNDEX	102	70	7.6	0.90 ± 0.09	80

The composite tubes consisted of seven filament-wound plies of carbon fabric in a $[\pm 15/0/\pm 45/\pm 15]$ layup. The tubes were manufactured by Rock West Composites (West Jordan, UT), with a wall thickness of 1.57 mm and an outer diameter of 63.50 mm, which allows for a thin wall assumption. The CE tubes were sanded on the exterior to obtain high dimensional tolerances. The filament winding process provides the tubes with a fiber volume fraction of 60%, and continuous reinforcement without breaks. The tubes had an unsupported length of 381 mm during all implosion experiments.

In underwater explosions, the diameter of the bubble created by the UNDEX is a function of the surrounding fluid pressure and explosive composition [17]. In the present study, the critical collapse pressure changed with exposure to the salt water environment, therefore the pre-pressure, which depends on the collapse pressure, varied for the different weathering times, giving rise to different bubble sizes. To maintain

similar loading conditions, it was necessary to select a standoff distance in such a way as to avoid any interaction between the initial bubble and the composite structure. Therefore, a distance of 102 mm was selected. Furthermore, results in previous work with similar experimental parameters showed that a 102 mm standoff distance ensures structural collapse and avoids bubble-structure interaction [16]. Increasing the distance further than 102 mm can potentially increase the total loading area of the specimen, however, increasing the loading area by increasing the standoff distance does not cause instability at earlier times. On the contrary, previous studies in which standoff distances of 204 mm and 305 mm were considered, the lower shock pressure and bubble pulse resulting from a larger standoff distance served to increase the duration of the implosion process [16]. For the present study, increasing the standoff distance of the explosive beyond 102 mm would only serve to increase the total time required for collapse, but would not alter the overall comparative conclusions observed between virgin and aged composite tubes. Furthermore, the pre-pressure selected was also shown to be optimal for the standoff distance case of 102 mm in the study mentioned previously. Increasing the pre-pressure above 80% can increase the chances of the tube imploding from the hydrostatic pressure, therefore 80% was selected as to avoid premature implosion.

2.1. Implosion Facility

The implosion experiments were conducted in a 2.1 m diameter semi-spherical pressure vessel. The vessel has a maximum pressure rating of 6.89 MPa and provides a constant hydrostatic pressure throughout the collapse event. Eight cylindrical optically-clear windows are mounted about the mid-span of the vessel, which allows for the specimen to be viewed by cameras and illuminated by high-intensity light sources. The

specimens were sealed on both ends using aluminum end caps, and fitted with rubber O-rings to avoid water leakage during pressurization. Cables were used in tension to suspend the specimen horizontally in the center of the pressure vessel, and to restrict any motion throughout the experiments. Four PCB 138A05 dynamic pressure transducers (PCB Piezotronics, INC., Depew, NY) were used to measure the changes in local pressure during the collapse of the tubes. The pressure transducers were mounted axially about the specimen such that the standoff distance, R_s between the sensing element and the outer surface of the specimen is 57 mm. The amplified outputs of the sensors were monitored by an Astro-med Dash 8HF-HS portable data recorder (Astro-Med Inc., West Warwick, RI) at a sampling rate of 2 MHz. Two Photron FastCam SA1 cameras (Photron USA, San Diego, CA) were used to obtain stereo images of the implosion process. A random speckle pattern was painted on the specimens for 3D DIC. The vessel was filled with filtered water for maximum optical clarity, leaving a small air pocket at the top of the vessel. Once the pressure vessel is filled with water, nitrogen gas was introduced into the air pocket to pressurize the vessel. For the hydrostatic initiated implosion experiments, the pressure was increased gradually until the CE tubes implode. For shock initiated implosion, the pressure was increased to 80% of the critical pressure, and an explosive was detonated to initiate implosion. The explosives used were RP-85 exploding-bridge wire detonators (Teledyne RISI, Inc., Tracy, CA). The RP-85 explosive has 80 mg of Pentaerythritol Tetranitrate (PETN), and 1031 mg of RDX (cyclotrimethylenetrinitramine), which combined provides the yield equivalent of 1778 mg of TNT. The experimental setup is seen in Figure 3.1.

Figure 3.1. Pressure vessel facility for implosion study

2.2. Weathering Facility

A submergence tank was used to expose the CE tubes to an elevated temperature saline water bath, shown in Figure 3.2. The submergence tank is composed of two cylindrical propylene tanks, with the volumetrically smaller tank placed inside of the larger tank. Both tanks are filled with deionized water, with the smaller tank having 3.5% NaCl content. The water in the larger tank is heated by four immersion heaters and maintained at a constant temperature of 65°C. The immersion heaters used are Polyscience LX Immersion Circulators (Cole Parmer, Vernon Hills, IL). Each heater can maintain a maximum temperature capacity of 98°C with temperature stability of $\pm 0.07^\circ\text{C}$ for a maximum of 20 L of fluid. The temperature of 65°C is selected as to not reach the glass transition temperature of 82°C of the composite materials. The weathering facility has float switches and pumps that add fresh water to either tank, such that the salinity in the inner chamber remains constant, and the water level in the outer chamber is always sufficient to operate the heaters. Before placing the CE tubes in the

high-temperature saline water bath, the specimens were placed in a desiccator for seven days to remove accumulated moisture from the environment. The CE tubes were submerged for 35 and 70 days in the smaller tank. All experiments were conducted the same day the specimens were removed from the accelerated weathering facility to avoid loss of moisture.

Figure 3.2. Accelerated weathering facility setup

2.3. Digital Image Correlation

A high contrast random speckle pattern was applied to the CE tubes by coating the specimen with white paint, and randomly placing black dots approximately 2 mm in diameter throughout the coated area. The Photron FastCam SA1 cameras were offset by 17° outside of the pressure vessel and set to record at 30,000 frames per second. The analyses of the high-speed images were performed using the commercially available VIC-3D 7 software (Correlated Solutions, Inc. Columbia SC). The VIC-3D software matches common pixel subsets of the random speckle pattern between a reference undeformed image and the deformed images. A calibration grid was submerged inside of the pressure vessel while it is filled with water, and manually translated in all degrees of freedom to calibrate the VIC-3D software for underwater experiments. Once calibration is performed, the DIC accuracy is validated by placing a CE tube inside of the pressure vessel filled with water, and the known outer radius of the specimen is

reconstructed using 3D DIC. In each experiment, the reconstructed outer radius is within 1 mm of the actual radius [13].

3. EXPERIMENTAL RESULTS

3.1. Mechanisms of Diffusion

To employ Fick's law of diffusion in a 1-D form, the experiments were designed to ensure that simplifying assumptions can be made. The assumptions are: the diffusion is constant throughout the tubes, there is no swelling in the tubes, the temperature and pressure remain constant, the tubes are initially free of moisture, and that the diffusion is one dimensional. Since the CE tubes are hollow and of thin wall nature, the latter is a reasonable assumption. In this case, Fick's second law of diffusion simplifies to [4].

$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{\left[\frac{-D(2n+1)^2 \pi^2 t}{4h^2} \right]} \quad \text{Equation 3.1}$$

In Equation 3.1, M_t is the total diffusion substance absorbed by the matrix at a given time t , M_∞ is the quantity of diffusion substance at saturation, D is the diffusion coefficient, and h is the thickness of the tube. When the specimen reaches 50% of the saturation mass, Equation 3.1 reduces to

$$D = 0.049 \frac{h^2}{t_{50}} \quad \text{Equation 3.2}$$

where t_{50} is the time required for the tube to reach 50% of the saturation mass. The rate of diffusion, or reaction rate, is governed by Arrhenius' equation, which can be used to model the diffusion coefficient as a function of temperature [18].

$$D = D_o e^{-\frac{E_a}{RT}} \quad \text{Equation 3.3 (a)}$$

$$\ln(D) = \ln(D_o) - \frac{E_a}{RT} \quad \text{Equation 3.3 (b)}$$

where D_o is an arbitrary constant, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature of the diffusion substance. The diffusion study was carried out by following ASTM Standard D5229 [19] for temperatures of 5°C, 25°C, 45°C, 65°C, and 85°C to obtain the temperature dependence of the diffusion coefficient for the CE tubes. The temperature of 85°C is above the glass transition temperature of the epoxy matrix; however, this temperature was only utilized for the diffusion study and not for the implosion experiments.

The mass gain percentage as a function of time is given in Figure 3.3 (a) for various temperatures. Using Equation 3.2, the diffusion coefficients can be readily obtained. The spread of diffusion coefficients at various temperatures will produce the activation energy for the composite. Once the diffusion coefficients are known, the respective logarithmic values are plotted against the inverse of the corresponding absolute temperature, shown in Figure 3.3 (b)

Figure 3.3. (a) Mass diffusion trend for different temperatures (b) Relationship between diffusivity and absolute temperature

Since the activation energy is assumed to be constant with respect to temperature, the AF can be obtained, which relates the temperature of the laboratory accelerated life

testing to the normal service temperatures. The AF is defined as the ratio between the standard working condition reaction rate and a higher laboratory test reaction rate.

$$AF = \frac{D_o e^{\frac{E_a}{RT_2}}}{D_o e^{\frac{E_a}{RT_1}}} = e^{\left(\frac{E_a}{R}\right)\left(\frac{T_2 - T_1}{T_1 T_2}\right)} \quad \text{Equation 3.4}$$

In this case, T_1 is the absolute elevated temperature of the salt water bath, and T_2 is the absolute temperature of the working condition. The temperature of the ocean varies with global position, however, if the average ocean temperature of 17°C is used as the reference, then the submergence times of 35 and 70 days in the elevated temperature salt water bath are equivalent to 3.8 and 7.6 years in normal working ocean temperature, respectively.

3.2. Tube Stiffness

Von Mises developed an analytical solution for the critical collapse pressure of isotropic cylinders [20]. Timoshenko and Gere showed, in greater detail, the derivation of the stability equations, partially based on Von Mises' work [21]. In Timoshenko's derivation, the equilibrium equations in the longitudinal, tangential, and radial direction for a hydrostatic loaded cylinder can be expressed respectively as:

$$a \frac{\partial N_x}{\partial x} + \frac{\partial N_{yx}}{\partial \theta} - N_y \left(\frac{\partial^2 v}{\partial x \partial \theta} - \frac{\partial w}{\partial x} \right) = 0 \quad \text{Equation 3.5 (a)}$$

$$\frac{\partial N_y}{\partial \theta} + a \frac{\partial N_{xy}}{\partial x} + a N_x \frac{\partial^2 v}{\partial x^2} - Q_y = 0 \quad \text{Equation 3.5 (b)}$$

$$a \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial \theta} + a N_x \frac{\partial^2 w}{\partial x^2} + N_y \left(1 + \frac{1}{a} \frac{\partial v}{\partial \theta} + \frac{1}{a} \frac{\partial^2 w}{\partial \theta^2} \right) + qa = 0 \quad \text{Equation 3.5 (c)}$$

where N_{ij} and Q_i represent forces and transverse shear forces; a and q represents the radius and external pressure; and v and w represent displacement components in the θ and r -direction in a cylindrical coordinate system, respectively. The equilibrium equation in the radial direction, described by Equation 3.5 (c), dominates the stability in

a cylindrical body under hydrostatic pressure. For the development of the critical collapse pressure in the case of hydrostatic loading, Timoshenko represented the N_{ij} and Q_i forces in terms of displacements and material properties (In the case of composites, the material properties are defined by the stiffness matrix in the classical laminate theory). In such a case, the governing material properties are the elastic moduli E_{ij} , Poisson's ratios ν_{ij} , and the shear moduli G_{ij} . The transverse shear forces, Q_i , are governed by the transverse shear moduli, G_{13} and G_{23} , which indicates that the shear properties have a substantial role in the stability of composite cylinders.

Previous work by the authors [22] has shown that the moduli E_{11} and E_{22} from a carbon fiber/epoxy composite decreased by 0.5% after 35 days when exposed to a 3.5% NaCl saline water solution with a temperature of 65°C, and 4% after 70 days of exposure, whereas the in-plane shear modulus G_{12} , which is greatly impacted by the matrix material, decreases by 28% and 33% after 35 and 70 days of exposure respectively. Similarly, in a different composite study, the matrix material was observed to degrade drastically in comparison to the fiber material when exposed to moisture at elevated temperatures [23]. For these reasons, the change in collapse pressure in the weathered CE tubes can be mostly attributed to the degradation in shear stiffness, G_{ij} . Quasi-static pipe stiffness compression tests were performed following ASTM Standard D2412 [24] to obtain the load-deflection behavior and stiffness of the CE tubes. For the determination of stiffness, the CE tubes were cut to 51 mm in length. The load-deflection curves for the 0, 35, and 70 days of exposure times are shown in Figure 3.4.

Figure 3.4. Compressive load vs. deflection for all weathering times

The linear portion in Figure 3.4 is the pipe stiffness of the tubes, which decreased by 5% after 35 days of exposure to the elevated temperature saline water. No appreciable changes in pipe stiffness was observed after 70 days. The load at failure, as well as the failure displacement, decreased by 23% and 8%, respectively, after 35 days of weathering. After 70 days of weathering, the failure load and displacements decreased by 26% and 12% in comparison to the virgin specimens, respectively. The quasi-static tests were performed with different loading and boundary conditions when compared to the impositions experiments. In addition, the tests mainly activated tension and compression at the lobes rather than shear. Therefore, Figure 3.4 shows the overall decrease in stiffness and increase in damage potential after weathering. However, it should be noted that the mechanisms of collapse include shear components, therefore the change in collapse pressure is not fully captured by the decrease in pipe stiffness or load bearing capabilities.

3.3. Hydrostatic Initiated Implosion

For hydrostatic initiated implosions, all of the specimens collapsed in a mode two shape. The H0 specimens collapsed at an average critical pressure of 1.17 MPa, whereas the H35 and H70 specimens collapsed at an average critical pressure of 0.93 MPa and 0.90 MPa, respectively. The DIC data shows that prior to collapse, the tubes had an average radial displacement of 1.5 mm.

3.3.1. Impulse Evaluation

The local pressure history is extracted from a pressure sensor located about the midspan of the specimen in the longitudinal direction and 57 mm from the outer surface, shown in Figure 3.5 (a). The pressure time history is seen in Figure 3.5 (b) for the different weathering times. For all experiments, the moment of wall contact represents time 0.

Figure 3.5. (a) Midspan sensor location and implodable deformation shape (b) Pressure time history for hydrostatic initiated implosions

When instability is reached, the walls of the tube accelerate inward, and the high pressure water moves towards the low pressure void created by the collapse of the

specimen. This is seen as the decay in local pressure highlighted in gray, referred to as the underpressure region. The pressure curve of the underpressure region is smooth until cracking occurs in the composite tubes, seen as spikes in the pressure curve. Initial cracking occurs at -0.8 ms for the H35 and H70 tubes, and further cracking is evident at -0.6 ms. For the H0 tubes however, initial cracking occurs at -0.5 ms. The cracking at earlier times experienced by the weathered tubes was expected, since exposure to the saline water bath decreases failure displacements and failure load. The underpressure region ends when the tube reaches wall contact and the velocity of the incoming water is arrested. The change in momentum of the water causes a pressure wave in the outward radial direction, seen as a large spike. The nonshaded area is referred to as the overpressure region. The impulse of the pressure pulse can characterize the damage potential of the implodable volume, given by the area under the pressure-time curve:

$$I = \int \Delta P \, dt \quad \text{Equation 3.6}$$

For the underpressure region, the impulse can be calculated from the initiation of collapse until wall contact. Similarly, the impulse from the overpressure region can be calculated from wall contact until the reflected pressure wave reaches the sensor, which occurs at 1.4 ms. The impulse from the underpressure and overpressure region are seen in Figure 3.6 (a) and Figure 3.6 (b), respectively.

Figure 3.6. (a) Underpressure region impulse (b) Overpressure region impulse

There are negligible differences in the underpressure impulse between the three weathering times. In contrast, the overpressure impulse generated by the H0 cylinder is larger in magnitude than the H35 and H70 impulses. Ideally, the underpressure impulse is equal to the overpressure impulse [25, 26]; however, due to thermodynamic, acoustic, and fracture losses, the overpressure impulse is lower. Since the underpressure impulses and the displaced volume are nearly the same, the thermodynamic and acoustic losses can be expected to be similar. Therefore, the decrease in overpressure impulse between weathering cases can be attributed to an increase in fracture losses. The maximum impulse from underpressure, overpressure, and losses are shown in Table 3.2.

Table 3.2. Impulse calculation results

Cases	Underpressure Impulse (N*s)	Overpressure Impulse (N*s)	Impulse Lost (N*s)
H0	428	238	190
H35	425	214	211
H70	425	209	216

3.3.2. High-Speed Photography and DIC

Key features of the implosion process are highlighted in Figure 3.7. Matrix and interfibrillar cracking initiates at roughly -1 ms, as shown by the spikes in Figure 3.5

(b). However, these cracks are not necessarily large enough to be visible in the high speed images. Therefore, the focus of this section is on the visible damage. For the H0 tubes, no visible damage is evident until wall contact is made, where cracks forms consistently with the fiber orientation of the outer ply. The surface cavitation seen at -0.2 ms should not be confused with visible damage. Through the thickness cracking is seen at 0.1 ms after wall contact is made, in which time the buckle propagates along the length of the tube, and further through thickness cracking is experienced in the longitudinal direction. For the H35 and H70 tubes, matrix fracture is visible at -0.2 ms, which leads to through thickness fracture when wall contact is reached. In the case of the H0 tubes, the through thickness cracks that forms are concentrated along the longitudinal direction, whereas for the weathered tubes, the large longitudinal crack branches radially after a certain distance of the buckle front is reached. The weathered tubes showed visible cracks at earlier times. Furthermore, the initial visible cracks for the H0 tubes appeared to be matrix cracking, as opposed to through the thickness cracks seen in the H35 and H70 tubes.

Figure 3.7. High speed images of the implosion process highlighting key features

The radial velocity data from a line about the center of the specimen is extracted, shown in Figure 3.8 (a). The extracted data is utilized to obtain the collapse velocity at giving instances in time and locations throughout the length of the composite cylinders, show in in Figure 3.8 (b). The center-point radial velocity of the specimen is shown as the shaded region of Figure 3.8 (b), for $t < 0$. The moment of wall contact is the vertical dashed line. The non-shaded region is the maximum radial velocity along the length of the tube as the buckle propagates longitudinally. From -4 ms to -1 ms, the curves for all weathered times are relatively smooth. The increase in velocity is higher for both weathered tubes as opposed to the virgin specimens, though the differences are within error. At -1 ms, the radial velocity plateaus for the H0 and H35 tubes and continues to increase for the H70 tubes. This increase is likely due to higher quantities of damage in the structure. At the instance prior to wall contact, the radial velocity of the H0 tubes is 6.8 m/s, whereas the velocities at the instance prior to wall contact for the H35 and H70 cases are 11.5 m/s and 14.1 m/s, respectively. The higher radial velocities prior to wall contact in the H35 and H70 tube arises from the degradation in material properties, which translates to lower stiffness and overall lower stresses and strains until failure. The non-shaded region is related to the maximum radial velocity along the length of the tube as the buckle propagates longitudinally. The velocities as the buckle propagate are very similar between all weathering cases, and the slightly higher radial velocities in the weathered tubes can be attributed to experimental error. However, the differences can also be due to loss in stiffness, which is consistent with previous results.

Figure 3.8. (a) Dotted line utilized for the velocity data extraction (b) Velocity profile of the different weathering times. The CenterPoint radial velocity is the shaded region, for $t < 0$. Wall contact is $t = 0$, denoted as the dashed vertical line. The maximum radial velocity associated with the propagation of the buckle front is the nonshaded region, $t > 0$. (c) Location of the buckle front as it propagates longitudinally

The rate in which wall contact is made during collapse (the propagation of the buckle front) can be obtained from the radial velocity data, defined as zero radial velocity. The location of the buckle front as it propagates along the length of the tube is shown in Figure 3.8 (c). The trend exhibited by the curve is nonlinear, in which case there is a deceleration associated with the buckle front. The deceleration of the buckle front propagation is associated with energy dissipation, change in tube stiffness due to shortening of the intact tube, and stiffening provided by the end caps. Since the location of the buckle front is difficult to obtain due to large errors introduced by fracture in the composite structures, as well as surface cavitation, the derivative of the longitudinal buckle location with respect to time introduces further error. However, the average buckle front velocity can be readily calculated, and is taken to be 109 m/s, 105 m/s, and 104 m/s for the H0, H35, and H70 tubes respectively. The buckle front propagation

velocity is ~4% higher for the H0 tubes when compared to the weathered tubes due to differences in collapse pressure. However, it should be noted that the critical collapse pressure for the H0 tubes is 20% higher.

3.3.3. Post Mortem Analysis

Once the experiments were completed, the pressure in the tank was released, and the specimens regained most of the original shape. The cross-section of the post mortem specimen is an ellipse, formed by two longitudinal cracks along the sides of the tube, located 180° apart. The inner major and minor diameters of the post-mortem specimens were measured, and the averages are shown in Table 3.3.

Table 3.3. Post mortem major and minor diameter averages for hydrostatic initiated implosion

Cases	Major Diameter (mm)	Minor Diameter (mm)
H0	61.396±0.58	58.95±1.18
H35	64.942±0.54	62.128±0.46
H70	64.897±0.18	62.077±0.43

The difference between the inner major and minor diameters is useful in understanding the extent of damage and permanent deformation the specimen sustained during collapse. For the H0 tubes, the difference between the major and minor inner diameters is 2.442 mm. In contrast, the difference between the inner major and minor diameters of the H35 and H70 tubes are 2.814 mm and 2.820 mm respectively. Overall, the H0 tubes had more residual structural integrity and were able to regain most of the original shape as opposed to the weathered tubes. In this case, the structural integrity is assessed based on the ability for the tubes to regain the original shape. The H0 tubes suffered two through thickness cracks 180° apart, with almost no significant cracks

elsewhere, shown in Figure 3.9. The post mortem images for the H35 and H70 are also shown in Figure 3.9.

Figure 3.9. Post mortem images for the hydrostatic initiated implosion

The H35 and H70 tubes experienced similar longitudinal cracks as the H0 tubes. However, the cracks in the weather specimens were shorter than the virgin structure. The shorter longitudinal cracks in the weathered specimens can be attributed to several factors. The collapse pressure for the weathered tubes is lower, therefore there is a lower potential to drive the buckle front and the longitudinal crack. Also, the longitudinal cracks in the weathered specimens branched out and formed circumferential cracking, as matrix and fiber cracks, as well as delamination in the specimens. The circumferential cracking in the weathered specimens leads to overall more structural damage, as opposed to the longitudinal cracks in the H0 tubes.

3.4. Shock Initiated Implosion

Shock initiated implosion experiments were conducted to understand the collapse mechanics of weathered cylinders under sub-critical pressures. A dynamic loading event

can initiate the structural instability in tubes, and their behavior can be further altered after significant material degradation from exposure to marine environments.

3.4.1. Pressure Evaluation

For the UNDEX case, the explosive was placed 102 mm from the outer surface of the specimen, with tourmaline pressure transducers placed 102 mm from the explosive, shown in Figure 3.10 (a). The local pressure history recorded by the tourmaline sensor about the midspan of the tube and 102 mm from the explosive is shown in Figure 3.10 (b). For all UNDEX experiments, time 0 is taken to be at the moment of detonation.

Figure 3.10. (a) Location of the specimen and pressure transducer relative to the explosive (b) UNDEX pressure history

When the explosive is detonated, an underwater shock wave is generated, seen as a large increase in local pressure. The specimen is loaded by the underwater shock wave, which causes it to deform radially. Though the process of implosion initiates when the shock impinges on the specimen, the energy supplied by the initial shock is not sufficient to drive the tube to complete collapse. The energy from the explosive causes the nearby water to evaporate, in which time the evaporated gas and the impulse

provided by the explosive creates an expanding cavitation bubble at the charge location. The cavitation bubble expands spherically, reaching its maximum volume at 2.2 ms. When the pressure inside of the cavitation bubble is lower than the pressure of the surrounding fluid, the bubble begins to collapse. The inward motion of the surrounding fluid compresses the gas in the cavitation bubble, and complete collapse of the bubble is reached at 4.6 ms. When the volume of the bubble is at its lowest, the arrested momentum of the water creates a bubble pulse, which loads the specimen further. At this time, the compressed gas in the cavitation bubble achieves a higher pressure than the surrounding fluid, causing the bubble to expand spherically outward again, and the bubble collapse process is initiated once more. The second bubble collapses at 7.9 ms after detonation. The bubble pulses, though smaller in magnitude, provide almost equal impulse as the initial shock due to the long duration of the pulse. The combined loading of the initial and reflected shocks, as well as the bubble pulses, bring the structures to dynamic instability and collapse.

3.4.2. High-Speed Images

The initial shock and subsequent reflected waves cause distortions in the high-speed images, which introduced pseudo displacements when DIC was employed, therefore the initial portion of the UNDEX event is not useful for DIC. The DIC data was utilized to accurately determine the moment of wall contact for the UNDEX initiated implosion. The high-speed images are better suited for determining important features in the UNDEX case, shown in Figure 3.11.

Figure 3.11. High speed images of the UNDEX initiated implosion process

At 3.40 ms, the initial shock, as well as several shock reflections has loaded the U0 tubes. The loading was insufficient to bring the tube to instability, and the tube is seen to be structurally stable. The cylinder also survived the loading of the initial bubble pulse. However, smaller surface cavitation bubbles form around the vicinity of the tube, seen at 5.10 ms. These cavitation bubbles collapsed on the surface of the tube after 5.40 ms of detonation, weakening the structure at the location of collapse. The second bubble pulse loads the structure further, and after several radial oscillations, the walls of the tube begin to accelerate inward. Initial cracking occurs at 9.40 ms after detonation, and wall contact is made at 10.40 ms. Total implosion is achieved at 12.30 ms after detonation. For the U35 tubes, the initial shock and shock reflections were insufficient to cause dynamic instability, similar to the U0 specimens. After 5.10 ms, a similar cavitation bubble forms on the surface of the U35 tubes, which collapses at 5.40 ms.

The collapse of the cavitation bubble caused a through thickness crack about the center of the specimen. The pressurized water leaked inside of the tube, thus decreasing the pressure difference between the inside of the tube and the surrounding fluid. The decrease in pressure difference delayed the implosion process, and wall contact was reached at 8.30 ms. At this time, most of the structure is damaged, and a large portion of the tube makes simultaneous wall contact. After 9.43 ms, the U35 tube completely collapsed in a catastrophic fashion. Unlike the U0 and U35 tubes, the initial cracking for the U70 tube occurred at much earlier times, induced by reflections of the UNDEX shock after 3.40 ms of detonation. Similar to the U35 tube, the U70 tube experienced through the thickness cracking as the initial visible crack, and the loading from the first bubble pulse caused catastrophic failure in the tube, having reached almost simultaneous wall contact throughout the tube at 5.10 ms. Total collapse of the tube was experienced at 5.40 ms.

For the U0 tubes, the initial damage was matrix cracking, induced by the collapse of a surface cavitation bubble, whereas for the U35, the initial damage induced by a similar surface cavitation bubble was through the thickness crack. For the U70 tubes however, the initial damage was through the thickness cracking, induced by the UNDEX and reflected shocks. Furthermore, material degradation led the U35 tube to collapse after 9.43 ms of the UNDEX detonation, a total of 2.87 ms before the collapse of the U0 tube. The U70 tube collapsed after 5.10 ms of detonation, 7.2 ms before the U0 tube. It is important to note that although the shock reflections caused through the thickness cracking in the U70 tube, the tube collapsed instantly after being loaded by the first

bubble pulse. In contrast, the U0 and U35 tubes survived the bubble pulses and collapsed due to accumulated damage from the repeated loading.

3.4.3. Post Mortem Analysis

Similar to the case of hydrostatic initiated implosion, the specimens subjected to underwater explosive blasts regained much of their original shape upon the completion of the experiment. The results for the inner major and minor inner diameters are presented in Table 3.4.

Table 3.4. Post-mortem major and minor inner diameter averages for shock initiated implosion

Cases	Major Diameter (mm)	Minor Diameter (mm)
U0	61.925±1.12	58.496±0.44
U35	61.963±1.00	58.128±1.46
U70	64.963±0.62	57.277±0.63

For all UNDEX cases, the minor diameter is less than the original inner diameter due to the accumulated damage and permanent deformation from repeated loading. It should be noted that the difference between the inner major and minor diameter is greater for the UNDEX case than that of hydrostatic initiated implosion. In the UNDEX case, the tubes suffered much more damage. Furthermore, a similar trend is found in the difference between the major and minor inner diameters; the nonweathered case regained most of its original shape in comparison to the weathered tubes. The weathered U35 and U70 tubes suffered more damage, seen in the inner diameter differences, and the high-speed images. A thin through thickness crack concentrated about the midspan of the U0 specimen in the longitudinal direction is seen in Figure 3.12. In the U0 specimens, most of the damage is concentrated along the main longitudinal cracks, with

smaller cracks branching out. Small portions of the delaminated area were observed around the location of the end caps. The U35 tube failed catastrophically, seen in the high-speed images. Almost instantaneous wall contact was made throughout the tube when the second bubble pulse loaded the specimen, and the high impact caused fracture both longitudinally and circumferentially. Fiber fracture was evident around the entire surface area of the tube, and large portions of delaminated area was observed at the end cap locations. Likewise, the U70 tubes imploded catastrophically. However, the large degree of circumferential cracking seen in the U35 tubes was not observed. Since the U70 tubes failed prior to the loading of the second bubble pulse, the damage accumulation before failure was not as large as the U35 specimens. In the U70 cylinders, the two longitudinal cracks were broad, with small circumferential cracks branching outward. Similar to the U35 tubes, a significant portion of the delaminated area was observed at the location of the end caps.

Figure 3.12. Post mortem images for shock initiated implosion

The post mortem images revealed that the weathered structures suffered higher quantities of damage in terms of fiber fracture, through thickness cracking, both longitudinally and circumferentially, and larger area of delamination.

4. CONCLUSIONS

The hydrostatic and shock-initiated implosions of environmentally degraded CE tubes were studied to understand the effect of saline water on the collapse mechanics of these composite structures. High-speed photography coupled with 3D DIC was utilized to obtain full-field deformations of the tubes throughout the collapse event. Dynamic pressure transducers were used to fully characterize the emitted pressure pulse during the collapse. The completion of these studies has yielded the following conclusions:

- Exposure to the elevated temperature saline water caused a reduction in collapse pressure by 20% after 35 days of exposure when compared to virgin specimens, and 24% after 70 days of exposure when compared to virgin specimens. CE tubes in underwater applications run the risk of premature failure if degradation is not accounted for in design.
- For quasi-static pipe stiffness experiments, 35 and 70 days of weathering led to a 23% and 26% decrease in failure load, respectively, and a decrease of 8% and 12% in failure displacement after 35 and 70 days of weathering, respectively. The drop in pipe stiffness shows the overall decrease in load bearing capabilities and increase in damage potential after weathering. However, the mechanisms of collapse include shear components, therefore the change in collapse pressure is not fully captured by the decrease in pipe stiffness.

- Weathered composites experienced lower overpressure impulse, which implies an increase in damage and fracture. Material property degradation is detrimental to the integrity of the structure; however, it could have less damage potential to surrounding structures since the impulse released is lower than that of non-weathered structures.
- The stiffness deterioration for weathered tubes led to a more catastrophic collapse event, as seen in the high speed and post mortem images. The weathered specimens experienced cracking at earlier times, with the two longitudinal cracks branching radially outward. The larger quantity of cracking and damage accumulation in the weathered specimens led to higher center point velocities during collapse.
- For hydrostatic initiated implosions, the H35 and H70 cases exhibited similar behavior, such as similar impulse, instance of initial cracking, buckle propagation velocity, and post mortem deformation.
- In the UNDEX case, the initial shock was insufficient to bring the nonweathered and weathered tubes to dynamic instability. In these cases, the combined loading of the UNDEX shock and bubble pulse generated sufficient energy to bring the tubes to dynamic instability. However, material property degradation in saturated specimens led to earlier instability.
- Specimens exposed to the saline water bath for 35 days suffered catastrophic failure during UNDEX loading. Two longitudinal through thickness cracks were observed, as well as radial cracks expanding from the main longitudinal cracks. Large portions of the inner ply delaminated at the end caps location. Also, specimens weathered for

70 days experienced slightly higher levels of failure. Therefore, fiber reinforced composite structures exposed to saline water can continue to degrade past saturation.

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Chapter 4 Hydrothermally Degraded Carbon Fiber / Epoxy Plates Subjected to Underwater Explosive Loading in a Fully Submerged Environment

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Experiments and Design

ABSTRACT

An experimental and computational investigation was conducted to evaluate the underwater blast response of fully submerged carbon fiber composite plates after prolonged exposure to saline water. The material in this study was a biaxial carbon fiber / epoxy composite with a $[\pm 45^\circ]$ fiber orientation layup. The plates were placed in a saline water bath with a temperature of 65°C for 35 and 70 days, which simulates approximately 10 and 20 years of operating conditions in accordance to Fick's law of diffusion coupled with Arrhenius's Equation and a reference ocean temperature of 17°C . Experiments were performed underwater in a 2.1 m diameter pressure vessel. The composite plates were placed in the center of the vessel underwater, and an RP-85 explosive was detonated, located 102 mm away from the center of the plate. Two cases of fluid hydrostatic pressure were investigated: 0 MPa gauge pressure, and 3.45 MPa gauge pressure. Two high speed cameras were utilized for three-Dimensional Digital Image Correlation, which provided full-field displacements and velocities of the composite plates during underwater blast loading. A third high speed camera captured the expansion and collapse of the gas bubble formed by the explosive. Moreover, the pressure fields generated by the explosive and gas bubble were recorded with tourmaline pressure transducers. Quasi-static material characterization of the composite plates was performed before and after prolonged exposure to saline water, which served to complete the numerical models. A coupled Eulerian–Lagrangian finite element simulation was performed by using the DYSMAS code. The diffusion of water into the composite material reached a point of saturation after the initial 35 days of exposure. Quasi-static results showed that after 35 days of exposure, the tensile modulus does not

change with exposure to saline water. However, the in-plane shear modulus decreases by 20%. After 70 days of weathering, the tensile modulus drops by 5%, and the in-plane shear modulus drops by 40%. For the case of 0 MPa hydrostatic pressure, the gas bubble interacts with the composite plate substantially, causing large deformations on the plate. In such an event, the out of plane displacement increases for exposure times of 35 and 70 days by 10% and 12% when compared to plates not exposed to saline water, respectively. For the case of 3.45 MPa hydrostatic pressure, the gas bubble does not visibly interact with the composite plate. In this case, the out of plane displacement for the 35 and 70 days case are similar to the virgin structures. The numerical simulations were in agreement with the experimental findings in terms of pressure history, bubble dynamics, and plate deformation. The numerical simulations showed that the displacement of fully submerged composite plates is driven by the displacement of fluid, as well as the size of the gas bubble formed by the explosive rather than the peak pressure generated by the explosive.

1. INTRODUCTION

The underwater blast response of fully submerged fiber reinforced composite plates after prolonged exposure to saline water was studied experimentally and computationally. Carbon fiber /epoxy composite plates were exposed to a salt water solution with 3.5% NaCl content and a constant temperature of 65°C for 35 and 70 days, which is equivalent to 10 and 20 years of service life, respectively, when compared to the average ocean temperature of 17°C. The overall stiffness of the plates decreased

after exposure to the saline water for 35 days, with a further drop in stiffness after 70 days of exposure.

The mechanical properties of composites are known to change when exposed to saline water due to moisture absorption by the matrix of the material [1]. Marine structures can also be subjected to shock, blast, and impact loading during their service life, therefore, material property change from saline water absorption needs to be accounted for in the design of such structures. Failure to account for the degradation can lead to catastrophic failure.

A well-established approach for determining the diffusion coefficients for epoxy resins, in terms of mass diffusions, is a Fickian model [2] which uses Fick's second law to predict how a material's concentration changes over time [3]. The rate of diffusion is governed by temperature, the composition of resin and curing agent, voids in the material, fluid pressure, and fillers. Previous studies showed that the mechanical properties of fiber reinforced plastics degrade over time when exposed to moisture due to an increase in mass, internal stresses due to swelling, loss of interlaminar strength, and debonding of fiber and matrix [4-6]. Work has been completed where the blast response of composite plates after prolonged exposure to saline water within an air medium was analyzed, as well as the blast response of such composites when one face of the plate is exposed to water, and the other face is exposed to air [7, 8]. Moreover, many experimental and numerical studies analyze the dynamic response of composite plates subjected to underwater explosives [9-12]. Other studies have focused on the interaction between the gas bubble generated by an underwater explosive and fully submerged structures [13-17]. However, no work exists on fully submerged composite

materials that have been exposed to saline water for prolonged time periods, or on the explosive gas bubble interaction with such materials.

The work presented aims to understand the response of composite plates subjected to underwater blast loads after prolonged exposure to saline water. Three-Dimensional Digital Image Correlation (DIC) coupled with high-speed photography was used to record and evaluate the full field deformation data. Pressure transducers were used to understand the loading conditions experienced by the composite plates. Quasi-static material characterization experiments showed that fiber-dominated properties are marginally affected by the exposure to saline water, whereas matrix dominated properties were decreased significantly after exposure to saline water, leading to higher out of plane displacements during blast loading when the fluid pressure was maintained at 0 MPa. However, experiments where the fluid hydrostatic pressure was increased to 3.45 MPa showed that there are no appreciable differences in out of plane displacement between virgin specimens and specimens exposed to saline water for prolonged time periods.

2. EXPERIMENTAL SETUP

A total of five experimental underwater explosion cases were investigated in this study. Each case was repeated twice, totaling in ten experiments. The hydrostatic pressure was varied between a gauge pressure of 0 MPa and 3.45 MPa. Three cases pertain to the hydrostatic gauge pressure of 0 MPa for the saline exposure times of 0 days, 35 days, and 70 days. Two cases pertain to the hydrostatic gauge pressure of 3.45 MPa for the saline exposure times of 0 days and 35 days. The 70 day exposure time was

not completed for the 3.45 MPa hydrostatic pressure case due to similarities in results between the 0 and 35 day exposures. Table 4.1 summarizes the experimental cases and their details.

Table 4.1. Details of experiments performed. The temperature of the water bath was a constant temperature of 65°C for all exposure times

Cases	Hydrostatic Pressure (MPa)	Weathering Time (Days at 65°C)	Equivalent Service Time (Years at 17°C)
c0p0	0	0	0
c35p0	0	35	10
c70p0	0	70	20
c0p345	3.45	0	0
c35p345	3.45	35	10

2.1. Material

The composite plates consisted of four plies of unidirectional carbon fabric oriented in a $[\pm 45^\circ]$ layup. The fabric used was Tenax HTS40 F13 24K 1600tex carbon fibers (1% polyurethane-based sizing finish) from Toho Tenax Inc. (Rockwood, TN). The resin/hardener mixture was a 100/30 weight ratio of the RIMR135/RIMH137 epoxy from Momentive Performance Materials Inc. (Waterford, NY). The plates were manufactured by the Vacuum Assisted Resin Transfer Molding (VARTM) at TPI Composites Inc. (Warren, RI). The resin mixtures were drawn into the fabric at a constant pressure of 730 mmHg. The process was completed on a smooth, heated Teflon top table with a temperature of 40°C. Once the resin had been drawn into the fabric, the plates were allowed to dry and harden on the heated table at 70°C for 24 hours. After the initial 24 hours, curing was completed by placing the plates in an oven at 70°C for 10 hours. All specimens were cut from a single sizeable composite sheet to minimize variations in the manufacturing process. The plates had a 1% void content, measured in

accordance to ASTM Standard D2734 [18], and a 60% fiber volume content. The final thickness of the plates was 1.25 mm.

2.2. Material Characterization Procedure

For the composite materials, quasi-static tensile and in-plane shear properties were obtained using an Instron 5585 and following ASTM Standard D3039 [19] and D3518 [20], respectively. To follow the ASTM Standard D3039, the $[\pm 45^\circ]$ s plates were cut at an angle to obtain $[0^\circ, 90^\circ]$ s fiber orientation specimens. The tensile and compressive properties of neat epoxy were obtained by following ASTM standard D638 - 14 [21] and ASTM Standard D695 - 15 [22]. A random speckle pattern was painted on one face of the specimens to employ 2D DIC and obtain full field strain data. The images were captured by a Prosilica camera model GC2450 from Allied Vision Technologies GmbH (Stadtroda, Germany). The tensile and shear experiments were used to quantify the effective material properties, as well as to support the computational models. The strain rate sensitivity of carbon and glass fiber composites, though not negligible, is minimal [23]. Therefore, the quasi-static characterization is used in the dynamic simulations.

2.3. Underwater Explosives Facility

The UNDEX experiments were conducted in a 2.1 m diameter semi-spherical pressure vessel which has a maximum pressure rating of 6.89 MPa and provides a constant hydrostatic pressure throughout the explosion event. Eight cylindrical optically-clear windows are mounted about the mid-span of the vessel, which allows for the specimen to be viewed by high-speed cameras and illuminated by high-intensity light sources. The specimens were placed in the volumetric center of the vessel and

clamped on all edges. The clamping fixture consisted of two aluminum plates with a central square cavity of 229 mm by 229 mm in dimension. The aluminum plates were bolted together with 40 screws, each screw having an applied torque of 18 N*m to maintain consistent boundary conditions for all experiments. A random speckle pattern was painted on the back face of the plates for 3D DIC. Four PCB 138A05 dynamic pressure transducers by PCB Piezotronics, INC., (Depew, NY) were used to measure the changes in local pressure during blast loading. The amplified outputs of the sensors were monitored by an Astro-med Dash 8HF-HS portable data recorder by Astro-Med Inc., (West Warwick, RI) at a sampling rate of 2 MHz. Two Photron FastCam SA1 cameras, by Photron USA, (San Diego, CA) were used to obtain stereo images of the composite plates. A third Photron FastCam SA1 camera was used to capture the dynamics of the gas bubble induced by the detonation of the explosive. The vessel was filled with filtered water for maximum optical clarity, leaving a small air pocket at the top of the vessel. Once the pressure vessel is filled with water, nitrogen gas was introduced into the air pocket to pressurize the vessel. The explosives used were RP-85 exploding-bridge wire detonators by Teledyne RISI, Inc., (Tracy, CA). The RP-85 explosive has 80 mg of Pentaerythritol Tetranitrate (PETN), and 1031 mg of RDX (cyclotrimethylenetrinitramine), which provides the yield equivalent of 1031 mg of TNT. The explosive was placed 102 mm from the centerpoint of the composite plate. The experimental setup is seen in Figure 4.1.

Figure 4.1. Pressure vessel facility for UNDEX study

The pressure transducers on either side of the explosives are placed 102 mm from the explosive. The pressure transducer in the back face of the composite plate is placed 121 mm from the explosive.

2.4. Weathering Facility

A submergence tank was used to expose the composite plates to an elevated temperature saline water bath, shown in Figure 4.2. The submergence tank is composed of two cylindrical propylene tanks, with the volumetrically smaller tank placed inside of the larger tank. Both tanks are filled with deionized water, with the smaller tank having 3.5% NaCl content. The water in the larger tank is heated by four immersion heaters and maintained at a constant temperature of 65°C. The immersion heaters used are Polyscience LX Immersion Circulators (Cole Parmer, Vernon Hills, IL). Each heater can maintain a maximum temperature capacity of 98°C with temperature stability of $\pm 0.07^\circ\text{C}$ for a maximum of 20 L of fluid. The temperature of 65°C is selected as to not

reach the glass transition temperature of 82°C for the composite materials. Before placing the plates in the high-temperature saline water bath, the specimens were placed in a desiccator for seven days to remove accumulated moisture from the environment. The plates were then submerged for 35 and 70 days in the saline water bath. All experiments were conducted the same day the specimens were removed from the accelerated weathering facility to avoid loss of moisture.

Figure 4.2. Accelerated weathering facility setup

2.5. Digital Image Correlation

A high contrast random speckle pattern was applied to the composite plates by coating the specimen with white paint, and randomly placing black dots approximately 2 mm in diameter throughout the coated area. The Photron FastCam SA1 cameras were offset by 17° outside of the pressure vessel and set to record at 18,000 frames per second. The analyses of the high-speed images were performed using the commercially available VIC-3D 7 software (Correlated Solutions, Inc. Columbia SC). The VIC-3D software matches common pixel subsets of the random speckle pattern between a reference undeformed image and the deformed images. A calibration grid was submerged inside of the pressure vessel while it is filled with water, and manually translated in all degrees of freedom to calibrate the VIC-3D software for underwater

experiments. Similar underwater calibrations for DIC have been performed in the past with high accuracy [24].

2.6. Finite Element Analysis

Computational simulations of the UNDEX loading event has been performed with the DYSMAS software. This software is developed and maintained by the Naval Surface Warfare Center, Indian Head. It consists of the Eulerian fluid solver GEMINI, the Lagrangian structural solver DYNA_N, and an interface module which couples the two. GEMINI is a high order Eulerian hydrocode solver for compressible, inviscid fluids. DYNA_N is a Lagrangian non-linear, explicit finite element code for structural applications. The interface module is a standard coupler interface which allows the fluid and structural codes to share the required variables for the fluid structure interaction problem. The computational models are built to capture the fluid structure interaction between the pressure front developed by the explosive and the composite materials.

3. EXPERIMENTAL RESULTS

3.1. Mechanisms of Diffusion

The diffusion coefficient of composite materials can be obtained by the simplified form of Fick's Second law of diffusion, given by [25]

$$D = 0.049 \frac{h^2}{t_{50}} \quad \text{Equation 4.1}$$

where t_{50} is the time required for the composite specimen to reach 50% of the saturation mass and h is the thickness of the composite. A diffusion study was carried out by following ASTM Standard D5229 [26] for temperatures of 5°C, 25°C, 45°C,

and 65°C to obtain the temperature dependence of the diffusion coefficient. The mass gain percentage as a function of time is given in Figure 4.3 (a). Using Equation 4.1, the diffusion coefficients can be readily obtained. Once the diffusion coefficients are known, the logarithmic values are plotted against the inverse of the corresponding absolute temperature values, shown in Figure 4.3 (b).

Figure 4.3. (a) Mass diffusion trend for different temperatures (b) Relationship between diffusivity and absolute temperature

The rate of diffusion is governed by Arrhenius' equation, which gives the diffusion coefficient as a function of temperature [27]

$$D = D_o e^{-\frac{E_a}{RT}} \quad \text{Equation 4.2}$$

where D_o is an arbitrary constant, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature of the diffusion substance. An acceleration factor (AF) can be defined as the ratio between the normal working condition temperature and a higher laboratory temperature. By Equation 4.2, the AF is defined as

$$AF = e^{\left(\frac{E_a}{R}\right)\left(\frac{T_2 - T_1}{T_1 T_2}\right)} \quad \text{Equation 4.3}$$

where T_1 is the absolute elevated temperature of the saline water bath, and T_2 is the absolute temperature of the working condition. Taking T_2 to be the average ocean

temperature of 17 °C, then the submergence times of 35 and 70 days in the elevated temperature salt water bath are equivalent to 10 and 20 years in normal working ocean temperature, respectively.

3.2. Mechanical Properties

3.2.1. Quasi-Static Mechanical Properties of Composite Materials

The specimens used for the quasi-static experiments were from the same batch of materials used for the blast experiments. Table 4.2 shows the effective elastic moduli, Poisson's ratio, in-plane shear moduli, and failure stresses and strains. The material properties were averaged over five tests.

Table 4.2. Effective quasi-static material properties for the carbon fiber and glass fiber composites.

Weathering Case	0 Days	35 Days	70 Days
$E_{1,2}$ (GPa)	78.40±1.80	78.00±2.10	74.90±2.60
G_{12} (GPa)	7.38±0.19	5.32±0.24	4.92±0.22
ν_{12}	0.039±0.01	0.040±0.01	0.042±0.01
Failure Tensile Strain (%)	1.46±0.09	1.38±0.09	1.36±0.07
Failure Shear Stress (MPa)	45.30±1.20	41.30±1.90	38.7±2.60
Failure Shear Strain (%)	4.92±0.79	7.25±0.25	7.28±0.89

Since fiber dominated properties are not affected by saline water exposure [28], there is a negligible change in the tensile modulus $E_{1,2}$ and the failure tensile strain after 35 days of exposure to saline water. After 70 days of exposure, the tensile modulus decreased by 5%. This likely occurs due to degradation in the bond between the matrix and the fibers, which decreases the load transfer capability from matrix to fiber. Matrix dominated properties are greatly affected by saline water, seen as a 20% decrease in the shear modulus G_{12} after 35 days of exposure to saline water. When compared to the virgin specimens, the drop in shear modulus for 70 days of exposure was 33%.

3.2.2. Quasi-Static Mechanical Properties of Neat Epoxy

The degradation of material properties from saline water exposure can be partially attributed to residual stresses caused by swelling in composites [3]. However, it is evident that there is further degradation when the material is exposed past the saturation point (where swelling has ceased). Further degradation can occur if the interface between the fiber and matrix deteriorates, as well as when hydrolysis occurs [29, 30]. To further understand the degradation process of the matrix, quasi-static tension and compression experiments were conducted on neat epoxy coupons by following ASTM Standard D638 - 14 and D695 - 15 [21, 22] respectively. The experimental results are shown in Table 4.3.

Table 4.3. Neat resin quasi-static tension and compression properties for all weathering cases

Weathering Case	0 Days	35 Days	70 Days
$E_{tension}$ (GPa)	1.86±0.09	1.55±0.13	1.43±0.09
$\nu_{tension}$	0.36±0.07	0.38±0.03	0.40±0.03
Failure Stress (MPa)	60.59±0.44	44.81±0.12	42.75±0.27
Failure Strain (%)	15.91±1.39	23.52±1.08	24.95±1.32
$E_{compression}$ (GPa)	2.73±0.08	2.52±0.05	2.52±0.06
$\nu_{compression}$	0.37±0.09	0.39±0.03	0.39±0.01

The tensile modulus $E_{tension}$ decreased by 16% after 35 days of exposure when compared to the virgin specimens, and decreased by a total of 23% after 70 days of exposure. Furthermore, the failure stress decreased by 26% and 30% after 35 days and 70 days of exposure, respectively, when compared to the control case of no exposure, therefore, there is further degradation seen in neat epoxy for specimens that are exposed to saline water past saturation. The compressive modulus also decreased by 8% with

exposure to saline water, when exposed to the saline water bath for 35 days. No appreciable changes were seen with an additional 35 days of exposure.

3.2.3. High Strain Rate Behavior of Neat Epoxy

The dynamic behavior of neat epoxy was obtained by using a Split Hopkinson Pressure Bar (SHPB) in compression. The SHPB setup is divided into three main components: The striker bar, the incident bar, and the transmitted bar. The neat epoxy specimen was placed between the incident bar and the transmitted bar. The striker bar was launched at the desired velocity, which impacts the incident bar, creating a stress wave that travels through the bar until it meets the interface with the neat epoxy specimen. At the boundary, the stress wave encounters an impedance mismatch, which reflects part of the wave back into the incident bar, and transmits part of the wave into the transmitted bar. Two strain gages are mounted on the incident bar, and two on the transmitted bar, which gives strain measurements that can be resolved to obtain the true stresses and strains in the specimen. When the stress wave in the incident bar reaches the epoxy specimen, there is a disequilibrium in the specimen since the force acting on the face in contact with the incident bar is not the same as that of the face in contact with the transmitted bar. Therefore, the stress and strain measurements are considered once equilibrium is reached, shown in Figure 4.4 (a).

Figure 4.4. (a) Force equilibrium in SHPB experiments (b) Dynamic behavior of neat epoxy exposed to saline water. The strain rate is 2000 s^{-1}

Force equilibrium is reached after 5% strain, and is maintained until 30% strain, in which time unloading occurs. For all weathering times, the strain rate applied was 2000 s^{-1} . The true compressive stress–strain curves of neat epoxy for the three different weathering times are shown in Figure 4.4 (b). In quasi-static loading, the epoxy yielded at a value of 85 MPa for virgin specimens, and 70 MPa for both cases of specimens exposed to saline water for 35 and 70 days. For dynamic loading, the flow stress of the material increased as the strain rate is increased. The dynamic yield strength was 130% higher than the quasi-static yield strength for all weathering times. Comparing the different saline water exposure times in dynamic loading shows that the dynamic yield strength decreased by 18% after 35 and 70 days of exposure to saline water.

3.3. UNDEX Loading

3.3.1. UNDEX Blast Characterization

A detailed schematic of the pressure sensor locations relative to the explosive is shown in Figure 4.5 (a). The pressure history of the underwater explosives for sensor 1

and sensor 3 are shown in Figure 4.5 (b) and Figure 4.5 (c) for the hydrostatic pressures of 0 MPa and 3.45 MPa, respectively.

Figure 4.5. (a) Detailed schematic of the pressure sensor and composite plate location relative to the explosive (b) Pressure history for the case of 0 MPa hydrostatic pressure (c) Pressure history for the case of 3.45 MPa hydrostatic pressure

For all experiments, $t = 0$ ms is taken to be when the explosive detonates. Considering sensor 1 in Figure 4.5 (b), there is a large pressure wave generated by the detonation of the explosive, seen at time 0.067 ms, the time required for the shock wave to travel 102 mm. The shock wave reflects from the walls of the pressure vessel, seen at time 1.30 ms. The detonation of the explosive creates a gas bubble, which expands spherically until a maximum volume is reached, then the bubble collapses, releasing a large pressure spike, seen at 11.70 ms. Considering sensor 3 in Figure 4.5 (b), the high

pressure peak of the shock wave is registered by the sensor at time 0.08 ms. When the cavitation bubble fully collapses at 11.70 ms, a large pressure spike with a magnitude comparable to the initial shock is seen on the front face of the plate. The bubble undergoes subsequent expansion and collapse, which ceases when the energy in the system has been entirely spent. For the case of 3.45 MPa hydrostatic pressure, similar characteristics of the UNDEX shock are seen, shown in Figure 4.5 (c). However, the gas bubble induced by the explosive reaches its maximum volume after 0.8 ms, and total collapse occurs at 1.66 ms. The collapse of the gas bubble creates a pressure spike of 14 MPa, about 15 times larger than the gas bubble pulse released in the case of 0 MPa hydrostatic pressure.

The maximum pressure generated by an UNDEX shock can be approximated by the following equations [31]

$$P_{max} = K_1 \left(\frac{W^{\frac{1}{3}}}{R} \right)^{A_1} \quad \text{Equation 4.4}$$

where W is the weight of the explosive, R is the distance of the sensing element from the explosives, and K_1 and A_1 are fitting parameters given by Shin [32]. The experimental value for the peak pressure at a distance of 102 mm (sensor 1) is taken to be 44 MPa, whereas the predicted value is 44.75 MPa. However, the peak pressure given by sensor 3, located behind the plate, is 29.20 MPa, whereas the theoretical peak pressure of an UNDEX shock located 121 mm from the source is 36.52 MPa. Therefore, there is an impedance mismatch between the fluid and the plate which prevented full transmission of the shock wave.

3.3.2. Bubble Dynamics

When an underwater explosive is detonated, the nearby water expands radially outward due to the impulse provided by the explosive, creating a gas bubble with an internal pressure higher than the surrounding fluid [31]. The gas bubble expands spherically until the internal pressure is lower than the pressure of the surrounding fluid, and gas bubble collapses radially inward. When the internal pressure of the gas bubble is once again larger than the surrounding fluid, the bubble expands radially outward. This occurs until the energy in the bubble has been spent. The initial maximum bubble radius, as well as the bubble oscillation period are given by

$$A_{max} = K_2 \frac{W^{\frac{1}{3}}}{(D+33)^{\frac{1}{3}}} \quad \text{Equation 4.5}$$

$$f = \frac{(D+33)^{\frac{5}{6}}}{K_3 W^{\frac{1}{3}}} \quad \text{Equation 4.6}$$

where K_2 and K_3 are fitting parameters, and D is the depth of water where the charge is located. The maximum bubble radius and bubble oscillation frequencies were obtained for hydrostatic pressures of 0 MPa and 3.45 MPa, given in Table 4.4.

Table 4.4. Maximum bubble radius and bubble oscillation frequency for the two ambient pressures studied

Case	Parameter	Experimental	Theoretical
Hydrostatic Pressure 0 MPa	Maximum Bubble Radius (mm)	109	155
	Bubble Oscillation Frequency (Hz)	60	36
Hydrostatic Pressure 3.45 MPa	Maximum Bubble Radius (mm)	50	49
	Bubble Oscillation Frequency (Hz)	720	650

For the ambient pressure of 0 MPa, there is a discrepancy of 30% between the theoretical and experimental bubble radius, and a 66% error between experimental and

theoretical bubble oscillation frequency. Since the maximum bubble radius was theoretical radius is 155 mm and the standoff distance was 102 mm, the bubble interacted with the composite plate, which prevented the bubble from achieving the maximum radial growth. Previous work has shown that in the case of a gas bubble collapsing near an elastic boundary, increasing the stiffness of the boundary decreases the maximum radius of the gas bubble [15]. For the 3.45 MPa ambient pressure, the experimental bubble radius matches with the theoretical radius, and the frequency of oscillation is within 10%, therefore the gas bubble does not interact with the composite plate.

In the case of 0 MPa ambient pressure, the bubble expands spherically outward. However, when the bubble interacts with the plate, the bubble deforms and loses the spherical geometry, seen in Figure 4.6 (a), and in Figure 4.6 (b) where the bubble radius is shown as a function of time in both the x and y direction.

Figure 4.6. Bubble dynamics for the case of 0 MPa hydrostatic pressure (a) Image sequence highlighting key features of the UNDEX generated gas bubble (b) Bubble grows as a function of time for the x and y axis of the bubble

The composite plate acts as a deformable boundary. However, the plate acts as a flow obstruction and influences the motion of the gas bubble. The gas bubble reaches its maximum diameter at 2.9 ms, and begins to collapse at 5.20 ms. As the bubble collapses, the surrounding fluid moves inward and the fluid in contact with the plate moves toward the collapsing gas bubble, forming a surface cavity on the plate, seen at 7.5 ms. The bubble reaches its minimum volume at 11.7 ms, in which instance the surface cavity on the composite plate collapses. As the surface cavity collapses, fluid moves towards the composite plate, causing the gas bubble to migrate towards the plate. After 24.2 ms, the bubble has reached its secondary maximum volume, and is attached to the composite plate.

For the ambient pressure of 3.45 MPa, the error between the theoretical and experimental bubble radius is negligible since the gas bubble did not interact with the plate upon expansion, seen in Figure 4.7 (a).

Figure 4.7. Bubble dynamics for the case of 3.45 MPa hydrostatic pressure (a) Image sequence highlighting key features of the UNDEX generated gas bubble (b) Bubble grows as a function of time for the x and y axis of the bubble

The gas bubble reached its maximum radius at 0.6 ms, and achieves full collapse at 1.6 ms. the second maximum radius occurred at 2.00 ms, and it is seen that the bubble does not maintain a spherical profile after the secondary expansion. Rather, the bubble migrates towards the plate, though contact with the plate is not achieved. Figure 4.7 (b) shows the bubble radius as a function of time. It can be seen that the radius in both x and y -directions are similar, showing that the expansion and contraction of the bubble is symmetric since there is no contact with the composite plate.

3.3.3. High Speed Photography and DIC

Full field deformation data was obtained by coupling the high-speed images with the technique of 3D DIC. The out of plane displacement at the centerpoint of a virgin specimen and the corresponding bubble growth in the x -direction are shown in Figure 4.8 (a) for the ambient pressure of 0 MPa.

Figure 4.8. (a) Bubble growth as a function of time and the corresponding out of plane displacement for a virgin specimen. The bubble growth is taken to be in the x -direction, whereas the out of plane displacement is taken at the centerpoint of the plate (b) Out of plane displacement comparison for the weathering cases of 0 days, 35 days and 70 days. The ambient pressure is 0 MPa

The plate and the bubble reach their respective maximum values at a similar time (2.70 ms), showing the coupling between the bubble growth and plate displacement. At 2.70 ms, the bubble ceases to grow and remains at a constant radius until 5.20 ms where collapse begins, therefore the plate ceases to displace out of plane and instead flexes back towards the original position. Once the bubble begins to collapse, the fluid draws the plate towards the gas bubble, causing a negative out of plane displacement. When the gas bubble collapses, it releases a large pressure pulse, and loads the specimen at 11.67 ms, causing a positive out of plane displacement in the plate.

The centerpoint out of plane displacements for the c0p0, c35p0 and c70p0 cases are shown in Figure 4.8 (b). Exposing the composite plates to the saline water bath for 35 and 70 days lead to an increase in the maximum out of plane displacements for the same loading condition and hydrostatic pressure. The c35p0 plates reached a maximum out of plane displacement which was 35% higher than the c0p0 plates. After an additional 35 days of weathering (c70p0), the composite plates experienced an out of plane displacement which was 40% higher than the c0p0 plates. Despite difference in mechanical properties between 35 days of exposure and 70 days of exposure, the out of plane displacement between the c35p0 and c70p0 was 5%, which is within experimental error. However, it is possible that the 5% different in out of plane displacement is caused by further degradation in the composite plates.

To investigate the effect of ambient pressure on the interaction of an UNDEX gas bubble interaction with a deformable boundary and the resulting response of such plate, the hydrostatic pressure of the fluid was increased to 3.45 MPa. The out of plane

displacement of the composite plate, as well as the growth of the gas bubble as a function of time is shown in Figure 4.9 (a).

Figure 4.9. Out of plane displacement and bubble growth behavior for the ambient pressure of 3.45 MPa (a) Bubble growth as a function of time and the corresponding out of plane displacement for a virgin specimen. The bubble growth is taken to be in the x-direction, whereas the out of plane displacement is taken at the centerpoint of the plate (b) Out of plane displacement comparison for the weathering cases of 0 days and 35 days

The plate and the bubble reach their respective maximum displacement values at a similar time (0.75 ms), in which time the gas bubble maintains a constant radius until 0.96 ms. When the bubble begins to collapse, the plate displaces back towards its original position. Once the bubble fully collapses, the large pressure pulse loads the specimen. The gas bubble continues to expand and collapse at a frequency of 720 Hz, which continues to load the specimen.

For the hydrostatic pressure of 3.45 MPa, the weathering times of 0 days and 35 days are presented, shown in Figure 4.9 (b). The out of plane displacement behavior for virgin plates and plates exposed to salt water for 35 days are similar. Since the maximum out of plane displacement is small (less than 3 mm), there is no damage in the composite plates. It is speculated that the out of plane displacement in the environmentally weathered plates seen in the 0 MPa ambient pressure are higher than virgin specimens

since there is a higher degree of damage induced by blast loading. However, since there is no damage in the 3.45 MPa hydrostatic pressure case, the out of plane displacements between 0 and 35 days of weathering is comparable [33].

3.4. Finite Element Results

To investigate the interaction between the bubble and composite plate, a dimensionless standoff parameter was utilized, such that [34]

$$\gamma = \frac{L}{R_{max}} \quad \text{Equation 4.7}$$

where L is the standoff distance from the explosive to the plate, and R_{max} is the theoretical maximum radius of the gas bubble. For a standoff distance of 102 mm and hydrostatic pressure of 0 MPa, the dimensionless standoff parameter was 0.65. Similarly, for a standoff distance of 102 mm and a hydrostatic pressure of 3.45 MPa, the dimensionless standoff parameter was 2. A final standoff parameter of 1 was selected where the bubble is gracing the plate. To achieve the dimensionless parameters of 0.65, 1 and 2 for the 0 MPa hydrostatic pressure case, the actual distances were 102 mm, 155 mm, and 310 mm, respectively. Similarly, to achieve the dimensionless parameters of 0.65, 1 and 2 for the 3.45 MPa hydrostatic pressure case, the distances were 33 mm, 50 mm and 102 mm respectively.

3.4.1. Hydrostatic Gauge Pressure 0 MPa

The correlation of the UNDEX pressure between the numerical model and the c0p0 case is shown in Figure 4.10 (a) for a standoff distance of 102 mm. The peak pressure predicted by the numerical model matches that of the experiment. Moreover, the decay

time in the simulation matches the experimental results, therefore the UNDEX loading in the numerical model is adequate. The reflections of the shock wave seen in the experimental pressure curve are not present in the simulations, since a non-reflecting boundary condition was used. Since the tank reflections were relatively small compared to the initial shock wave generated by the UNDEX, the non-reflective boundary condition is appropriate for this model.

Figure 4.10. Numerical model validation for the 0 MPa hydrostatic pressure case and a standoff distance of 102 mm. The dimensionless standoff parameter is 0.65. The model was validated in terms of (a) Pressure history recorded at 102 mm from the charge and (b) Centerpoint out of plane displacements extracted from the numerical model and the DIC results

The centerpoint out of plane displacement for the c0p0 plates for a representative experiment and the numerical model are shown in Figure 4.10 (b). The quality of the correlation between the experimental data and numerical simulations is quantified using the Russell Comprehensive error measurement (RC) [35]. The Russell Comprehensive error measurement evaluates the difference between two transient data sets by quantifying the variation in magnitude and phase, which is determined as excellent, acceptable, and poor correlation by the following scores: excellent is $RC = 0.15$, acceptable is $0.15 < RC < 0.28$, and poor is $RC > 0.28$. The RC between the experimental

and simulated displacement data is 0.20, giving an acceptable score for correlation. Furthermore, the numerical model predicted the peak centerpoint displacement within 5%, with only the phase being in error. Due to the accurate prediction of out of plane displacement, the numerical model was extended to include different standoff distances of 102 mm, 155 mm, and 310 mm, giving dimensionless standoff parameters of 0.65, 1, and 2, respectively. The pressure profiles for the given dimensionless standoff parameters are shown in Figure 4.11 (a).

Figure 4.11. The hydrostatic pressure of the fluid is 0 MPa. (a) Pressure curves for the dimensionless standoff parameters of 0.65, 1, and 2. The corresponding distances in which the pressure is taken are 102 mm, 155 mm and 310 mm, respectively. (b) Corresponding centerpoint out of plane displacement profiles for the mentioned dimensionless standoff parameters

The pressure magnitude decreases as the standoff distance is increased. The pressure difference between standoff distances of 102 mm and 155 mm (dimensionless standoff of 0.65 and 1) is 55%. However, the difference in maximum out of plane displacement between these two cases is 2%, shown in Figure 4.11 (b). It appears that the maximum out of plane displacement has a higher dependency on the interaction between the plate and the bubble rather than the magnitude of the shockwave pressure. The difference in

pressure between the standoff distances of 102 mm and 310 mm (dimensionless standoff of 0.65 and 2) is 80%, whereas the difference in out of plane displacement is 25%.

3.4.2. Hydrostatic Pressure 3.45 MPa

The experimental and numerical pressure for the c0p345 case is shown in Figure 4.12 (a) for a standoff distance of 102 mm. The simulation predicts the pressure magnitude of the initial shock within an acceptable range.

Figure 4.12. Numerical model validation. The hydrostatic pressure considered was 3.45 MPa with a standoff distance of 102 mm. The dimensionless standoff parameter is 2. The model was validated in terms of (a) Pressure history recorded at 102 mm from the charge and (b) centerpoint out of plane displacements extracted from the numerical model and the DIC results

The centerpoint out of plane displacements for experiments and simulations for the c0p345 plates are shown in Figure 4.12 (b). The numerical model had an RC score of 0, giving an excellent correlation between the simulation and the experiment. The numerical model was extended to include different dimensionless standoff parameters to compare the results with the case of 0 MPa hydrostatic pressure. The standoff distances selected were 33 mm, 50 mm, and 102 mm, giving dimensionless standoff

parameters of 0.65, 1, and 2, respectively. The pressure history for the dimensionless standoff parameters of 0.65, 1 and 2 are shown in Figure 4.13 (a).

Figure 4.13. The hydrostatic pressure of the fluid is 3.45 MPa. (a) Pressure curves for the dimensionless standoff parameters of 0.65, 1, and 2. The corresponding distances in which the pressure is taken are 33 mm, 50 mm, and 102 mm, respectively. (b) Corresponding centerpoint out of plane displacement profiles for the mentioned dimensionless standoff parameters

Decreasing the standoff distance from 102 mm to 50 mm (dimensionless standoff distance of 2 to 1, respectively) increased the UNDEX pressure by 40%, which led to an increase in peak out of plane displacement of 190%. Further decreasing the standoff distance from 102 mm to 33 mm (dimensionless standoff distance of 2 to 0.65) increased the peak UNDEX pressure by 90%, which increased the peak out of plane displacement by 250%, seen in Figure 4.13 (b). In this case, increasing the peak pressure, as well as increasing the interaction between the gas bubble and the composite plate greatly increases the out of plane displacements of the composite plate.

To understand the effect of the fluid hydrostatic pressure on the underwater blast response of composite plates, a comparison between the pressures of 0 MPa and 3.45 MPa is shown in Figure 4.14 for each of the dimensionless standoff distances.

Figure 4.14. Dimensionless standoff parameter comparison for hydrostatic pressures of 0 MPa and 3.45 MPa

The out of plane displacement of a composite plate can be expressed as

$$D_{11} \frac{\partial^4 w}{\partial x^4} + D_{22} \frac{\partial^4 w}{\partial y^4} + 2(D_{12} + 2D_{66}) \frac{\partial^4 w}{\partial x^2 \partial y^2} + 4D_{16} \frac{\partial^4 w}{\partial x^3 \partial y} + 4D_{26} \frac{\partial^4 w}{\partial x \partial y^3} + C_f \frac{\partial w}{\partial t} + (\rho h + M_f) \frac{\partial^2 w}{\partial t^2} = F \quad \text{Equation 4.8}$$

where M are moments, W is the out of plane displacement, ρ is the density of the composite plate, h is the thickness of the plate, F is the blast loading force, D are components of the stiffness matrix obtained from classic laminate theory, C_f is the damping coefficient of the fluid, and M_f is the added mass of the fluid.

The three dimensionless standoff parameters show that the out of plane displacement depends on both the total hydrostatic pressure, interaction between bubble and plate, and the shockwave magnitude. Lower hydrostatic pressures yielded higher out of plane displacements for the same dimensionless standoff parameters since the added mass of the fluid depends on the hydrostatic pressure of the fluid [36]. Therefore, increasing the hydrostatic pressure also increases the added mass coefficient, which in turn yields lower out of plane displacements for similar loading and boundary conditions.

4. CONCLUSIONS

The underwater blast response of fully submerged fiber reinforced composite plates after prolonged exposure to saline was studied experimentally and computationally. The following conclusions can be drawn based on the findings of this study:

- The mass of the carbon fiber plates increased with exposure to saline water. The initial water absorption followed a linear trend of Fickian diffusion, therefore it was possible to employ Fick's second law of diffusion to obtain the diffusion coefficient of the composite material. Mass saturation was reached within the first 35 days of exposure. Furthermore, an Acceleration Factor based on Arrhenius's equation was used to correlate the laboratory time exposure to real service time, which yielded the equivalent of 10 years of service life for 35 days of laboratory exposure to saline water, and 20 years of real service life for 70 days laboratory exposure.
- The tensile modulus $E_{1,2}$ did not decrease within 35 days of exposure to the saline water bath, and decreased by 5% after 70 days of exposure. The tensile failure strain did not change considerably with exposure to saline water. The shear modulus G_{12} decreased after 35 days of exposure to saline water by 28%, and decreased by 33% after 70 days of exposure to saline water. Shear dominated properties are greatly affected by saline water exposure.
- The tensile modulus $E_{tension}$ for the neat epoxy decreased by 16% after 35 days of exposure, and 23% after 70 days of exposure. For neat epoxy, the tensile properties continue to decrease after saturation has been reached. Furthermore, the compressive modulus $E_{compression}$ decreased by nearly 8% after 35 days of exposure, with no appreciable change after an additional 35 days of exposure.

- Dynamic experiments using an SHPB showed the strain rate dependency for the neat epoxy, both in virgin specimens and specimens exposed to saline water. The dynamic yield strength decreased by 18% after 35 days of exposure, with no apparent further degradation from 35 days of exposure to 70 days of exposure, similar to the quasi-static results in compression.
- During the UNDEX experiments, for the case of 0 MPa hydrostatic pressure, the maximum centerpoint out of plane displacements increased by 35% after 35 days of exposure to the saline water at 65°C. For 70 days of exposure to the saline water, the composite plates experienced an out of plane displacement which was 40% higher than virgin specimens. Increasing the hydrostatic pressure of the fluid to 3.45 MPa showed that there is no appreciable difference in out of plane displacements between virgin specimens and specimens which have been exposed to saline water for 35 days.
- The numerical simulations were within an acceptable range for the case of hydrostatic pressure of 0 MPa, and within an excellent agreement for the case of hydrostatic pressure of 3.45 MPa when considering the initial peak out of plane displacement. The out of plane displacement of the plate is governed mainly by the hydrostatic pressure of the fluid (which also governs the gas bubble diameter), and the distance between the explosive charge and the composite plate.
- The numerical simulations showed a dependency between the fluid pressure and the out of plane displacement of composite plates. Lower hydrostatic pressures yielded higher out of plane displacements for the same dimensionless standoff parameters.

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Chapter 5 Foam Filled Aluminum Structure Design for Mitigating High Pressure Pulses in Underwater Implosions

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ABSTRACT

The pressure differential between an air-filled structure and the surrounding fluid for underwater applications can potentially lead to instabilities and collapse of the structure. When air-filled structures collapse underwater, large pressure pulses are emitted into the surrounding water which can damage nearby structures. The present study aims to mitigate the high pressure spikes generated in underwater implosions, as well as mitigate the energy radiated into the environment by imploding aluminum tubes. Experiments were performed underwater in a pressure vessel designed to simulate a free-field environment by maintaining constant hydrostatic pressure throughout the collapse event. Thin walled aluminum cylinders were placed in the pressure vessel, and the hydrostatic pressure was increased until instability and collapse occurred. To mitigate the pressure pulses generated by implosion, closed cell PVC foam rods of varying densities were suspended concentric with the aluminum tubes. The foam densities of the solid rods were 45 kg/m^3 and 100 kg/m^3 . Three-Dimensional Digital Image Correlation was coupled with high-speed photography to obtain the full-field displacements and velocities of the aluminum tubes during collapse. Moreover, the pressure fields created during the structural collapse were recorded with tourmaline pressure transducers and coupled with the full-field deformations to analyze the implosion event. The 45 kg/m^3 foam reduced the peak pressure pulse generated during the implosion event by 30%, whereas the 100 kg/m^3 foam reduced the peak pressure pulse by 50%. Furthermore, the 45 kg/m^3 foam decreased the energy emitted by the implosion by 16%, whereas the 100 kg/m^3 foam decreased the energy emitted by the implosion by 43%. Full field displacement data showed that both foam densities reduced

the radial velocity of the tubes during implosion, as well as reducing the peak centerpoint decelerations of the tube prior to wall contact by 45% and 62% for the 45kg/m³ and the 100 kg/m³ foam, respectively. Post mortem images showed that the tubes with no foam filler suffered tearing at the boundary of the tubes, whereas tubes with foam fillers did not tear at the boundaries, thus maintaining higher degree of structural integrity.

1. INTRODUCTION

Air-filled structures for underwater applications are susceptible to implosion due to the pressure differential between the interior and the surrounding fluid. When an air-filled structure implodes, a large pressure spike is emitted into the surrounding fluid which can damage nearby structures and living organisms. This study aims to mitigate the high pressure spikes generated in underwater implosions, as well reduce the energy emitted by the collapse of such structures. Experiments were performed underwater in a pressure vessel designed to simulate a free-field environment by maintaining constant hydrostatic pressure throughout the collapse event. Thin walled aluminum hollow cylinders were placed in the pressure vessel and the hydrostatic pressure was increased until instability and collapse were reached. To mitigate the pressures and energies associated with implosion, foam rods of varying densities were placed concentric to the aluminum tubes. The study emphasizes in maintaining the critical collapse pressure of the tubes unchanged, as well as minimize the volume which the foam rods occupy inside of the aluminum tubes. Full field displacements were recorded using high-speed

photography coupled with Digital Image Correlation (DIC). Pressure-time history of the collapse event was recorded using tourmaline pressure transducers.

When cylinders implode underwater, the walls of the structure will displace inwards with a certain velocity, in which case the surrounding water rushes towards the collapsing structure, causing a drop in local pressure. When the walls of the hollow structure come into contact, the momentum of the incoming fluid abruptly changes, which causes sharp pressure pulses that are released into the fluid medium. Early work on implosion characterized the acoustic pulses emitted during the collapse of glass spheres, as well as the potential to damage nearby structures [1]. This work led to the creation of robust computational models for the implosion characterization of metallic structures [2]. The study of underwater implosions was extended to understand the collapse of metallic tubes of varying lengths to produce different modes of collapse, as well as study the pressure pulses emitted by different buckling modes [3, 4]. The implosion process of metallic structures was further studied by employing the technique of DIC for underwater applications [5] which allowed for understanding the structural velocity during collapse. In underwater implosions, the energy emitted into the surrounding fluid is of importance since it can potentially damage nearby structures [6], where work was done to characterize the flow energy that is radiated into the fluid [7]. To mitigate the large pulses and energy associated with implosion, structures were coated with polyurea in the interior and exterior for metallic and composite structures [8, 9]. Such work showed that coating cylinders on the inside with polyurea substantially decreases the sharp pressure pulses and the energy emitted during underwater implosion of cylindrical structures. Furthermore, work has been completed which aims to increase

the collapse pressure of metallic and composite structures by the addition of sandwich foam cores. In such application, a second geometrically smaller tube is placed inside of a larger tube, with a foam core in between [10-13]. However, since the collapse pressure increases in such applications, the sharp pressure spike drastically increases with increasing foam core density [14]. To date, there is no work done where the energy emitted during implosion is mitigated by the use of soft foam filler materials without the use of a secondary, geometrically smaller tube providing stiffness between the filler material and the outside tubular structure. It is important to mitigate the sharp pressure spikes and the energy radiated into the fluid without increasing the stiffness and collapse pressure of underwater structures.

This work aims to mitigate the high pressure pulse and energy released by aluminum tubes during implosion by placing soft foam fillers inside of the structures. The pressure data was utilized to compare the peak pressures during implosion between empty tubes and tubes with the foam fillers, as well as obtain the energy spent in deforming the filler material. The high-speed images coupled with DIC gave information on the structural deformation of the tubes which were filled with foam material. The two filler materials used showed the capability of reducing the pressure spike during implosion, as well as reduce the radial velocity and wall contact propagation velocity during implosion.

2. EXPERIMENTAL SETUP

2.1. Materials

A total of three experimental implosion cases were investigated in this study. Each case was repeated twice, totaling six experiments. The three cases pertain to the

hydrostatic initiated implosion of the control case (No Filler), and tubes with concentric foam rods of 45kg/m³ density, 100 kg/m³ density. Figure 5.1 (a) shows a schematic of the aluminum tubes and relevant dimensions, and Figure 5.1 (b) shows the foam rods used.

Figure 5.1. (a) Aluminum cylinder with relevant dimensions (b) Foam filler location and dimensions inside of the aluminum tubes

The specimens were sealed on both ends with aluminum end-caps fitted with o-rings to prevent water from leaking inside of the implodable volume during pressurization.

Table 5.1 summarizes the experimental details.

Table 5.1. Experimental case summary

Case	Filler Type	Filler Density (kg/m ³)	Inside Volume (mL)	Filler Volume (mL)	Collapse Pressure (MPa)
NF	No Filler	No Filler	1114	No Filler	1.61±0.02
H45	PVC Foam	45	1114	190	1.61±0.01
H100	PVC Foam	100	1114	190	1.61±0.01

Since the majority of the volume in the PVC foam rods is air, the collapse volume of the PVC foam rods is assumed to be equal to the no filler case. The critical collapse pressure of the aluminum tubes was not altered by placing the foam rods inside, and comparisons between the three experimental cases can be readily made.

2.2. Material Characterization Procedure

Quasi-static compression tests were performed for the two foam densities using an Instron 5585 and following ASTM Standard D1621-16 [15]. The compression experiments yielded the compressive elastic modulus, the crush strength, the plateau region of the foams, and the densification point of the materials. The quasi-static behavior of the foam gives an understanding of the energy absorption capabilities for the foams used.

The dynamic behavior of the foams was obtained by using a Split Hopkinson Pressure Bar (SHPB) in compression. The SHPB setup is divided into three main components: The striker bar, the incident bar, and the transmitted bar. The foam specimens were placed between the incident bar and the transmitted bar. The striker bar was launched at the desired velocity, which impacts the incident bar, creating a stress wave that travels through the bar until it meets the interface with the foam specimen. At the boundary, the stress wave encounters an impedance mismatch, which reflects part of the wave back into the incident bar and transmits part of the wave into the transmitted bar. Two strain gages were mounted on the incident bar, and two on the transmitted bar, which gives strain measurements that can be resolved to obtain the stresses and strains in the specimen. Due to the low impedance of the PVC foams, a modified SHPB setup was utilized, consisting of aluminum 6061 alloy bars. A solid incident bar was used to achieve high strain rates, and a hollow transmission bar was used to increase the transmitted signal intensity [16]. Aluminum caps were used to seal the ends of the hollow transmission bar. Clay pulse shapers were used to minimize the effect of the caps on the stress waves.

2.3. Underwater Implosion Facility

The implosion experiments were conducted in a 2.1 m diameter semi-spherical pressure vessel. The vessel has a maximum pressure rating of 6.89 MPa and provides a constant hydrostatic pressure throughout the collapse event. Eight cylindrical optically-clear windows are mounted about the mid-span of the vessel, which allows for the specimen to be viewed by cameras and illuminated by high-intensity light sources. Cables were used in tension to suspend the specimen horizontally in the center of the pressure vessel, and to restrict any motion throughout the experiments. Four PCB 138A05 dynamic pressure transducers from PCB Piezotronic Inc (Depew, NY) were used to measure the changes in local pressure during the collapse of the tubes. The pressure transducers were mounted axially about the specimen such that the standoff distance, R_s , between the sensing element and the outer surface of the specimen is 57 mm. The amplified outputs of the sensors were monitored by an Astro-med Dash 8HF-HS portable data recorder from Astro-Med Inc. (West Warwick, RI) at a sampling rate of 2 MHz. Two Photron FastCam SA1 cameras from Photron USA (San Diego, CA) were used to obtain stereo images of the implosion process. A random speckle pattern was painted on the specimens for 3D DIC. The vessel was filled with filtered water for maximum optical clarity, leaving a small air pocket at the top of the vessel. Once the pressure vessel is filled with water, nitrogen gas was introduced into the air pocket to pressurize the vessel. The pressure was increased gradually until the tubes imploded. The experimental setup is seen in Figure 5.2.

Figure 5.2. Pressure vessel facility for implosion study

2.4. Digital Image Correlation

A high contrast random speckle pattern was applied to the aluminum cylinders by coating the specimen with white paint, and randomly placing black dots approximately 2 mm in diameter throughout the coated area. The Photron FastCam SA1 cameras were offset by 17° outside of the pressure vessel and set to record at 30,000 frames per second. The analyses of the high-speed images were performed using the software VIC-3D 7 from Correlated Solutions, Inc. (Columbia SC). The VIC-3D software matches common pixel subsets of the random speckle pattern between a reference undeformed image and the deformed images. A calibration grid was submerged inside of the pressure vessel while it is filled with water, and manually translated in all degrees of freedom to calibrate the VIC-3D software for underwater experiments. Once calibration is performed, the DIC accuracy is validated by placing a cylinder of known radius inside of the water filled vessel, and the known radius is reconstructed using 3D DIC [5]. Prior to each experiment, such procedure was carried out to ensure the validity of the results.

3. EXPERIMENTAL RESULTS

One of the purposes of this study was to minimize the amount of filler material used while also decreasing the pressure spikes and energy released due to an implosion event. To obtain a reasonable radius for the foam rods, implosion control experiments were performed with no foam material inside. The DIC data showed that the maximum radial velocity at the centerpoint of the tubes occurred when the tubes had a radial displacement of 18 mm, therefore the tube radius was chosen to meet the foam rods when the maximum centerpoint radial velocity is reached. Placing the rod at such location will decrease the kinetic energy of the tube as it collapses. For a tube with no foam material, the total potential energy is given by

$$PE = PV \quad \text{Equation 5.1}$$

where P is the critical collapse pressure, and V is the volume of the aluminum cylinder. As the tube collapses, the potential energy is converted into energy in the aluminum structure, as well as energy in the surrounding fluid. A balance of energy can be written as

$$P\Delta V = E_{Deformation} + KE_{Tube} + E_{Afterflow} + E_{Air} \quad \text{Equation 5.2}$$

where KE_{Tube} is the kinetic energy of the tube, and E_{Air} is the energy required to compress the internal air, given by

$$E_{Air} = -n * R * T * \ln\left(\frac{V_{Final}}{V_{Initial}}\right) \quad \text{Equation 5.3}$$

When the implosion event is complete, most of the potential energy has been converted into plastic deformation of the aluminum tube, compressing the internal air,

and in radiated energy going into the fluid. At the end of the implosion event, the energy balance equation becomes

$$PV = E_{Deformation} + E_{Afterflow} + E_{Air} \quad \text{quation 5.4}$$

where $E_{Afterflow}$ is the energy radiated into the fluid [17]. If the energy radiated into the fluid and the energy spent in compressing the air are known, then the energy spent deforming the structure can be obtained. For structures with internal foam rods, the equation can be written as

$$PV = E_{Deformation} + E_{Foam} + E_{Afterflow} + E_{Air} \quad \text{Euation 5.5}$$

Similarly, if the energy spent in deforming the foam is known, as well as the energy radiated into the fluid, the energy spent in plastically deforming a foam filled structure can be obtained.

3.1. Constitutive Behavior of Closed Cell Foam

When the aluminum cylinder reaches dynamic instability, the walls accelerate towards the midpoint of the tube. In the case where a foam rod is placed inside of the cylinders, the walls of the tubes will impinge on the foam rod as the tube collapses. A line contact is made between the foam and the aluminum tube, and it is assumed that the collapse is symmetric, therefore the foam is loaded in equilibrium during collapse. This type of loading is similar to uniaxial compression, therefore such experiments were conducted for the two foam densities both in quasi-static and dynamic loading, shown in Figure 5.3(a).

Figure 5.3. (a) Stress-strain behavior for the H45 and H100 PVC foams. The quasi-static strain rates of $\dot{e} = 0.002 \text{ s}^{-1}$ were in accordance to ASTM standard D1621-16. The dynamic compression characteristics of the foams for strain rate of $\dot{e} = 2000 \text{ s}^{-1}$ were achieved by using an SHPB (b) Energy density for the H45 and H100 PVC foam as a function of strain obtained by integrating the quasi-static stress-strain curve

The compression constitutive behavior of closed cell foams can be described by several phases of deformation, mainly the elastic region, the crush point (0.65 MPa for the H45 foam and 2.15 MPa for the H100 foam), the plateau region, and the densification region. At high strain rates, there is a strain hardening effect in the PVC foams, where the H45 foam reached the plateau region at 0.75 MPa, 15% higher than the quasi-static strain rate, and the H100 foam reached the plateau region at 3.15 MPa, 46% higher than the quasi-static strain rate. These strain rates are comparable to the deformation occurring during implosion. The area under the stress-strain curve for quasi-static strain rates yields the energy density of the foams, shown in Figure 5.3 (b) for quasi-static compression. The H100 foams can absorb higher quantities of energy for the same strains, where at 20% strain, the energy density of the H45 foam is $1 \cdot 10^{+05} \text{ J/m}^3$, whereas for the H100 foam it is $3.10 \cdot 10^{+05} \text{ J/m}^3$, three times higher than the H45 foam. The energy absorption capabilities of the PVC foams depend on the strain rate and loading type [18] therefore, the results above cannot be readily applied to obtain the

energy absorbed by the foam during underwater implosions. However, these results can be used qualitatively to understand which foam is better suited for energy absorption.

3.2. Implosion Pressure Results

All specimens collapsed in a mode two shape at a critical pressure of 1.61 MPa. The local pressure history was extracted from a pressure sensor located about the center of the specimen in the longitudinal direction and 57 mm from the outer surface. The pressure history is shown in Figure 5.4 for the different foam filler cases. For comparative purposes, the time in which tubes make wall contact is taken to be $t = 0$ ms. It should be noted that the aluminum walls of the tubes that have H45 and H100 foam fillers do not make wall contact, therefore $t = 0$ ms is taken to be when there is an increase in pressure in the underpressure region.

Figure 5.4. Pressure time history for hydrostatic initiated implosions. The pressure shown was taken from the midpoint of the specimen from the pressure sensor 57 mm from the outer wall of the tube. Time 0 ms is taken to be the initial point of wall contact for the NF tubes. The foam filled structures H45 and H100 do not have metal-metal wall contact, therefore time 0 ms is taken to be the initial abrupt increase in pressure

Higher radial velocity in the tube will yield a higher drop in local pressure, therefore, it is expected that placing a foam rod inside will decrease the velocity of both the tube

and fluid, with a higher density foam impacting the velocity decrease more than foams of lower density. When the walls of the tube make contact with the foam, there is a decrease in radial velocity of the tube, which in turn reduces the velocity of the incoming fluid, in which case the accompanying local drop in pressure is not as substantial as it is when there is no foam located in the tube. The H45 foam rod decreased the peak pressure spike by 30% when compared with the tubes with no foam filler, and the H100 foam decreased the peak pressure spike by 50% when compared to the control case. To further understand the potential of damage which is associated with implosion, the pressure data can be represented in terms of impulse, given by

$$I = \int_{t_i}^{t_f} \Delta P \, dt \quad \text{Equation 5.6}$$

The impulse is a representation of the magnitude and duration of a pressure pulse; therefore, lower impulse will yield less damage to nearby structures. The maximum impulse generated from implosion for a tube with no foam filler was 315 Pa*s, whereas for a tube with an H45 foam rod was 285 Pa*s, and for tubes with H100 foams was 232 Pa*s. The H45 foam did not decrease the impulse generated by implosion in a significant way (less than 10%), whereas the impulse decreased by 26% when a H100 rod is used.

3.3. Energy Considerations

To further understand the energy absorbed by the foam, the energy released into the fluid can be calculated, given by [17]

$$E_{Afterflow} = \frac{2\pi R_s}{\rho_o} * I^2 \quad \text{Equation 5.7}$$

where R_s is the distance from the centerpoint of the tube to the pressure sensor, ρ_o is the fluid density, and I is the impulse. The energy radiated into the fluid for an aluminum

tube with no filler was calculated to be 62 J, whereas tubes with an H45 foam rod was 52 J, and 35 J for a H100 foam rod, given in Table 5.2. The energy percentage radiated into the fluid in terms of the total potential energy is readily calculated to be 3.4% for the NF case, 2.9% for the H45 case, and 1.9% for the H100 case.

The volume of the implodable structure was not zero at the end of the collapse process, therefore all of the potential energy was not converted into different forms of energy after implosion. The final volume of the tubes were obtained by performing a water overflow test, and the total potential energy converted into fluid energy, compressing the internal air and structural deformation is taken to be $E_{converted} = P_{cr}*(V_i - V_f)$, given in Table 5.2 for all cases. Furthermore, the final volume of the foam rods was obtained by filling the tubes with water after implosion and measuring the total inside volume, and then subtracting the residual volume obtained from the water overflow test. The tabulated results for the maximum radiated energy in the fluid, final tube volume, crushed foam volume, final centerpoint thickness, and energy converted are given in Table 5.2. For the NF case, the residual volume gives 440 J available in the tube after implosion. For the H45 case, there is 700 J available energy after implosion, and for the H100 case there is 725 J.

To obtain the final strain in the foams, the centerpoint thickness was calculated and the overall wall thickness of the tubes were subtracted, giving the values shown in Table 5.2. The H45 foams were strained to 83% of the original foam diameter, where the H100 foam rods had 60% strain. According to the high strain SHPB compression results, for 83% strain, the H45 rod can absorb $\sim 5.7*10^5$ J/m³, whereas for 60% strain, the H100 foam can absorb $1.6*10^6$ J/m³, which is over two times as much as the H45 foam. The

total volume crushed for the H45 foam rod is then taken to be 78 mL at 83% strain, and for the H100 foam the foam crushed at 60% was 58 mL. The corresponding energy for the H45 at the mentioned crushed volumes and strains is 45 J, and 95 J for the H45 and H100 foams, respectively. Therefore, the H100 foam is capable of absorbing almost two times as much energy as the H45 foam. It should also be mentioned that these values were calculated from SHPB compression results, whereas the loading experienced by the foams during the collapse of aluminum cylinders is not the same as uniaxial dynamic compression, though these two loading conditions are in the same order of strain rates. In light of this, these values are taken to be rough estimates of the energy absorbed by the foams, and not as entirely accurate values.

Table 5.2. Calculation of after flow energy, final tube volume by the water overflow method, final foam volume, total potential energy converted, and final centerpoint thickness of the aluminum tubes after implosion

	NF	H45	H100
Energy Converted (J)	1400	1215	1120
Afterflow Energy (J)	62	52	35
Compressed Air Energy (J)	175	126	112
Foam Compression Energy (J)	N/A	45	95
Deformation Energy (J)	1163	992	878
Final Tube Volume (mL)	240	365	420
Crushed Foam Volume (mL)	N/A	78	58
Final Centerpoint Thickness (mm)	1.0657	4.1960	9.9747

The energy required to compress the air, E_{Air} , is relatively high in this study in comparison to previous studies [19] where the energy is ~3%. However, in this study,

the volume of air is five times higher than the study mentioned. The critical collapse pressure of aluminum tubes can be obtained from the Von Mises equation [20]

$$P_{cr} = \frac{Eh}{a} \frac{1}{n^2 + \frac{1}{2} \left(\frac{\pi a}{l} \right)^2 - 1} \left\{ \frac{1}{\left[n^2 \left(\frac{\pi a}{l} \right)^2 + 1 \right]^2} + \frac{h^2}{12a^2(1-\nu^2)} \left[\left(n^2 + \left(\frac{\pi a}{l} \right)^2 \right)^2 - 2n^2 + 1 \right] \right\} \quad \text{Equation 5.8}$$

where a is the radius, E is the Young's modulus of the material, h is the thickness of the tubes, n is the mode shape of collapse, ν is the Poisson's ratio, and l is the length of the tube. The total potential energy varies with P_{cr} and volume, where P_{cr} is a function of the volumetric parameters, radius and length, therefore changing the volume of implodable tubes will also alter the collapse pressure, and ultimately the total potential energy in the system. Furthermore, increasing the volume will also alter the energy required to compress the internal air during collapse. The ratio between E_{Air} and $P_{cr} * V$ is shown in Figure 5.5 (a), with varying length and maintaining the radius at a constant value of 31.75 mm, with the wall thickness remaining constant as well, therefore changes in volume are due to changes in length. Moreover, care has been taken to change the collapse mode as the length of the tube changes.

Figure 5.5. Dependence of the energy required to compress the air as a function of total volume of the implodable tubes. (a) The volume of the implodable was varied by changing the length and maintaining the radius and thickness constant. (b) The volume of the implodable was varied by changing the radius and maintaining the length and thickness constant

As the length of the tube increases, the volume increases, and the ratio between E_{Air} and $P_{cr} * V$ asymptotically approaches 0.14. The energy required to compress the air for the radius of 31.75 mm will have a maximum of 14% of the total energy. Figure 5.5 (b) shows the ratio between E_{Air} and P_{cr} where the radius is varied, and the length is maintained at a constant 381 mm, therefore the volume change is varied by changing the radius only. As the radius is increased and the length is maintained constant, the critical collapse pressure decreases, whilst the volume increases. The trend shows that the volume will become large enough where the total potential energy will be insufficient to bring about any significant deformation in the structure and achieve full collapse, though the point of instability is still possible.

The total energy spent in deforming the specimen is taken to be as the difference between the energy converted, and the remaining energy quantities such as after flow energy, foam compression energy, and air compression energy. The ratio between the deformation energy and the available potential energy is shown in Figure 5.6.

Figure 5.6. Ratio of potential energy and potential energy converted for the aluminum tubes with no filler, and for tubes filled with H45 and H100 foam rods

Previous studies have shown that the energy spent in deforming a metallic cylinder during implosion is about 90% of the potential energy [19], however, in this study the deformation energy is shown to be 65% of the total energy converted for the NF case. In the present study, this deformation energy was taken indirectly from the energy balance equation, such that $E_{Deformation} = E_{Converted} - E_{Afterflow} - E_{Air}$. Where $E_{Converted}$ is used rather than $E_{Potential}$, which yields lower values for $E_{Deformation}$. For the H45 foams, 55% of the energy is spent deforming the structure, and 50% of the energy was spent in deforming the structure for the H100 foam case. Placing foam inside of metallic cylinders lowers the amount of energy going into deforming metallic structures during implosion.

To understand the role that the foams play on the overall final volume of the tubes, post mortem DIC images of the NF, H45, and H100 foam rods were taken, and the full field contours of the depth are given in Figure 5.7 (a).

Figure 5.7. Post mortem full field DIC images of the aluminum tubes with no filler, H45 foam filler, and H100 foam filler. The contours are the Z-coordinate (depth) of the tubes, with a reference zero point being the end-cap locations. (b) Line slice along the length of the tube taken from one boundary to the other boundary

From the full field displacements, it can be seen that the foam prevents the tubes from reaching wall contact; rather, the aluminum tube has higher deformation in locations not in contact with the foams. To further analyze the post mortem DIC images, a line slice at the center of the tubes were taken longitudinally, and the values were plotted as a function of tube length, shown in Figure 5.7 (b). The maximum deformed radius for the NF case was ~31 mm, which is expected since full wall contact occurred. The tubes also have an increase in the Z coordinate values at around ± 100 mm, which occurs from bending of the tubes during implosion. In contrast, the H45 and H100 tubes appear to have a flat profile in the Z coordinate curve shown. Based on Figure 5.7 (b), the H45 had a longer crushed length than the H100 foam, as well as lower final thickness. Calculating the final foam volume after implosion based on Figure 5.7 (b) also proved to be reliable.

3.4. DIC Results

The high-speed photography and DIC results provided full field displacements and velocities throughout the collapse event. The change in radius at the centerpoint of the specimens was extracted and plotted over time, shown in Figure 5.8 (a). As previously mentioned, the moment of wall contact is taken to be $t = 0$ ms.

Figure 5.8. (a) Radial displacement taken about the centerpoint of the tubes. The location of the foam rod is highlighted, giving the time in which contact with the foam occurs. (b) Radial velocity of the tubes taken about the centerpoint of the specimens. The time in which the tubes come in contact with the foam was taken from the displacement profile

The initial change in radius for all of the cases are shown to be similar until contact with the foam is made at -0.65 ms. For the NF tubes, the radial change continues to have a linear trend until wall contact is made, seen as a minimum radial displacement of -29.5 mm. The H45 tubes obtained a minimum radial displacement of -24 mm, and the H100 tubes had a minimum radial displacement of -22 mm. It is evident that the foam rods prevent the tube from reaching full wall contact (metal on metal contact), therefore the moment of “wall contact” for the H45 and H100 tubes is taken to be the point of zero radial velocity, seen in Figure 5.8 (b).

In underwater implosions, the maximum pressure peak emitted by the collapse of structures is governed by the change in velocity of the incoming fluid, which is directly related to the structural velocity [8, 21, 22], therefore to mitigate the pressure spike, it is necessary to reduce the maximum radial velocity of the tubes prior to wall contact. For the NF tubes, the maximum velocity occurs at 0.65 ms, and is maintained until wall contact ($t = 0$ ms), giving a 0.35 ms plateau region of maximum radial velocity. The

change in radial velocity can be immediately seen in the H45 and H100 tubes at the point of contact with the foam rod. To understand the mitigating effect of the foam rods, the Joukowsky equation is considered, which calculates the peak transient pressure in a fluid when a valve is suddenly closed as a fluid is in motion, such that $\Delta P = \rho * c * \Delta v$, where ρ is the density of the fluid, c is the speed of sound in the fluid, and Δv is the change in velocity (deceleration) of the fluid [23]. The maximum change in velocity during wall contact is the determining factor in the peak pressure emitted during implosion, taken to be $1.36e^{+05}$ m/s² for the NF case. The H45 and H100 foams decreased the change in velocity of the tubes by 45% and 62%, respectively, which is seen as a decrease in peak pressure.

To further understand the collapse behavior of the tubes, radial velocity data was extracted from a centerline along the length of the tube. The velocity along the length of the line was plotted as contour colors, giving a three dimensional view, where the x-axis is time, the y-axis is the length of the tube, and the contour colors are the radial velocity magnitude, therefore, the velocity at every time instant is known along the tube length, shown in Figure 5.9 for the NF, H45, and H100 cases. The tube length 0 mm corresponds to the center of the tube since the collapse is symmetric longitudinally.

Figure 5.9. DIC contours of radial velocity for the tubes with No Foam filler, as well as tubes with H45 and H100 foam rods. The velocity contours were extracted from a line ranging from the center of the tube to the end cap boundary

The maximum radial velocity does not occur at the centerpoint of the specimen during collapse. Rather, the maximum radial velocity occurred from 120 mm to 180 mm (end of the tube) from the center point, taken to be ~ 35 m/s. Similarly, for the H45 case, the highest velocity occurs at the location of 120 mm until 180 mm, however, the maximum velocity reached was ~ 27 m/s. For the H100 case, this behavior is not seen. The radial velocity appears to be constant throughout the length of the tube during the implosion process. Therefore, the rigid H100 foam mitigates the velocity of the tube in such a way as to maintain a constant radial velocity throughout the implosion event. It was mentioned previously that the velocity of the structure during implosion governs the overall pressure spike released when wall contact is made. Moreover, as wall contact is made longitudinally, similar pressure spikes will occur since water continues to rush towards the air volume. It is evident then that decreasing the midpoint radial velocity is insufficient for mitigating the pressure spikes associated with implosion; the velocity of the structure must be decreased prior to wall contact throughout the length of the tube, in which case the H45 and H100 foams were successful in doing.

When wall contact is made, the radial velocity becomes 0 m/s. The zero velocity point can track the rate in which contact area propagates longitudinally as the tube

collapses. The points of wall contact along the length of the tube are shown in Figure 5.10. It should be noted that the location corresponding to 0 mm is taken to be the center of the tube.

Figure 5.10. Wall contact propagation measured along the length of the tube. The contact location is shown for one half of the tube due to the axis-symmetric nature of implosion in the longitudinal direction. The location of the end cap is taken to be 190 mm from the centerpoint of the tube

The point of wall contact is taken to be 10 mm for the center of the tube since when the tube collapses, a line contact is made with a certain length, rather than a single point. As wall contact propagates longitudinally, the energy in the system is being spent, and the unsupported length of the tube decreases. When the energy in the system is insufficient to continue to collapse the remaining unsupported tube length, the wall contact propagation ceases, and the collapse event ends, which occurs at 1.05 ms for the NF case. The total collapse length of the NF tube reached to 140 mm, whereas for the H45 and H100 tubes, the total wall contact length was 125 mm and 115 mm, respectively. Shorter wall contact lengths imply that part of the available energy in the system which deforms the structure was absorbed in crushing the foam, rather than propagating the contact zone further. This behavior is directly correlated with previous

discussions of larger residual volumes in foam filled tubes. Moreover, the average wall contact propagation velocity for the NF tubes was calculated to be 121 m/s, with the contact propagation velocity being 95 m/s for the H45 tubes and 88 m/s for the H100 tubes.

3.5. Post Mortem Analysis

To highlight the catastrophic failure of aluminum tubes after implosion, cross sectional post mortem images were taken for the NF, H45, and H100 cylinders, shown in Figure 5.11. The images shown are characteristic of the experiments performed for the different cases.

Figure 5.11. Cross-sectional area post mortem images of the cylinders for the different foam density fillers and a no filler case. The left specimen is the no filler case, the center specimen is the H45 foam filler, and the right specimen is the H100 filler case

The NF tubes show wall contact throughout most of the inner diameter of the tube, though the ends of the tube do not make wall contact. Tearing is seen at the bottom of the cross section, which occurs at the end cap location. Due to plastic deformation, the diameter at the end of the tube ceased to be 63.5 mm. The largest deformed diameter for the NF tube was 76 mm, where the minimum deformed diameter was 71 mm. For the H45 tubes, the walls of the aluminum tube did not come in contact. Moreover,

tearing did not occur at the end cap location. However, the tube became distorted, with a major deformed diameter of 76 mm and a minor deformed diameter of 71 mm, similar to the NF case. Unlike the NF and H45 cases, the H100 tube had a major and minor deformed diameter close to the original undereformed values. The H100 foam absorbed a significant amount of the available energy in the system, therefore less energy was spent deforming the structure. Tearing at the boundaries was not seen, and wall contact was not made for the H100 tubes. The tubes with a foam rod had lower radial velocities during collapse (Figure 5.8 (b) and Figure 5.9), and the wall contact point was further from the end cap boundaries (Figure 5.7 and Figure 5.10), therefore the catastrophic failure of implosion in these cases was not in the same degree as tubes with no foam filler.

4. CONCLUSIONS

The hydrostatic initiated implosion of aluminum tubes with PVC foam rod fillers was studied. Foams of varying densities were selected to investigate the effect of foam density on the energy absorption capabilities of the foams. The foam rods were used to mitigate the high pressure pulses emitted during implosion, as well as to provide additional structural stability to the aluminum tubes after implosion. High-speed photography coupled with 3D DIC was utilized to obtain full-field deformations of the tubes throughout the collapse event. Dynamic pressure transducers were used to fully characterize the emitted pressure pulse during the collapse. The completion of this study has yielded the following conclusions:

- For quasi-static uniaxial loading, the H100 foams had a plateau region two times larger than H45 foams, which showed that for the same strains, the H100 foams can absorb over twice as much energy as the H45 foams. When considering high strain rate loading applied by the SHPB, the H100 foam had a plateau region which was over three times larger than the H45 foams.
- The foam material did not alter the critical collapse pressure of the tubes; therefore, the available potential energy was similar for tubes with foam fillers. The foam rods were designed in such a way as to contact the walls of the aluminum tube when the maximum radial velocity was reached to gradually decrease the radial velocity prior to wall contact and reducing the overpressure spike associated with implosion. Such a design reduces the peak pressures during implosion while also minimizing the volume occupied by the foam rods.
- Placing tubes of H45 density decreased the peak pressure spike released during implosion by 30%, whereas the H100 foam rod decreased the peak pressure spike released by 50% when compared to tubes with no filler material. Furthermore, the Afterflow energy released to the fluid after implosion decreased by 16% when a foam filler of H45 density was placed inside of the aluminum tubes, and by 43% for a H100 foam (almost three times more than the H45 foam). Placing foam rods inside of the implodable volume also decreased the total energy spent in deforming the specimen.
- The DIC results showed that the maximum radial velocity at the centerpoint of the tubes with no filler material occurred at -0.65 ms prior to wall contact and was maintained until wall contact was reached at time 0 ms. The foam tubes were

designed to meet the aluminum walls at the initial time where maximum velocity is reached to gradually decrease the velocity prior to wall contact. Reducing the radial velocity prior to wall contact directly reduces the deceleration magnitude when wall contact occurs, therefore will also decrease the pressure spike released during implosion. The foam rods also decreased the maximum radial velocities experienced throughout the length of the tube, with the H100 foam reducing the radial velocities along the length of the tubes by over 22% more than the H45 foams. The energy absorbed by the foams also decreased the total length of wall contact, and the rate in which wall contact was made during implosion.

- Placing foam rods inside of implodable aluminum volumes kept the walls of the tubes from coming in contact. The H45 and H100 foams absorbed roughly 2.5% and 5% of the total potential energy, respectively. Tubes with no foam fillers showed tearing at the end cap boundary, whereas tubes with foam fillers did not show tearing around the boundaries, directly related to the amount of energy spent in deforming the structure for all cases. Therefore, placing foam rods inside implodable volumes provides structural integrity after catastrophic collapse under hydrostatic pressures.

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Chapter 6 Further Considerations

The main focus of this dissertation is on the changes of mechanical properties in composite materials. The change in mechanical properties can be due to mechanical stress, such as cyclic loading, as well as thermal stress such as thermal expansion. Moreover, mechanical property changes can also arise from chemical changes, such as those occur in UV radiation exposure, and hydrolyzation from moisture exposure. Furthermore, nuclear changes are possible, which can occur in environments where ionizing radiation occurs, which can include UV radiation, as well as other nuclear applications.

The first four chapters presented in this dissertation deal with the degradation of composite materials which occurs from exposure to marine environments, and how composite structures behave under different dynamic loading events after environmental exposure. However, the areas discussed can be further expanded to fully understand the degradative effects.

1. BONDING

To further understand the degradative effects of UV radiation exposure and moisture absorption, the bonding between fiber plies needs to be understood, as well as the bonding between fibers and matrix. Successful Double Cantilever Beam experiments can be conducted after exposure to saline water and ultraviolet radiation. Such experiments can shed light on the mechanisms of failure for environmentally degraded composite materials in dynamic loading conditions. Furthermore, fiber pullout tests can be conducted on environmentally weathered fiber/epoxy droplets as highlighted by

Miller [1]. These experiments can aid in understanding the debonding of the fiber and matrix interface which occurs as a results of water exposure.

2. DEPENDENCY ON STRAIN RATE

Chapter 4 showed the quasi-static and high strain rate behavior of neat epoxy after exposure to saline water. However, this chapter does not deal with the full range of strain rate dependency in UV radiation exposure for neat matrix materials. Furthermore, the chapter does not include the full range of strain rate behavior after saline water exposure for neat epoxy. Experiments can be conducted under several quasi-static and high strain rates for different matrix materials after exposure to UV radiation, as well as saline water exposure. Further experiments can be conducted on fiber reinforced composite materials and have a full understanding of the compressive strain rate behavior after exposure to both saline water and ultraviolet radiation.

3. MULTIPLE ENVIRONMENTAL EXPOSURE

To gain additional knowledge on the dynamic behavior of composites after exposure to marine environments, composite structures can be exposed to ultraviolet radiation for prolonged time periods, and then exposed to saline water. The same can be done vice versa, where saline water exposure is performed first, followed by ultraviolet radiation exposure. Furthermore, an alternating cycle of ultraviolet radiation and saline water exposure can be completed. This type of environmental exposure is likely more closely related to real service conditions.

4. THERMAL CYCLIC EXPOSURE

Cyclic exposure can also be completed in terms of high temperatures and low temperatures. The temperature variation in certain locations can greatly vary between day and night. Furthermore, marine vehicles can be translate to several parts of the world in short time periods. Therefore, there is a need to understand the high/low temperature cyclic variation. The form of degradation will mainly be focused on the thermal expansion and contraction. Such cyclic expansion and contraction can create crack growth in composite structures, as well as debond fibers from matrix, as well as debond fabric plies.

5. IMPLOSION OF UV RADIATION EXPOSED CYLINDERS

Chapter 1 showed that the shear modulus G_{12} decreases quite drastically with exposure to saline water. The decrease in shear stiffness was shown to be the main contributor to the decrease in collapse pressure for saline water exposed composite tubes, as shown in Chapter 3. However, in terms of ultraviolet radiation exposure, it was shown in Chapter 2 that G_{12} increases with UV radiation exposure, therefore composite cylinders will likely see an increase in critical buckling pressure. An experimental study can be conducted on composite cylinders exposed to ultraviolet radiation which will investigate the critical collapse pressure of such tubes, the pressure spikes generated during implosion, as well as the energy emitted by ultraviolet radiation exposed composite cylinders.

6. IMPLOSION OF ENVIRONMENTALLY DEGRADED SANDWICH STRUCTURES

The implosion of composite structures was discussed in Chapter 3. In marine applications, underwater structures can be reinforced with foam cores for energy absorption. These sandwich structures can also degrade when exposed to saline water. In a composite sandwich there is an outer composite skin, a foam core, and an inner composite skin. Exposure to saline water will degrade the outer skin, and moisture can penetrate the thickness of the outer skin and reach the interface where the composite is adhered to the foam. Moisture can potentially alter the bonding between skin and foam, causing drastic changes in the collapse pressure of sandwich structures.

7. NUCLEAR APPLICATIONS

The material change of composites due to ionizing radiation can be further studied. Chapter 2 deals with the exposure to UV light, which can cause ionization. To further understand such process, composites can be exposed to longer time periods of UV radiation, which can give rise to different mechanical response under dynamic loading. Furthermore, composites can be exposed to ionizing radiation which have more energy, thus causing higher degree of ionization, which in turn give rise to different forms of material degradation.

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Appendix

Appendix A.Compression After Impact Fixture Design - ASTM Standard D7137

Compression After Impact experiments were conducted in Chapter 1. The fixture necessary to carry out the such experiments was completed by following ASTM Standard D7137 [1], with modifications made to simplify the manufacturing process. The fixture was manufactured as six distinct parts: The base plate, the top plate, side support plate, bottom guide plate, side guide plate, and top guide plate. The dimensions for the distinct parts are shown in this section. All dimensions are given in inches. The base plate is shown in Figure A.1

Figure A.1. The thickness of the support plate is 0.50 inches (a) support plate schematic with relevant dimensions. The dimensions are taken with reference to the top left corner. (b) Three-Dimensional schematic of the base plate

The four holes of 0.38 inches in diameter closest to the edges of the plates are through holes, designed to keep the fixture in place when mounted on the Instron 5585.

The remaining holes of 0.25 inches diameter are tapped holes for $1/4'' - 20$ screws.

These the side plate support and the bottom guide plates. The side support plate is shown in Figure A.2

Figure A.2. Schematic of the side support plate. The side support is “L” shaped with a thickness of 0.50 inches. Two side support plates are mounted on the base plate. (a) side view schematic of the side support plate (b) Three-Dimensional schematic of the side support plate (c) Side face of the side support plate where all dimensions are given with reference to the top left corner (d) bottom face of the side support plate where all dimensions are given with reference to the top left corner. Note that the bottom left corner is located on the left side of Figure A.2 (a)

For the side support plate, the side portion consists of 1/4" – 20 tapped holes, whereas the bottom portion consists of 0.25 inch through holes. The bottom guide plate is placed directly on the base plate, where the dimensions are shown in Figure A.3

Figure A.3. (a) Bottom guide plate schematic where all relevant dimensions are given with reference to the top left corner (b) Three-Dimensional Schematic of the bottom guide plate

The bottom guide plates have two 0.25 inch diameter through holes. Two plates are mounted directly on the base plate. A knife edge was manufactured to make a line contact with the composite specimen and maintain the composite plate in place during compression. The side guide plates are similar to the bottom guide plates, which are shown in Figure A.4

Figure A.4. (a) Side guide plate schematic where all relevant dimensions are given with reference to the top left corner (b) Three-Dimensional Schematic of the side guide plate

The side guide plates have two 0.25 inch in diameter through holes. Two side guide plates are mounted on the side support plate. The side guide plates also make a line contact with the composite plate which keep the specimen from buckling under compression while the experiments are being performed.

To compress the specimens, a top support plate with two top guide plates are used. The top support plate is shown in Figure A.5

Figure A.5. (a) Top support plate schematic, where all relevant dimensions are given with reference to the top left corner (b) Three-Dimensional Schematic of the top support plate

For the top support plate, the four holes are 1/4" – 20 tapped. Two top guide plates are mounted on the top support plate. The schematic for the top guide plate is shown in Figure A.6

Figure A.6. (a) top guide plate schematic where all relevant dimensions are given with reference to the top left corner (b) Three-Dimensional Schematic of the top guide plate

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Appendix B. Mixed Mode I – Mode II Interlaminar Fracture Toughness of Unidirectional Fiber Reinforced Polymer Matrix Composites – ASTM Standard D 6671

Double cantilever beam experiments were conducted to obtain the fracture toughness of the carbon fiber / epoxy composite materials used in Chapter 1, Chapter 2, and Chapter 4. The experiments were completed by following the guidelines of ASTM Standard D 6671 [1]. The fiber orientation of the composite specimens was $[0^\circ, 90^\circ]$ to prevent shearing during loading, with a total of four plies. The specimens were prepared by the Vacuum Assisted Resin Transfer Molding with a Teflon strip of 38 mm in length inserted along the thickness center of the specimens to create an initial crack. Once the specimens were completed, hinges were glued at the crack with J-B Weld. The load was applied using an INSTRON 3345 and the images were recorded using a Prosilica camera model GC2450. A typical experimental setup is shown in Figure B.1

Figure B.1. DCB specimen and experimental setup

Tick marks were placed on the specimen starting at the crack tip with increments of 6 mm to better track the crack propagation during the experiments. For a composite material such as the one utilized, the load-point compliance is

$$C = \frac{2a^n}{3E_1I} \quad \text{Equation B.1}$$

where a is the crack length, I is the moment of inertia, E_I is the young's modulus in the fiber direction, and n is an experimentally determined parameter. A typical Load/Displacement profile is shown in Figure B.2 for a virgin specimen

Figure B.2. Load as a function of INSTRON head displacement during DCB experiment

The load-displacement curve shows an increase in load with subsequent drops in load, caused by the opening of the crack. As the crack propagates, the load required to drive the crack decreases. To experimentally determine the exponent n in Equation B.1, the inverse of the compliance, $1/C = P/\delta_c$ is plotted in a double logarithmic graph, shown in Figure B.3

Figure B.3. Double logarithmic plot of the carbon fiber / epoxy virgin DCB specimens

The exponent is given by the absolute value of the slope of the line shown in Figure B.3, taken to be 3. Obtaining the compliance of the material is necessary for obtaining the energy release rate, G_{IC}, given by

$$G_{IC} = \frac{nP_c\delta_c}{2wa} \quad \text{Equation B.2}$$

The crack opening δ_c can be obtained from the inverse of the compliance $1/C = P_c/\delta_c$. The energy released rate is shown in Figure B.4

Figure B.4. Mode I interlaminar fracture resistance of the carbon fiber/epoxy virgin specimens

The energy released rate is taken to be as the average of the flat line shown in Figure B.4, given as 605 kJ/m². The energy released rate for composites exposed to saline water was not calculated since the material lost considerable stiffness, therefore there was a curvature to the composite beam during loading.

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Appendix C. Experimental and Computational Investigation of Blast Response of Carbon-Epoxy Weathered Composite Materials

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ABSTRACT

An experimental study, with corresponding numerical simulations, was conducted to investigate the blast response of weathered Carbon-Epoxy composite plates. The dynamic behavior of the composite plates with and without prior exposure to an aggressive marine environment was explored using a shock tube apparatus coupled with a high speed photography system. In order to simulate prolonged exposure in an aggressive marine environment, specimens were submerged in an elevated temperature, 3.5% salt solution for 0, 30 and 60 days. The saline solution temperature was maintained at 65°C to accelerate the aging process. Finite element modeling (FEM) for the blast loading experiments was performed using the Ls-Dyna code. Models have been developed for both the simply supported and fixed boundary condition cases.

Tensile and four point bend tests were performed to characterize the quasi-static mechanical behavior of the composite material before and after prolonged exposure to aggressive marine environments. After 30 and 60 days of submergence, the tensile modulus decreased by 11% and 13%, the ultimate tensile strength decreased by 12% and 13%, and the ultimate flexural strength decreased by 22% and 22%, respectively.

Dynamic blast loading experiments were performed on simply supported and fully clamped specimens, to determine the effects of the boundary conditions on the Carbon-Epoxy specimen response. The Weathered (30 and 60 days) and Non-Weathered (0 day) specimens displayed dramatically different behavior after being subjected to a blast load. For the simply supported case, Non-Weathered specimens displayed an average maximum out of plane displacement of 20 mm and recovered elastically. Weathered specimens, both 30 and 60 days exhibited similar initial transient behavior but failed

catastrophically due to through thickness cracking at the point of maximum deflection. For the fixed boundary condition, the Non-Weathered specimens displayed an average maximum out of plane displacement of 5.57 mm, whereas the 30 day and 60 day weathered specimens displayed a maximum out of plane displacement of 6.89mm and 6.96mm, respectively. The corresponding numerical simulations matched well with the experimental data. However, for the fixed boundary case, the beam vibration of the simulation was off phase with the experimental results due to imperfect boundary conditions in the experiments.

KEYWORDS

Accelerated Weathering; Composite; Shock Physics

1. INTRODUCTION

A series of experiments were conducted to study the blast response of weathered Carbon-Epoxy composite plates subjected to simply supported and fully clamped boundary conditions. The blast loading was created using a shock tube and the structural response of the composite plate was recorded using high speed photography in conjunction with a 3D Digital Image Correlation (DIC) technique used to obtain full-field data.

In the marine community there is an increasing interest to use composite materials for the construction of structures due to their high strength to weight ratio, reduced radar signatures, and noise dampening properties [1]. Composite materials have been used to create small parts within ships such as fins and rudders, thus reducing the weight of

vessels [1]. However, composites have lower impact resistance than steels and can degrade due to the undersea environment. Thus, studying the effects of the degradation of mechanical properties of composite materials, in particular on shock response, is of high priority.

To date, there have been numerous studies on the mechanical response of composite materials subjected to a dynamic loading. Abrate has written a detailed review of literature on the impact of laminated composites [2]. The review covers work from the late 1970s to early 1990s with a focus in discussing the experimental and theoretical approaches of early composites work. In the 2000s work by Zaretsky et al [3] and Yuan et al [4] focused on the damage of composite materials when subjected impact loading, specifically low velocity impacts. Current studies by Avachat and Zhou [5] have experimentally and computationally modeled the dynamic failure of sandwich composites subjected to underwater impulsive loads. However, these studies did not focus on the effect of aggressive marine environments on the dynamic response.

Accelerated life testing methods simulate long term exposure to marine environments are used to study the effects of exposure on the mechanical properties of materials. In these investigations, composite materials are subjected to marine aging through submersion in seawater baths at elevated temperatures [6-14]. Nakada and Miyano [15] have developed prediction methods for the long term fatigue life of fiber reinforced plastic (FRP) laminates under elevated temperature and absorption conditions. The long term effect of submersion on composite sandwich structures was studied by Siriruk et al [16] with a focus on the interface between the face sheets and the core. Park et al [17] presented the effects of aging after an impact event on polymer

composites. Submersion studies focus on the degradation of material properties due to the diffusion of water into the composite. Elevated temperatures are used to increase this rate of diffusion, therefore requiring additional data to determine the relationship between the exposure time in the accelerated life test and an equivalent time in a typical operating environment.

Diffusion studies to find an acceleration factor relating ALT submersion times to an equivalent time at operating temperatures have been conducted, including studies involving weight gain monitoring of samples to find diffusion coefficients [18]. Rice and Ramotowski [19] used the Arrhenius equation to derive a method for finding this acceleration factor using the matrix material of the composite. The acceleration factor was found to be dependent on the experimentally determined activation energy of the matrix.

Computational investigations of the mechanical response of composite materials have become more prevalent in recent years. LeBlanc et al. [20] were able to correlate experimental results of the dynamic shock response of composite plates with finite element simulations using LS-DYNA. Arbaoui et al. [21] investigated modeling the response of composites in a split Hopkinson pressure bar (SHPB) experiment and were able to successfully correlate experimental data to their simulations.

In the current study, the blast responses of weathered and Non-Weathered Carbon-Epoxy plates are compared. Additionally, computational models for the 0 and 30 day submergence conditions are developed to simulate the dynamic experiments. The simulations are shown to have good correlation to the experimental results.

2. MATERIAL AND SPECIMEN GEOMETRY

The composite material used in this investigation is a Carbon-Epoxy (CE) plate produced by Rock West Composites. The carbon fiber is a 2x2 twill weave cured in an epoxy resin. The plate is 2.92 mm thick and composed of a 670 GSM 12k carbon fiber fabric (Aksaca 12K A-42) and PT2712 low viscosity epoxy produced by PTW&W Industries, Inc. Fiber volume fraction of the material is ~60%. The total thickness of the Carbon-Epoxy plate is made up of four twill woven plies, and the density of the composite is 1.45 g/cm³. An image of the composite material and the fiber construction is shown in Figure C.1.

Figure C.1. Zoomed representation of the 2x2 twill weave fiber composite plate

The specimen dimensions for the different experiments are shown in Table C.1. Dimensions were chosen to meet experimental specifications including ASTM standards D3039/D 3039M- 000 (tensile) [23], D7264/D7264M-07 [24]: Procedure B (four point bend) and prior shock tube studies [28]. Prior to mechanical testing, all specimens were desiccated for 48 hours to remove accumulated atmospheric moisture.

Table C.1. Composite specimen dimensions by experiment type

Experiment Type	Tensile	Four Point Bend	Shock tube
Dimensions (L cm x W cm)	25.4 x 2.54	15.24 x 1.27	20.32 x 5.08

3. EXPERIMENTAL SETUPS AND METHODS

To obtain the blast response of the Carbon-Epoxy composite, the specimens were subjected to blast loading using a shock tube apparatus. Prior to blast loading, the specimens underwent a procedure to artificially accelerate the underwater aging of the material. The experimental details of the blast generating apparatus, high speed photography data acquisition, weathering process and the quantification of accumulated weathering are described in detail below.

3.1. Shock Tube Apparatus

A shock tube apparatus is used to generate a pre-determined amplitude of blast loading that is imparted to the composite plates. High speed cameras, coupled with 3D DIC were used to record the side and back face transient response during loading. A schematic of the shock tube setup along with high speed cameras is shown in Figure C.2.

Figure C.2. Shock Tube apparatus with high speed camera setup

The 8 meter long shock tube is composed of four separate sections: driver section, driven section, converging conical section, and reduced diameter muzzle. A 0.127 mm thick Mylar diaphragm separates the driver and driven sections, while the driver section is pressurized using helium gas. Under a critical pressure of ~ 0.25 MPa, the diaphragm bursts, releasing a high pressure wave. The high pressure travels down the length of the driven section and develops into a shock wave front. The shockwave then reaches the muzzle section, and the pressure of the event is captured by two piezoelectric pressure transducers that are mounted flush to the interior of the muzzle. The shockwave then impacts the specimen and the pressure from the impact is reflected back into the muzzle. The reflected pressure is the loading that the specimen experiences. Figure C.3 (a) is a plot of the pressure created by the shock tube apparatus as a function of time, as recorded by a pressure sensor 20 mm from the end of the muzzle exit for the simply supported case. Figure C.3 (b) shows the pressure history for the clamped plates.

Figure C.3. Shock tube pressure profile for (a) Simply supported composites and (b) Fixed supported beams

3.2. Digital Image Correlation (DIC)

High speed photography coupled with 3D DIC was utilized to capture full field displacements and velocities on the back surface of the specimens during blast loading. Two Photron FastCam SA1 cameras, coupled with 3D DIC, were used to track the 3D displacements of the composite plates during blast loading, while a side view camera is positioned to record the out of plane displacements. The specimen was positioned vertically with the muzzle normal to the specimen, with a gap of (~ 0.1 mm) between the muzzle face and specimen. The processing of the high speed images from the experiments was performed using the VIC-3D software package, which matches common pixel subsets of the random speckle pattern between the deformed and undeformed images. The matching of pixel subsets was used to calculate the three-dimensional location of distinct points on the face of the plate. This provided full field displacement history of the transient event. For the blast experiments, a frame rate of 50,000 fps was utilized for an inter-frame time of $20\mu\text{s}$.

3.3. Accelerated Weathering Facility

A submergence tank was created to subject the composite plates to an elevated temperature saline solution. The tank is composed of two high temperature polypropylene reservoirs. A double wall was created by placing the volumetrically smaller tank inside of the larger tank, creating a fluid boundary to separate the immersion heaters from the internal salt solution, and prevent any unwanted salt water corrosion. A 3.5% salt solution fills the internal tank where specimens were submerged for 30 and 60 days. The immersion heaters in the external tank were used to heat the external boundary of deionized water and through convection and conduction, heat the internal saline solution. The outer tank is insulated and maintained at 65°C which was chosen to increase the rate of water diffusion in the composite material, while remaining below the published 71.7 - 95.6 °C glass transition temperature range of the composite's epoxy matrix. The immersion heaters chosen to heat the submergence tank were Cole Parmer PolyScience LX Immersion Circulators. The maximum capacity of each heater is 20 liters of fluid with a temperature range of ambient to 98°C. Temperature stability is $\pm 0.07^{\circ}\text{C}$. Figure C.4 shows a schematic of the weathering facility.

Figure C.4. Accelerated Weathering Facility

3.4. Determining the Acceleration Factor

The dominant factor contributing to material degradation during prolonged submersion is fluid absorption in the matrix. In order to mathematically relate the experimental submergence of the composite plate to actual service submergence time, a water diffusion study of the matrix material was conducted. The study assumes that the only factor in the degradation of the composite is the accumulated water in the matrix material via diffusion. The relationship between the accelerated life test and service time immersion is governed by the Arrhenius equation. This equation describes the temperature dependence of the rate of reaction for a given process.

$$k = Ae^{\frac{-E_a}{RT}} \quad \text{Equation C.1}$$

Where k is a rate constant, A is a prefactor, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature. A series of three salt water solutions were prepared, and maintained at different temperatures, T_a , T_b and T_c , to determine the diffusion coefficients and water saturation limits for the epoxy matrix. The spread of diffusion coefficients at various temperatures produced Arrhenius activation energy values for the matrix material, mathematically related to an Acceleration Factor (AF). Disks of the matrix material were submerged in 3.5% saline solution and their weight recorded periodically until the saturation limit was reached. To calculate the diffusion coefficient, the following expression can be used. [27]

$$\frac{m_t}{m_s} = \frac{4}{h} \sqrt{\frac{Dt}{\pi}} \quad \text{Equation C.2}$$

where m_t is the mass of water absorbed at the time t , m_s is saturated water mass, D is the diffusion coefficient, and h is the disk thickness. The diffusion coefficient can be

determined through a simplification of Equation C.2 when specimens reach 50% of the total saturation. A solution of the diffusion coefficient is approximated as:

$$D = 0.049 \frac{h^2}{t_{50}} \quad \text{Equation C.3}$$

where t_{50} is the time it takes to reach 50% of total saturation. Recasting Equation C.1 to reflect the diffusion coefficient gives the following expression:

$$D = D_o e^{-\frac{E_a}{RT}} \quad \text{Equation C.4}$$

where D_o is an arbitrary constant. Equation C.4 can be rewritten as

$$\ln(D_T) = \ln(D_o) - \frac{E_a}{RT} \quad \text{Equation C.5}$$

The acceleration factor, AF , is the ratio between the normal working condition reaction rate and a higher test reaction rate. Using equation C.5 the acceleration factor is obtained [22]

$$AF = e^{\left(\frac{E_a}{R}\right)\left(\frac{T_2 - T_1}{T_1 T_2}\right)} \quad \text{Equation C.6}$$

where T_1 is the theoretical service temperature and T_2 is the accelerated weathering temperature. To determine the AF , a diffusion study was performed. Three beakers of 3.5% salt solution were prepared and maintained for 60 days at different temperatures: 22°C, 45°C, and 65°C. Three epoxy disks of PT2712 were submerged in each of the three beakers to ensure repeatability at each temperature. All 9 epoxy disks were desiccated for 48 hours to remove moisture and the mass recorded before submergence. Throughout the duration of the experiment, epoxy disks were periodically removed from their beaker, dried, weighed, and placed back in their respective beaker in accordance to ASTM D5229 / D5229M – 14 [29]. The percent mass increase was recorded for all epoxy disks for 60 days, and plotted versus time.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The Carbon-Epoxy composite material was subjected to prolonged submergence in a saline solution at high temperature to increase the rate of weathering. A diffusion study was performed to relate the experimental weathering time to service time and quasi-static tests were conducted to determine the effects of weathering on the mechanical behavior of the composite material. In order to evaluate the dynamic behavior of the Carbon-Epoxy composite, shock tube experiments were performed to characterize the effects of weathering on the dynamic response of Carbon-Epoxy composite. The dynamic response of the Carbon-Epoxy composite was also compared with numerical results.

4.1. Acceleration Factor Results

The average percent increase in the mass of the epoxy disks for each temperature as a function of time is shown in Figure C.5 (a). Total saturation was obtained by the 65°C samples at 60 days and the remaining temperature trials reached at least 50% saturation during the trial t_{50} .

Figure C.5. (a) Epoxy mass increase over time (b) Activation energy calculation

Knowing the t_{50} value and the thickness of the material, the diffusion coefficient D was calculated. Figure C.5 (b) shows the natural log of D plotted vs. $1/T$. The slope of the linear trend gives the activation energy of the epoxy matrix. The AF is then solved for, with the experimental submergence temperature (65°C), and is displayed in Figure C.6 (a) and as a function of temperature. Figure C.6 (b) shows that with a decrease in service temperature, the AF will increase. Similarly, with increase in service temperature, the AF will decrease.

From the diffusion study, the calculated acceleration factors range from 48 to 18, corresponding to service temperatures of 10°C to 22°C respectively. With 30 days of accelerated ageing the real weathering time will be between 1.5 to 4 years of aging due to diffusion, depending on service temperature. For 60 days, the range is between 3 and 8 years. Since the diffusion of water into the epoxy matrix is a dominant factor contributing to composite material degradation, the calculated AF is a strong estimate used to correlate experimental versus service weathering times. However, it should be noted that after prolonged accelerated ageing, there is possible debonding between the fibers and the matrix, leading to further material degradation.

Figure C.6. Acceleration factor (a) exponential variation of AF versus an increase in service temperature (b) visual representation of AF at various service depths

4.2. Quasi-Static Test

Material testing was performed to establish the quasi-static mechanical properties of the composite material before and after accelerated environmental exposure. The average quasi-static behavior of the material before and after submergence is listed in Table C.2. From the quasi-static results it is shown that prolonged submergence reduced the modulus and strength of the Carbon-Epoxy significantly from the Non-Weathered material. The change in quasi-static results between 30 and 60 days is minor which corresponds to the fact that the matrix reached total saturation at 30 days. Since the majority of the degradation effects are accumulated during diffusion, this supports the assumption that water diffusion into the epoxy material is the primary factor in degradation of the mechanical properties of the composite to the ageing time frames considered in this study.

Table C.2. Quasi-static properties after various submergence times

Weathering Case	0 Days	30 Days	60 Days
Tensile Modulus (GPa)	53	47	46
Ultimate Tensile Strength (MPa)	563	496	492
Ultimate Flexural Strength (MPa)	4545	426	424

4.3. Shock Tube Experimental

The following experimental results of the shock tube study compare the Weathered (30 days) and Non-Weathered (0 days) cases. Weathered experiments for 30 and 60 days show similar quasi-static and dynamic behavior, so the 60 day weathering case will not be presented. The comparison between 0 and 30 day blast scenarios will suffice. Two different support conditions for the plate under dynamic loading were considered; a simply supported case and a fixed boundary support. Figure C.7 shows a schematic of the simple support boundary and of the fixed boundary case.

Figure C.7. Simply supported and clamped support experimental schematic

The simply supported case is considered first. The 3D DIC full field out of plane displacement of the Non-Weathered and Weathered cases are shown in Figure C.8 (a). The full field out of plane displacement are on the same scale, from 0 to 40 mm. From 0 to 1 ms, the Non-Weathered and Weathered composite specimens display similar out of plane displacements, however the change in behavior can be noted at 1.2 ms. While the Non-Weathered composite maintains, the Weathered composite buckles at 1.4 ms at the moment of maximum deflection. At 1.6 ms, a crack develops through the thickness of the composite plate leading to a complete through thickness fracture of the plate.

Figure C.8. (a) Full field out of plane displacement evolution for simply supported case (b) Center point out of plane displacement from 3D DIC

Using the full field 3D DIC data, the center point out of plane displacement is plotted for the 0 and 30 day weathering cases in Figure C.8 (b). Observed cracking of the 30 day weathered composite is determined to be at 1.6 ms from the 3D DIC. The rate of deformation remains consistent between experiments, but the load bearing capacity significantly decreases, as an effect of weathering, leading to brittle catastrophic failure.

After 30 and 60 days of weathering the damage mechanisms leading to catastrophic failure showed different behavior. Due to brevity, the images captured by the side

camera are not presented. However, from the side view images, delamination is seen developing from the compression side of the specimen, further propagating through the composite thickness. Commonly, continuous fiber composites do not behave well in compression due to the localized fiber buckling under compression. This behavior typically leads to localized buckling of the material while in compression. After significant time in submergence, the matrix material's mechanical properties inevitably deteriorated leading to failure in compression. This failure, therefore, compromised the structure leading to crack propagation in the composite laminate. The fibers in the post mortem images are short in nature meaning brittle, catastrophic failure occurred through fiber fracture rather than fiber pullout. Additional quantitative evidence of matrix initiated and matrix dominant failure is apparent in the DIC, in-plane strain data. The maximum strain achieved prior to through fracture in all weathered experiments is between 1.6-1.7%. The failure strain of the carbon fiber is 2.1% and for Carbon-Epoxy composite it is 1.7% [25]. This implies that while the damage occurs during the dynamic blast loading, the carbon fibers have not reached their failure limit. Thus, during blast loading matrix cracking and delamination happens first leading eventually to fiber failure.

The case for the fixed boundary investigates the effect of zero displacements and rotations at the boundaries. In order to fix the boundaries of the composite, two vice clamps with knurled grips were utilized. Figure C.9 (a) shows the 3D DIC images of the full field behavior for the Non-Weathered and Weathered cases. Throughout the duration of the shock, the behavior of the composite material displays similar out of plane displacement for both weathering cases. Unlike the simply supported case, where

the 30 day weathering case fractured, with fixed boundaries, the 30 day weathering case returns to its original undeformed state. For the simply supported case, the maximum moment is at the center of the plate, thus it fails at that region. However, for the fixed boundary case, the maximum moments are at the boundary, which increase the rigidity of the plate, and lowers the center point deflection. It should be noted that the maximum moment for the fixed-fixed boundary case is lower than the maximum moment for the simply supported case. The maximum out of plane displacement occurs at ~ 0.6 ms for the fixed boundary case. The center point displacement history for this case is given in Figure 9 (b).

Figure C.9. (a) Full field out of plane displacement evolution for Fixed-Fixed boundary (b) Center point out of plane displacement from 3D DIC data

Both weathering cases reached the maximum out of plane displacement at similar times. However, the 30 day weathering case reached a larger magnitude of center point displacement, indicating a reduction in stiffness of the material due to ageing. The magnitude in out of plane displacement increased by a factor of 23.75 % between the Non-Weathered and the 30 day weathered case. At ~ 5 ms, the 30 day weathered case reaches a region where the specimen no longer goes through beam oscillations, and the

displacement linearly decays to zero. This behavior implies that the strain energy stored in the 30 day weathered case dissipated at a faster rate than Non-Weathered case. It should be noted that the fixed boundary condition case does sustain minimal grip slippage of less than 0.5 mm. Due to the slight slipping at the boundaries, the ability of the specimen to recover is hindered, since the material that slipped out of the clamps during the outward deflection will encounter a resistive frictional force while it slips back into the clamps during specimen recovery.

5. FINITE ELEMENT MODELING

Finite element modeling (FEM) for the blast loading experiments was performed using the Ls-Dyna code available from the Livermore Software Technology Corporation. Models have been developed for both the simply supported and fixed boundary condition cases. Based on the mechanical testing which indicated minimal additional material degradation beyond 30 day ageing, the 60 day weather scenario is not considered in the FEM study. All simulations were performed with Ls-Dyna release 6.1.1 in double precision mode.

5.1. Finite Element Model Description

The models for the simply supported and fully fixed boundary condition configurations are shown in Figure C.10 (a). In each of the models the composite specimens were modeled with fully integrated solid elements and consist of 4 through thickness elements. Each layer represents one of the 4, 2x2 twill woven plies in the plate. In the simply supported model, the full length of the 19.7 cm specimen is modeled

with the pin supports located at 15.2 cm center-center spacing. Automatic Surface to Surface contact is defined between the pins and the back face of the plate. The full length of the specimen is accounted for to allow the plate to slide against the pins as the out of plane deflection occurs. In the fixed boundary condition configuration, only 15.2 cm of the specimen is modeled with all degrees of freedom along the top and bottom edges fixed. This approach is taken for computational efficiency as any additional elements beyond the fixed edge would also be fully fixed and thus sustain no strain or deformation. The material model used in the numerical simulation is the Mat_Composite_Failure_Option_Model (Mat_059, Option = Solid). This is an orthotropic material definition capable of modeling the progressive failure of the material due to any of several failure criterion including tension / compression in the longitudinal and transverse directions, compression in the through thickness direction, and through thickness shear. Mechanical properties determined from the quasi-static experimentation were used to create the model. Although mechanical properties are known to change with respect to the rate of loading, the quasi-static properties for each weathering scenario were sufficient to conduct the numerical study. The support pins were modeled as linear elastic steel with appropriate material properties.

The blast loading was applied to the surface of the composite plate by applying the pressure profile measured during the respective experiments to the composite specimen in the models. This ensures that there is consistent loading between the model and experiments. Due to the width of the specimens being larger than the internal diameter of the shock tube, there is a need to numerically capture the spreading of the pressure over the specimen surface that occurs as the plate deforms outwards. During the onset

of loading there is a uniform pressure loading over the central circular area corresponding to the inner shock tube diameter which is equal to the pressure recorded during the experiment. However, as the specimen deforms outwards there is a “venting” of the gas as a gap forms between the shock tube face and the specimen. This results in an expanded loading area over the face of the plate which is assumed to vary linearly from the measured pressure profile at the inner surface of the shock tube to zero at the outer edge of the plate. The linear variation in pressure is accounted for in a stepwise fashion as shown in Figure C.10 (b). A similar computational approach is documented by Yazici et al [26].

Figure C.10. (a) Finite element model details. (b) Pressure loading schematic

5.2. Finite Element Model Correlation to Test Data

The correlation of the finite element models to the corresponding experimental results consists of comparisons between pointwise (centerpoint) time histories as well as the full field deformation profiles. A comparison between the experimental and finite element simulation full field out of plane displacement for the simply supported case is shown in Figure C.11.

Figure C.11. Full field simulation and experimental visualization

The center point displacement data captured during the experiments with the DIC method is used as a pointwise time history basis to correlate and validate the finite element model results. The center-point time history correlation between the experimental data and the corresponding computational simulation for the simply supported and fully fixed boundary condition configurations are provided in Figure C.12 and Figure C.13, respectively. The correlations presented show that there is a high level of agreement between the experiment and simulations, both temporally and in terms of displacement magnitudes. For both the simply supported and fully fixed conditions the simulation and experiment results exhibit nearly consistent results during the initial deformation up to the point where maximum value is obtained. For the 0 Day Simply supported case the model results display a slightly faster recovery after maximum out of plane displacement although the rise time and peak displacement are in excellent agreement. For the fixed support condition models, both 0 and 30 day weathering, it is seen that although the rise time and maximum displacement values are in very good agreement, the numerical models recover significantly more rapidly than the corresponding experiments. The authors believe that this difference in the recovery process between the model and experiments is due to the difficulty in matching a “Fully Fixed” numerical boundary condition to a corresponding experimental condition.

During the experiments the composite specimens were clamped between two grips on the top and bottom to provide maximum gripping force. However, due to the forces involved during the blast loading, a minimal amount of material slippage was observed during the out of plane deformation process as a result of the material being “drawn” in from the grips. During the recovery phase this material must be forced back into the grips, which tends to slow down the process as compared to the numerical model. Even a very small amount of material slippage within the grips has the effect of “shortening” the length of a buckled beam and preventing a return to its un-deformed shape. Finally, it is seen from Figure C.12 that the onset of damage for the 30 Day Simply Supported case occurs slightly later than the corresponding experimental fracture. Although the computational models utilize experimentally based values of compressive and tensile strengths, these values are a nominal value representing a statistical basis of multiple tests and the true value for any given specimen is +/- from that average. Furthermore, the models assume a uniform specimen in terms of material properties and does not account for manufacturing variability or minor internal defects which can contribute to the onset of damage or slightly weaker/stronger areas of the plates as compared to the gross material strengths. That the model is able to predict the onset of damage in a consistent manner as observed during the testing is significant. Overall, it is shown that the models are able to accurately predict the transient response of the composite specimens, particularly the initial rise and peak displacement.

Figure C.12. Simply supported condition – Center point time history correlation

Figure C.13. Fixed support condition – Center point time history correlation

6. CONCLUSIONS

A series of experiments were conducted to investigate the dynamic behavior of Carbon-Epoxy composite materials after the specimens were subjected to aggressive marine environments. A 3D DIC technique was utilized with high-speed photography to record the dynamic behavior due to blast loading of said materials. Based upon experiments performed to study effects of prolonged submersion, it was concluded after significant salt water exposure, the mechanical properties of a carbon/epoxy composite material were degraded. The summary of the results are as follows:

- The diffusion study showed that the AF for the composite material ranged from 18 to 48. This corresponds to a range of service temperatures from 22 °C to 10 °C. The actual aging time of the composite ranges from 1.5 to 4 years for 30 days of submergence and 3 to 8 years for 60 days of submergence.
- After 30 days of exposure, the quasi-static mechanical properties decreased significantly. The tensile modulus, tensile strength, and ultimate flexural strength decreased by 11%, 12%, and 22% respectively.
- After 60 days of submergence the quasi-static mechanical properties of the composite essentially did not change from the properties at 30 days submergence.
- Shock loading experiments displayed vastly different behavior with respect to 0 day versus 30 and 60 day exposures.
 - For the simply supported case, the Non-Weathered (0 day) composite plates displayed maximum out of plane displacement on average of ~20 mm. After multiple oscillations the plates elastically returned to their original form. Internal damage was not measured/quantified post mortem in these experiments.
 - For the simply supported case, the 30 and 60 day plates showed similar out of plane displacements versus time as the 0 day specimens, but catastrophically failed at roughly 20 mm. The plates displayed delamination on the compression face of the.
 - It can be concluded that brittle-like failure occurred throughout the dynamic event since the region of failure there was visible evidence of short fibers, thus implying fiber fracture rather than fiber pullout.
 - For the fixed-fixed support case, the Non-Weathered (0 day) composite displayed a maximum out of plane displacement of 5.57 mm. The fixed boundary restrained the

out of plane displacement of the plates and thus sustained lower deflection magnitudes than the simply supported case.

- For the fixed support case, the 30 day and 60 day plates showed similar out of plane displacements. However, the frequencies of beam oscillations in these cases were lower than the 0 day case. This is due to the reduction in the stiffness of the material with ageing.
- The numerical results for both boundary conditions are in good agreement with the experimental data.

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