Composite Structures xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Hydrostatic and blast initiated implosion of environmentally degraded Carbon-Epoxy composite cylinders

Carlos Javier, Helio Matos, Arun Shukla*

Dynamic Photo Mechanics Laboratory, Department of Mechanical, Industrial and Systems Engineering, University of Rhode Island, Kingston, RI 02881, United States

ARTICLE INFO

Keywords:
Accelerated weathering
Implosion
Service life
Composites
Shock

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.

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

---

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

https://doi.org/10.1016/j.compstruct.2018.04.055
Received 14 February 2018; Received in revised form 12 April 2018; Accepted 16 April 2018

Please cite this article as: Javier, C., Composite Structures (2018), https://doi.org/10.1016/j.compstruct.2018.04.055

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 1 summarizes the experimental cases and their details.

The composite tubes consisted of seven filament-wound plies of carbon fabric in a [± 15/0/ ± 45/ ± 15] layup. The tubes were manufactured by Rock West Composites (West Jordan, UT), with a wall thickness of 1.65 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, 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

Table 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