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Dynamic failure of clamped metallic circular plates subjected to underwater impulsive loads

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ABSTRACT

The dynamic response and failure of monolithic metallic plates subjected to water-based impulsive loads are investigated experimentally. The analysis focuses on the effects of plate thickness, fluid–structure interaction parameter, and patch size of loading area on deformation and failure modes in clamped solid 5A06 aluminum alloy plates under air-backed and water-backed loading conditions. The plates are subjected to impulsive loads of different intensities using a projectile-impact based underwater non-contact explosive simulator. 3D digital imaging correlation method is used to capture the dynamic response of plates to make comparison with postmortem analysis. Depending on the loading rate, the inelastic deformation is the primary failure mode of the plates. The different linear relationships between deflection resistance and applied impulse are identified experimentally, considering the influences of the effects of plate thickness, fluid–structure interaction parameter, and patch size of loading area. The results show that the effect of loading area is the most influential factor on transverse deflection. The results affirm that the plate under water-backed condition shows a 53% reduction in the maximum plate deflection compared with the plate under air-backed condition. Quantitative structure–load–performance relation is carried out to facilitate the advanced study on metallic structures and provides guidance for structural design.

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1. Introduction

Military and civilian ship structures, such as the hull and keel structures, are exposed to various environmental loadings, which include high and low temperature extremes, transient impulsive loads, and corrosive sea water. Additionally, the structures are designed to survive from both surface and underwater explosions and weapons impact. The material properties, blast-resistant performances, and geometric design of sub-structures must be well-understood and quantified.

Clamped structures are representative of the underwater vessel, which have attracted a great amount of interest to investigate the dynamic responses. Recently, experimental and theoretical studies on the metallic and composite sandwich plates have been conducted by many researchers [1–14]. Metallic solid and sandwich structures have been studied in terms of constituent material behavior, structural hierarchy, topological characteristics and complex loading involving fluid–structure interactions. Using light gas gun-based impact loading to generate exponentially underwater pressure impulses, Deshpande [2] and Espinosa [15] designed novel non-explosion impulsive simulators to exert planer pressure wave on targets. A number of topological cores were investigated, including the corrugated core, prismatic diamond core, honeycomb core, and metal foam [4,8,9,16,17]. Constitutive relations have been developed for sandwich structures, accounting for dynamic crush behavior of core and plasticity in constituents by Deshpande [18,19] and Xue [20]. The deformation of sandwich is divided into three phases: phase I is the fluid–structure interaction, which is up to the point of the first cavitation of the fluid; stage II is the core compression until the front and back faces get an equal velocity, and is followed by the bending and stretching of stage III. McShane et al. [16] analyzed the three phases by making comparisons among the fully decoupled model, cross-coupled model, and fully-coupled model, to investigate the fluid–structure interaction effect during the deformation of plates. The results indicate that the Taylor's analysis based on a free-standing front face-sheet underestimated the transmitted momentum by 20–30% due to the continued fluid loading during the whole deformation of sandwich. Fleck and Deshpande [19,21] examined the fully-coupled fluid–structure

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interaction in their analytical models to predict the transmitted momentum and deformation of the metallic sandwich. The parallel research [12] on different sandwich cores was based on the similar analytical model. These articles concluded that metallic sandwich structures outperform monolithic plates when the deformation is dominated by bending. However, Schiffer [5,17] reported that sandwich plates may or may not outperform rigid plates of equal mass in terms of the impulse imparted to the structure in a blast event.

The solid metallic panels are the basic components of significant metallic structures, which have been studied experimentally and theoretically for several decades. Neglecting the elastic effect, Jones [22] studied the rectangular and circular solid metallic panels under different loading conditions and proposed the 'bound' solution for the structural dynamic response. Considering the bending and shearing, Schiffer [7] developed a model for elastic deformation of composite solid plates subjected to underwater impulsive loads, considering the effect of fluid–structure interaction. Nurick [23] conducted comprehensive experiments on fully clamped circular and rectangular steel plates subjected to blast loads. With the increase of impulsive intensities, failure modes are divided into three phases: mode I, inelastic deformation, which is caused by plastically bending and stretching; mode II, tearing at the supports. Plate stretching is followed by tensile rupture at the supports; mode III, shearing at supports. Shear failure occurs at the supports with negligible plastic deformation in the remainder of the beam. The typical discing and petalling failure modes in impulsively loaded clamped plates were analyzed by Lee and Wierzbicki [24,25], and the tensile tearing modes were reminiscent mode II of failure modes for impulsively loaded beams. Balden [26] made experimental and numerical investigations into the shear rupture modes (mode III) of impulsively loaded clamped circular plates. Kazemahvazi [27] presented an experimental study on the failure modes of low strength copper plates subjected to underwater blast loads. It was concluded from the micrographs that the local failure mechanism is tensile necking, regardless of whether the macroscopic mode is petalling or shear-off. Zamani [28] presented the results of analytical and experimental studies on the response of steel and aluminum circular plates in two different media of air and water. A verified empirical prediction of normal deflection was presented considering the material strength, normal deflection, and intensity of impulses. Until now, detailed experimental validation needs to be attempted to provide more correct analysis and numerical predictions, especially in dynamic underwater situations for which the literature is scarce.

The high strength–weight ratios and high stiffness–weight ratios are the remarkable requirements of ship structures to resist transverse impulsive loads. Light structures, such as sandwich and some aluminum alloy solid panels, outperform the traditional steel plates in terms of these mechanical properties. To investigate the blast resistance and failure modes of the clamped plate as a function of applied impulses, the geometric property and loading configuration is important to the optimal design of vessel structures [4]. Despite recent advances in understanding the dynamic response of solid metallic plates, several issues remain. One is the lack of design relations that quantify the dynamic response as functions of both geometric parameters and load configurations. To obtain such relations, diagnostics that can provide in-situ, time-resolved measurements are required to record the dynamic deformation. Additionally, studies focused on plates that were in contact with water on only one side and with air on the opposite side, but the plates in contact with water on both sides were not considered especially in the experimental studies. The water-backed plate is the more common condition for most marine structures.

The objective of this work is to identify the dynamic response of solid metallic panels subjected to underwater impulsive loads experimentally. The focuses of present analysis are on understanding the deformation, failure modes and associated mechanisms, and quantifying the blast resistance of panels as functions of plate thickness, fluid–structure interaction parameter, and loading conditions. Experiments are conducted under three distinct loading conditions: (1) an air-backed condition, with the plate in contact with water on the impulse side; (2) a water-backed condition, with both sides of the plate in contact with water, and (3) the plates subjected to impulsive loading over a central loading patch, with the loading patch size $r = 0.7$. The results are presented in normalized forms to gain insight into underlying trends that can be used to design more blast-resistant structures.

2. Fluid–structure interaction experiments

2.1. Experimental detail

In order to generate predictable and controlled high-intensity underwater impulsive loads for testing marine structures, a projectile-impact based fluid–structure interaction experimental simulator was designed to measure temporal and spatial evolution and failure of structures, as shown in Fig. 1. A planar pressure pulse is generated by firing a projectile at a sliding piston. In order to obtain much higher intensity of underwater impulses, the dimensions of the water chamber similar to that used by Zhou [10] and Deshpande [2]. Important features of this setup include the ability to generate pressure waves of a wide range of intensities, the ability to simulate the loading of air-backed, water-backed, changeable loading areas and integrate high-speed photography.

Figure 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 with water. It is made of armor steel and has an inside diameter of 66 mm. A thin piston plate is mounted at the front end and the specimen is located at the rear end. A projectile is accelerated by the gas gun and strikes the piston plate, generating a planar pressure pulse in the shock tube. According to the analysis of Deshpande [2], the mass of the projectile is an important factor affecting the peak pressure and decay time of planer impulse. In order to obtain two different decay times of the impulses, 5 mm thick (0.13 kg) and 12 mm thick (0.22 kg) projectiles are used, respectively. Initial velocities of projectile in the range of 20–220 m/s are used to delineate the effect of loading rate on the deformation of the structures. This velocity range corresponds to peak pressures between 10 and 300 MPa, which are captured by the pressure transducers [29] mounted at the top of water tube. Monolithic aluminum plates of thickness 0.5 mm, 1.0 mm, 1.5 mm are used.

2.1.1. Air-backed condition

Clamped specimens are tested by using the air-backed shock simulator sketched in Fig. 1 (a). Six equally spaced clearance holes for bolts are drilled into the aluminum plates on a pitch circle of radius 65 mm, to clamp the plate onto the end of the water tube. Two 0.5 mm thick annular rubber rings and a 5 mm thick annular steel ring are used to ensure that the specimens were edge clamped fully. The effective loading region of clamped air-backed plates has the same radius as the water column in this configuration, $R = 3$ mm. The 3D digital imaging correlation method (DIC) is used to capture the dynamic responses of monolithic plates temporally and spatially. Two high-speed cameras Phantom v12.2 are put at the back of the specimen directly, in appropriate degrees, to ensure the error analysis conducted in the calibration is acceptable and obtains accuracy and stability results. In all of the tests, the cameras are ~25° from the axial line of the specimens. The selected frame rate and resolution are 33,000 frames and 384×384 pixels, respectively. During the calibration and post analysis, the business analysis software ARAMIS is used to achieve the corresponding parameters.

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