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Dynamic response of circular composite laminates subjected to underwater impulsive loading

Wei Huang[a,b,c], Wei Zhang[d,*], Tuo Chen[d], Xiongwen Jiang[d], Jiayi Liu[a,b,c]

[a] School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration (CISSE), Shanghai 200240, China
[c] Hubei Key Laboratory of Naval Architecture and Ocean Engineering Hydrodynamics (HUST), Wuhan 430074, China
[d] High Velocity Impact Dynamics Lab, Harbin Institute of Technology, Harbin 150080, China

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ABSTRACT

The dynamic response and failures of carbon/epoxy composite laminates subjected to underwater impulsive loading are investigated experimentally. The effect of impulsive intensity and thickness of laminates on dynamic deformation, failure modes, and associated mechanisms is identified and quantified respectively. The plates are subjected to underwater impulsive loads of different intensities with a lab-scaled underwater explosive simulator. 3D DIC is employed to capture the dynamic response in terms of response rate, mid-span deflection, and deflection-profile history during the elastic response process, followed by a series of postmortem non-destructive investigation and microscopic examinations to examine the failure modes and its distributions, and analyse the associated mechanisms. The results show that the intensity of impulse, thickness and failure of panels affect the dynamic response of laminate plates significantly. The non-surface failure has very limited influences on the tendency of the deflection-impulse relationship, and the local failure on the surface occurring later than the delamination and fiber fracture through the thickness of laminates. The blast resistance of composite laminates is not enhanced continuously with the increasing thickness due to the inconsistent changes of failure modes. With similar areal mass, meanwhile, composite laminates perform better blast-resistant performance than that of the metallic structures.

1. Introduction

The response of fiber-reinforced composite to both contact-induced dynamic and water-based impulsive loads is of great importance in the design of blast-resistant marine structures for naval and offshore industry applications in which fiber-reinforced composite materials are progressively employed for its high strength-to-weight ratios, high stiffness-weight ratio, and excellent magnetic resistance. However, before such materials can be adopted extensively, a great number of investigations should be devoted to foster understanding and quantification of the dynamic response and failure of fiber-reinforced composite laminates to such high-intensity impact and impulsive loadings.

Studies on the dynamic response and damage of metallic structures subjected to underwater impulsive loads have been interested a few decades. Earlier theoretical and experimental analysis on the dynamic response of rigid plate was conducted by Taylor who concluded that the momentum transmitted to the plate is decreased by reducing the mass of the plate and established the one-dimension fluid-structure interaction model which involves in the cavitation effect [1]. With the scaled down laboratory fluid-structure interaction experiments was exhibited and validated [2,3], a considerable body of literature on the dynamic behavior of beams, plates and shells made of solid and sandwich metal subjected to air and water blast loadings was reported by previous researchers [4–7] who focused on different core topologies, structural geometries and mechanical properties, which indicated that blast resistance of metallic sandwich plates outperforms their solid counterparts at identical areal mass when they are subjected to underwater impulsive loading.

Composites are anisotropic elastic solids and they exhibit a response which results in a full spectrum of elastic waves propagating in the radial direction as subjected to transverse impulsive loading [8]. Previous studies on the dynamic response of composite laminates mainly focused on the contact-based impulses such as drop weight and projectile penetration [9,10]. Corresponding results show that the dominant failure modes of composite laminates include matrix cracking, fiber breakage, and interlaminar delamination. Hashin [11] indicated that matrix material, composite layup and geometric aspects such as

* Corresponding author.
E-mail address: zhdawei@hit.edu.cn (W. Zhang).

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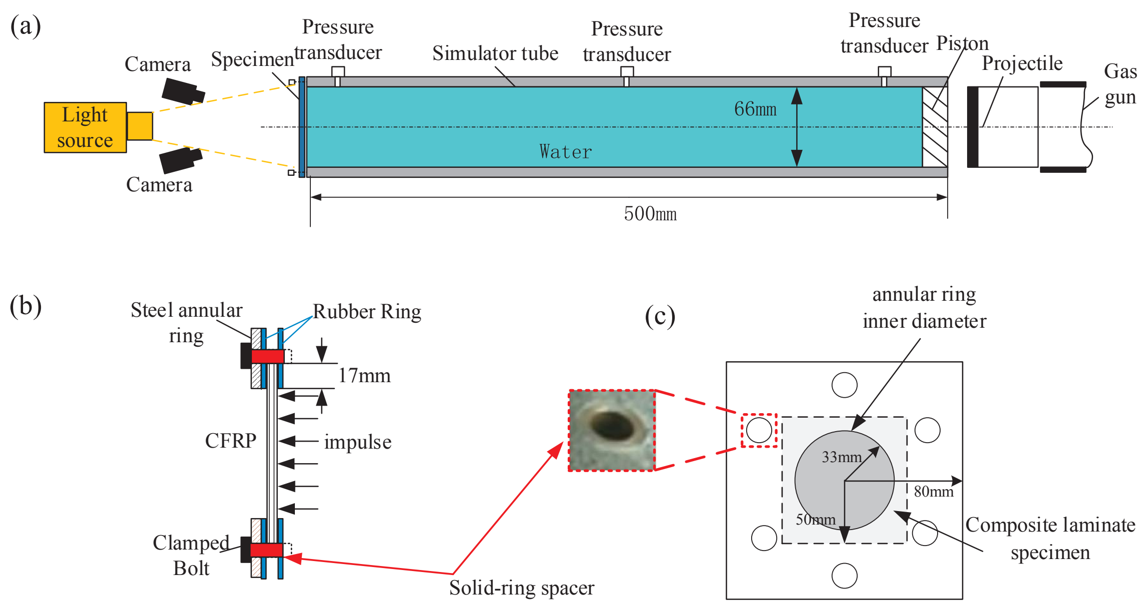

Fig. 1. Sketch of the air-backed fluid-structure interaction experimental setup, (b, c) boundary condition of the composite laminate specimen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

size, thickness, and loading area are significant factors on the failure modes of composite laminates. Heimbs et al. [10] conducted experimental and numerical investigations on the impact behavior of CFRP laminates subject to high-speed impact and observed that there is fiber failure in addition to delamination and matrix cracks as impact velocities close to the ballistic limit. Other authors [12–16] employed theoretical and experimental approaches to study the dynamic response and failure mechanisms of laminates subjected to high-speed impact loads by taking the impact angles, fiber orientation, and the curvature of panels into account. Li et al. [17] studied the dynamic failures of flat and single-curved woven basalt/epoxy laminates subjected to air blast loading experimentally, demonstrating that failure mechanism is influenced by the curvature and thickness of laminates. Meanwhile, the fiber-reinforced composite laminates are extensively used as face sheets of composite sandwich structures with foam or wood cores which are proved as outperformed blast-resistant structures [18,19].

Underwater blast loading of submerged structures leads not only to dynamic response of structures but also to the complicated fluid-structure interaction effect (FSI) in surrounding water. Using the fluid-structure interaction experimental setup, LeBlanc and Shukla [20] employed the strain histories obtained from experiments and computations to study the failure modes and energy dissipation by the E-Glass/Epoxy laminates. Latourte et al. [21] identified and quantified the failure modes, damage mechanisms and their distributions of glass-reinforced composite laminates and sandwich structures subjected to underwater impulses. Blast-resistance improvement of sandwich versus monolithic composite panels was, therefore, established specially at sufficiently high impulses per areal mass [21–23]. Zhou [24] performed experimental study concerning the role of fiber orientation, fiber stiffness and angle of structure obliquity on the blast resistance of monolithic carbon-fiber and glass-fiber/epoxy composite. A theoretical model that considered the transverse shear was established by Schiffer and Tagarielli [25]. In the model, the propagation of flexural waves in the plates as well as fluid-structure interaction prior and subsequent to water cavitation are taken into account. Then, Schiffer and Tagarielli [26] presented experiments and numerical simulation to study dynamic deformation and failure of glass/vinylester and carbon/epoxy composites as well as the sequence of cavitation events in water. Despite there is increasing interest in the mechanical response of fiber-reinforced laminates subjected to impulsive loading recently, only limited study has been reported on the composites to underwater impulses, and very limited experimental data exists concerning the dynamic response. The lack of the design relations that quantify the dynamic response and failure modes as functions of geometrics of laminates and varying loading intensities, and the diagnostics that provides in-situ, time-resolved response measurements make it necessary to conduct experimental studies comprehensively on the composite laminates.

The objective of the present study is to characterize the dynamic response and failure of carbon/epoxy fiber-reinforced composite (CFRP) laminates subjected to underwater impulsive loading, using the fluid-structure interaction experimental setup. Dynamic response parameters, including response time, response velocity, maximum transverse deflection and deflection-profile history, are analyzed for the fiber-reinforced composite laminates by employing the 3D digital imaging correlation analysis. Deflection resistance, failure modes and associated mechanisms and their spatial distributions of laminates are identified and quantified as functions of thickness of laminate and underwater impulsive intensity. Comparative analysis of the blast resistance and dynamic response is carried out between composite laminates and metallic sandwich panels with similar areal mass.

2. Fluid-structure interaction experiment methodology

2.1. Experimental detail

In order to generate predictable and controlled high-intensity underwater impulsive loads to test marine structures, a projectile-impact based fluid-structure interaction experimental simulator was designed to measure the temporal and spatial evolution and failure of structures, as shown in Fig. 1. Planar pressure pulses are generated by firing a projectile to impact the sliding piston. Important features of this setup include the ability to generate pressure waves of a wide range of intensities, and the ability to simulate the loading of air-backed, water-backed, changeable loading areas and integrate high-speed photography.

Fig. 1 shows the fully edge-clamped plates under air-backed and water-backed conditions respectively. The shock tube is a 500 mm-long cylinder, which is horizontally mounted and filled up with water. It is made of armor steel and has an inside diameter of 66 mm. A thin piston plate is mounted on the front end and the specimen is located at the rear end. A projectile accelerated by the gas gun strikes the piston plate, generating planar pressure pulses in the shock tube. According to the

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