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Experimental investigation on dynamic failure of carbon/epoxy laminates under underwater impulsive loading

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ABSTRACT

The dynamic response and failure modes of carbon/epoxy laminates subjected to underwater impulsive loading are experimentally investigated in this work. The effects of impulse intensity and fluid-structure interaction (FSI) on the failure modes of the clamped laminates were also assessed. A lab-scale underwater explosive simulator was utilized to impart the controlled impulsive loading with three different decay times on the laminates. The 3D Digital Image Correlation method with high speed photography was used to capture the dynamic response of the laminates. A series of microscopic examinations was conducted to analyze the failure mechanism of the laminates. The results show that the composite laminates provided higher blast resistance than aluminum plates in the same thickness. The fiber breakage, delamination and matrix crack were the main failure modes of the laminates subjected to underwater impulsive loading. The fiber breakage occurring at the center and the boundary of the plate was mainly caused by the stretching and shear-off, respectively. The damage extent of the laminates was increased with the impulsive loading increasing or FSI parameter decreasing. The results obtained in this study provide a potential application guidance for laminates in marine structure lightweight design.

1. Introduction

Carbon fiber reinforced composites play an important role in the modern naval hull construction design with the significant advantages, including high specific strengths, low specific weight and excellent designed flexibility [1,2]. Monolithic and sandwich constructions are the most common architectures of composite materials applied to build the composite hull, especially in warship and marine structures [3]. These load-bearing structures are exposed to potential damage threats, such as blast loading and impact [4]. The dynamic mechanical behavior and protective performance of the fiber reinforced composites under those extreme loads is of great concern to the shipbuilding industry with the wide and increasing application of composite materials.

In the past few decades, a large number of investigations were concerned with the analysis of the dynamic failure of composite materials subjected to blast loading [5–12]. For instance, Shokrieh [5] proposed a nonlinear equation of motion for laminated composite panels subjected to blast loading. The finite-difference method was used to establish the governing equations of the clamped laminated composite plates, and a progressive damage model was developed to predict the different failure modes based on the modified rules of material properties. Tekalur [6,7] studied the dynamic damage behavior of vinyl ester based carbon fiber composites and E-glass fiber composites subjected to blast loading. The failure modes of the two kinds of composite laminates were

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divided into permanent deformation, fiber breakage and delamination, and the carbon fiber laminates behaved stiffer than the E-glass fiber composite under dynamic loading. Li [8] investigated the effects of the fiber layers ($(0/90)_9$, $(0/90)_{18}$, $(0/90)_{28}$) and curvature radii (R = 500 mm and 250 mm) of laminates on the blast response and failure modes of woven basalt/epoxy panels. The results showed that the curvature could influence the failure modes of the composite panels and the addition of the thickness greatly enhanced the blast resistance of composite laminates. Langdon and Lemanski [9,10] tested the performance of aluminum alloy-glass fiber reinforced polypropylene-based fiber-metal laminates (FMLs) subjected to localized blast loading. They found that the plastic deformation was the main failure mode of the black face, and the maximum deflection of the panel presented a linear relationship with the impulse loading. Kumar [11,12] measured the dynamic response of curved carbon composite panels under air blast loading and used the 3D Digital Image Correlation (DIC) technique to measure the response parameters (the deflection and velocity of out-plane) during the experiments. They found that fiber breakage and inter layer delamination were the two dominant types of the failure mechanisms of carbon composite panels. Huang [13] studied the effects of polypropylene and epoxy on the blast resistance of flax-reinforced composites, and found that flax/polypropylene composite showed the superior shock resistance than flax/epoxy composites.

In underwater blast conditions, the fluid-structure interaction plays a very important role in the dynamic response of composite structures. Thus, it is essential to obtain the failure mechanism of composite panels subjected to underwater blast loading. The seminal works were conducted by Latourte [14] and Wei [15]. They performed a series of experimental investigations on the mechanical behavior of composite panels, and proposed a three-dimensional finite element fluid-structure interaction model to analyze the failure modes and damage mechanisms of glass reinforced plastic composite panels. The delamination process of composite panels was controlled by the impulse loading rate, and the quantitative relationship was built between the distribution of the delamination and the impulse. Recently, the reports of Schiffer and Tagarielli [16,17] presented an analytical model for the dynamic response of the fully clamped cross-ply laminated panels subjected to underwater shock loading. The model could predict that the propagation of flexural waves were along the thickness direction in the panels. Then they used a transparent shock tube apparatus to investigate the dynamic deformation of circular clamped glass/vinyl ester composite panels subjected to underwater impulse loading and the sequence of cavitation events in water. The theoretical predictions were in good agreement with experiments [18]. LeBlanc and co-workers [19–22] studied the influences of laminate modification, panel thickness and panel curvature on the dynamic response of E-Glass/vinyl ester composite panels subjected to underwater explosive loading through the experiments and computational simulations. The 3D DIC technique was used to measure the dynamic deflection of the panels in experiments. The tests and simulation results showed a high level of correlation. Meanwhile, they found that the shock resistance of the composite panels was increased with the thickness and curvature. Based on the researches above, Avachat [23,24] analyzed the damage of composites sandwich structures subjected to underwater impulsive loads and found that the primary failure modes were shear cracking of the front panel and core collapse. Comprehensively, these researches showed that the glass fiber composites presented a significant potential in blast resistance. Carbon/epoxy laminates also presented a broad application prospect in marine structure. However, for carbon fiber reinforced plastics laminates, less attention and few literature were focused on the dynamic deformation and failure mode of laminates subjected to underwater blast loading.

The objective of this study is to investigate the dynamic failure of carbon/epoxy laminates subjected to underwater impulsive loading by the experimental method. The 3D DIC technique with high speed cameras was applied to observe and obtain the real-time deformation and the damage behavior of laminates. The effects of impulse intensity and fluid-structure interaction on the failure modes of laminates were assessed in this research. Additionally, the post-mortem analysis by the optical microscope and scanning electron microscope was conducted to characterize the failure mechanisms of carbon/epoxy laminates.

2. Experimental study

2.1. Experimental setup

In order to analyze the dynamic failure of carbon/epoxy laminates, a lab-scaled non-explosive underwater shock loading simulator was designed to perform the underwater impulsive loading experiments, according to the researches of Deshpande [25] and Espinosa [26]. The exponentially decaying underwater shock wave could be generated by the simulator.

The schematic of the experimental setup is sketched in Fig. 1. The shock tube was a rigid steel cylinder with the length of 750 mm and the inside diameter of 66 mm. The thickness of the tube wall was 7 mm. Along the vertical axis of the shock tube, an aluminum piston with 20 mm thickness was sealed at the front end, and the composite specimen was mounted at the breech end. The tube was horizontally mounted and filled with water. A steel projectile with the diameter of 66 mm was accelerated by the light gas gun to strike the sliding piston for generating the planar impulsive loading in water.

The peak pressure and decay time constant of the underwater impulsive loading can be adjusted by varying the velocity and mass of the flyer plate, respectively [25,26]. The projectiles with three thickness of 5 mm (0.131 kg), 10 mm (0.260 kg) and 15 mm (0.396 kg) were chosen for the experimental tests, as shown in Fig. 2. The velocity of the projectile ranged from 50 to 210 ms^{-1}, monitored by the laser-velocity gate. The pressure histories generated in the shock tube were measured through the high frequency piezoelectric pressure transducers. The pressure transducer consisted of an in-built charge amplifier, an oscilloscope with the rise time less than 1μs and the resonant frequency above 500 kHz. Hence, the effect of loading rate on the deformation and failure behavior of the specimen plates could be delineated in this study.

Two Photron-SA-Z high-speed cameras were used to capture the stereo images of the response of laminates. The image framing rate and resolution were selected at 50000 frames and 384 × 384 pixels in all tests, respectively. In the calibration and post analysis,