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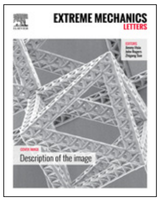

Dynamic collapse mode evolution in carbon composite tubes

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A R T I C L E   I N F O

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A B S T R A C T

An experimental study on the hydrostatic implosion of carbon-fiber reinforced epoxy composite tubes is conducted to explore unique failure and damage mechanisms of collapse. Experiments are performed in a pressure vessel designed to provide constant hydrostatic pressure through the collapse. Filament-wound carbon-fiber/epoxy tubes are studied using high-speed photography to explore the effect of complex damage on the modes of failure. 3-D Digital Image Correlation technique, which is first calibrated for the underwater environment, is used to capture the full-field deformation and velocities during the implosion event. Fourier Series deformation models are used to extract buckling modes from displacement data. The results reveal that the presence of damage in the structure can cause the mode shape to change as the structure deforms.

1. Introduction

Composite materials have attracted significant attention in underwater marine applications due to their promise of reduced weight, improved corrosion resistance, and for submerged structures, greater potential operating depths. These advantages drive an increase in the presence of these materials in marine industry, such as in sonar domes, masts, and hull sheathings [1]. One of the greatest obstacles to widespread adaptation of composites is a lack of complete understanding of these materials, especially under extreme loading conditions [1]. Recent work by the authors has sought to expand the current knowledge of composite behavior by examining the problem of implosion [2].

An implosion is a structural failure that can happen to a thin-walled structure that contains a low pressure fluid and is subjected to high external pressure. When the external pressure reaches a critical value, instability in the structure occurs, resulting in a rapid and often catastrophic collapse. During this collapse, the boundaries of the structure and surrounding fluid are accelerated to high velocities and suddenly stop once the collapse is completed. This abrupt change in momentum releases a pressure wave into the surrounding fluid, which can damage nearby structures [3–5]. The implosion of glass spheres as well as metallic tubes has been studied by several authors who characterized the pressure pulse emitted during collapse as well as the mechanics of the collapse itself [5–10]. However, significantly less understanding exists of the implosion of composite materials, and existing studies mainly focused on determining critical pressures [11–14]. In none of these studies were deformations studied in real-time during the implosion event.

This work seeks to expand understanding of the mechanics of the collapse of composite tubes by investigating the dynamic evolution of the collapse shape throughout the implosion event, and in the presence of damage. It is demonstrated that due to changes in stiffness brought about by large-scale damage, the collapse shape may change dramatically, which can have consequences in the resulting pressure field.

2. Materials

The composite structures in this study are filament-wound carbon/epoxy tubes with an inner diameter of 60.3 mm. These tubes consist of seven layers of unidirectional carbon fabric reinforcement arranged in a

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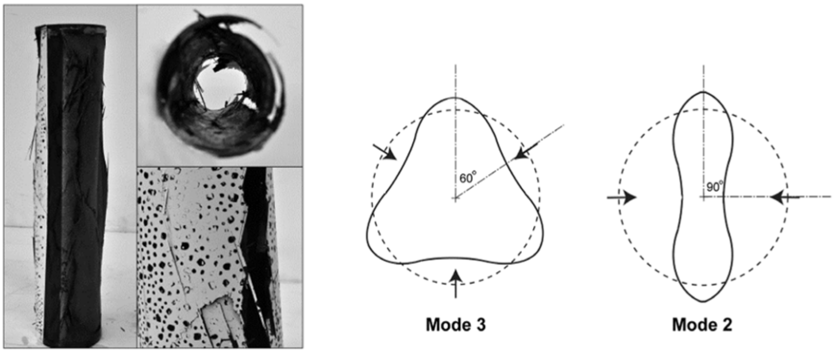

Fig. 1. Post-mortem of imploded carbon/epoxy tube (left) and illustrations of buckling mode shapes (right).

[±15/90/±45/±15] layup, and are manufactured by Rock West Composites (West Jordan, UT) with a nominal wall thickness of 1.52 mm and an unsupported length of 279.4 mm. The dimensions are selected as to provide specimens with a relatively low expected collapse pressure, and a high R/t ratio (>18) so that thin-wall assumptions may be used. Two experiments are performed in this series to demonstrate repeatability.

3. Experimental procedure

A 2.1 m diameter spherical pressure vessel with a maximum pressure rating of 6.89 MPa is used to provide constant hydrostatic pressure to perform implosion experiments. Several Plexiglass windows mounted about the midspan of the pressure vessel allow the specimens to be viewed by high-speed cameras and adequately lit by two high intensity lights.

Prior to set-up, all composite tube specimens are sealed using aluminum end caps. The specimen is suspended in the center of the pressure vessel using several steel cables. A random, high-contrast speckle pattern is applied to a region covering the entire length of the specimen and approximately half of the circumference using flat black paint. Two high-speed cameras (Photron SA1, Photron USA, Inc.), offset by 17° are used to capture stereo images of the patterned region of the specimen at 36,000 frames/s throughout the implosion event. The stereo images are analyzed using commercially available image correlation software, VIC3D.

3-D Digital image correlation (DIC) is a well known experimental tool used to determine real-time, full-field displacements across the viewable surface of a specimen [15]. This technique is calibrated for underwater experiments based on previous work [16] for confidence in the accuracy of measured displacements and velocities. Using the referenced calibration method, in-plane and out-of-plane measurements may be determined within 1.2% and 2.5% error, respectively.

The vessel is then flooded with water that is filtered for maximum optical clarity, leaving a small air pocket at the top. Once the vessel is filled, nitrogen gas is introduced into the air pocket to pressurize the vessel. The pressure inside the vessel is increased at a gradual rate (0.083 MPa/min) until the specimen collapses, at which time the data acquisition system is triggered.

4. Results and discussion

The two composite tubes in this study collapsed dynamically at a hydrostatic pressure of 1.54 and 1.66 MPa. The collapse pressures and the process of collapse in both the tubes were very similar, thus, data is presented of a single representative case. Upon completion of the implosion, the tubes are seen to collapse in a completely flat mode 2 shape (see Fig. 1). However, it is observed in high-speed images that deformation initiates in a higher order shape early in the event. In addition, post-mortem inspection revealed three longitudinal, through-thickness cracks spaced evenly about the circumference of the tubes at 120° intervals (see Fig. 1). This damage pattern implies a mode 3 collapse shape, which is characterized by three symmetric lobes of maximum deflection spaced at equal intervals about the circumference of the tube (see Fig. 1).

FEA of this specimen, as reported in previous work [2], reproduces the observed critical pressure with excellent accuracy, but also predicts a pure mode 3 collapse shape. This represents the initial stages of collapse quite well, but fails to capture the fully flattened shape of the final collapse. To address these apparent contradictions, DIC is used to generate displacement contours for the entire surface for each recorded image.

The radial displacement across the visible circumference of the tube at its midspan is plotted over the duration of the implosion event in Fig. 2. The dashed line in the image in Fig. 2 illustrates where data was extracted from. In this figure, $t = 0$ ms represents the moment of wall contact at the center of the tube.

In this figure, additional evidence of the observed mode-switching phenomenon is found. Between $t = -3$ ms and $t = -1$ ms, there appears to form a lobe of positive displacement and a valley of negative displacement separated by approximately 60°. A pure mode 3 buckling shape consists of three lobes equally spaced around the circumference of the tube by 120°. This implies that the separation between a lobe and adjacent valley would be 60° (Fig. 1), showing that in the initial stages of deformation, the tube conforms to a mode 3 shape. Following this time, the lobe centered at $\theta = 32°$ appears to spread until it covers the majority of the visible circumference at $t = 0$ ms. This gives evidence that as one lobe begins to dominate the viewable surface, a mode 2 deformation pattern dominates the structure.