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Experimental and numerical investigation on a multi-layer protective structure under the synergistic effect of blast and fragment loadings

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ABSTRACT

The main function of a multi-layer protective structure of a combatant ship is to prevent the inner cabins from being destroyed by anti-ship weapons. The damage effect of these weapons on ship structures mainly comes from the blast wave and fragments. The motivation of this study was to investigate the synergistic effect of blast wave and fragment impact loadings on the multi-layer protective structure. A protective structure model with four layers and a metal casing filled with TNT charge (MCTC) which was used to simulate the warhead of an anti-ship weapon were designed and manufactured. An experiment was conducted in which the MCTC exploded inside an empty cabin of the first layer of the multi-layer protective structure. The distribution of fragments and the equivalent bare charge of the MCTC were determined by a numerical method. From experimental results, the failure pattern of the multi-layer protective structure under the synergistic effect of blast wave and fragment impact loadings was presented. The synergistic effect for the stiffened plates was also presented in the experiment by comparing the deformation and the rupture of the air-backed and water-backed stiffened plates. On the other hand, the agreement between numerical results and experimental results validated the numerical method, which enabled the numerical model to be used to predict the response of a full scale structure under loadings of anti-ship weapons. Finally, a discussion of synergistic effects of blast and fragment loadings on a multi-layer structure was presented and suggestions for the design of a protective structure are put forward.

1. Introduction

The impulsive load inside a naval vessel is mainly due to an explosion, which is clearly a major hazard that can result in severe structural damage and loss of life. The explosion source is assumed to be an anti-ship missile, striking the hull just above the water line. Internal blast occurs when the hull is breached before detonation. Weapons designed to explode inside the target have armor piercing or semi-armor piercing capability with delayed action detonation to maximize the caused damage [1]. Under such circumstances the simultaneous effect of blast wave and fragments applied to a structure can cause responses more severe than the sum of the damage generated in the structure through the independent application of the loads, particularly for the close-range internal explosions [2–4]. This simultaneous loading is considered to be synergistic in the sense that the simultaneous damage is greater than the sum of the impact and non-impact loadings. Considering the serious damage effect caused by the anti-ship missile, multi-layer protective structures have been applied to combatant ships [5,6], as shown in Fig. 1(a). The main function of the multi-layer protective structure is to prevent inner cabins from being destroyed by weapons. Generally, the multi-layer protective structure includes three layers, as shown in Fig. 1(b). When the warhead of a missile pierces the broadside plate and explodes, the empty cabins (A–C) of the first layer supply a large space for the propagation of the shock wave. A confined explosion causes more severe structural damage than a similar external free-air explosion, and this damage depends on geometrical parameters of the space where the explosion occurs [7,8]. Since the first-layer cabins without any crew and important equipments have enough space in the longitudinal direction, venting holes are arranged in the transverse bulkhead of the first-layer cabins to reduce the pressure buildup in a partially confined space and the resulting structural damage [9–12]. The cabins of the second layer are usually filled with liquid such as water, and denoted by G in Fig. 1(b). These liquid cabins are designed to stop fragments and to reduce the blast pressure associated with an explosive event. When the high-speed fragments penetrate a liquid cabin, high pressure shock wave is

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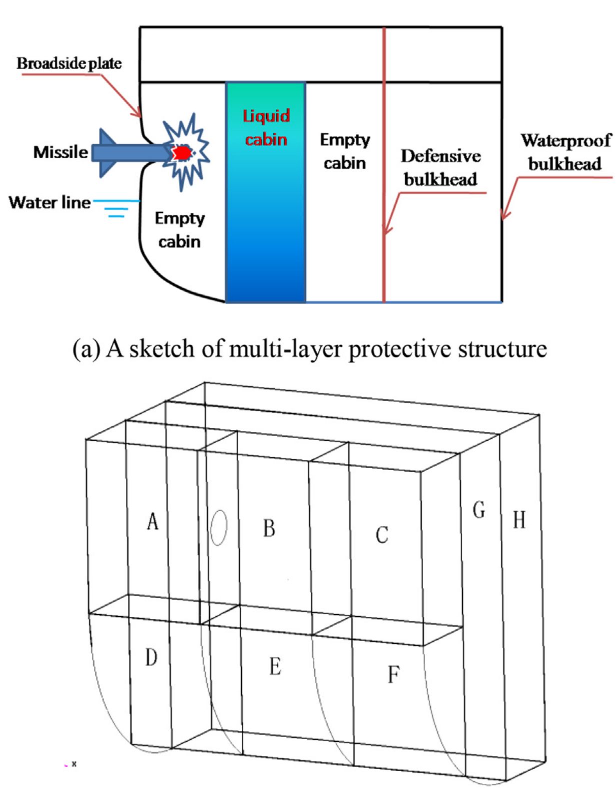

(a) A sketch of multi-layer protective structure

(b) Arrangement of cabins

Fig. 1. A sketch and arrangement of cabins of a multi-layer protective structure. (a) A sketch of multi-layer protective structure; (b) Arrangement of cabins.

generated in the liquid and kinetic energy of the fragments transfer to the surrounding walls of the cabin, which is known as hydrodynamic ram [13]. The high pressure combined with the fragments can result in the deformation and failure of the fluid-contained structure, the velocities of fragments decrease significantly in the process of penetrating the liquid cabin according to the previous researches [14–22]. The third layer is composed of an empty cabin denoted by H in Fig. 1(b). It includes a defensive bulkhead, which is usually armored and used to prevent the fragments that have penetrated the liquid cabin. All in all, for a multi-layer protective structure, the waterproof bulkhead must be protected from being destroyed by anti-ship weapons.

The damage effects from the cased charge of anti-ship weapons mainly include the blast wave and fragments, and these two factors influence each other [23–26]. The combined effect of blast wave and fragment impact loadings on the protective structure is still not completely understood. Knowledge of how the blast wave and the fragment impact influence the structural behaviors is quite limited. Nevertheless, the standard design methodology is that these threats are treated independently of each other [27]. A stiffened steel plate is a basic structural member in ship and offshore structures. Most previous works on synergistic effect of blast wave and fragment impact loadings on steel plates assumed that the fragments have already hit and perforated the target plate, and these perforations were idealized as pre-manufactured holes or generalized shapes. Schleyer et al. [28] presented a study on square plates with a central hole, and the results produced by a simplified analytical approach combined with Lagrangian finite element simulation indicated no significant reduction in the resistance. Rakvåg et al. [29] conducted a series of tests on thin ductile steel plates with idealized pre-formed holes to investigate the combined effect of pressure and fragment loading on steel plates. In their work, a simplification was proposed that fragments struck and perforated the flexible target before the pressure load arrived. Their results were valid for a combined blast and fragment loading case in condition that the stand-off distance was large enough for fragments to reach the plate before the blast wave and that fragments must perforate the structure. However, an explosion of a cased charge that occurs in a confined or partially confined cabin of a multi-layer protective structure corresponds to a much more complex case. The complexities mainly lie in: (i) the fragments produced by the metal casing will perforate plates of the cabins, (ii) the blast wave will aggravate the damage of plates and (iii) the intensity of blast wave will decrease with the increase of the venting area due to the damage of plates.

To understand the behavior of structures under the synergistic effects of blast and fragment loadings, full scale blast tests are required. However, these tests are limited due to security restrictions and lack of considerable resources required. Dynamic tests are usually conducted on small scale models to determine the response characteristics of a geometrically similar full-size structure. Because tests with cased charges will induce more uncertainties and complexities, no scaling law adequately suitable for the problem is available. Recent advances in FEM make it possible to investigate the fluid structure interaction effects due to large deformations in the plated structure [30,31]. However, further efforts are still needed to improve the numerical procedure for general applications of response prediction of structure under the synergistic effect of blast wave and fragment impact loadings.

The motivation of this paper was to investigate the synergistic effect of blast wave and fragment impact loadings and the subsequent damages on the multi-layer protective structure. Another purpose of the model experiment was to develop an experimental data set which would validate the numerical method. This would enable the validated model to be used with confidence to predict the response of a full scale structure under the loadings of anti-ship weapons. The outline of the paper is as follows:

(1) In Section 2, the experimental setup was presented, including the details of the multi-layer protective structure designed and manufactured by the present authors, the MCTC, the measuring point arrangement and the experimental method. Besides, the distribution of fragments and the equivalent bare charge of the MCTC were obtained by using a numerical method.
(2) Experimental results and discussions were presented in Section 3. The failure pattern of the multi-later protective structure under the synergistic effect of blast wave and fragment impact loadings, the releasing effect of the venting hole in the transverse bulkhead, the function of liquid cabins of the multi-layer protective structure and the shock responses of inner cabins were investigated. The synergistic effect of blast wave and fragment impact loadings for a stiffened plate was also presented by comparing the deformation and rupture of the air-backed and water-backed plates in the experiment.
(3) The computational procedure was presented in Section 4. The description of the FE models and the material models utilized was listed in detail. The comparisons between experimental results and numerical simulations were also presented, including the deformation and rupture of the multi-layer structure, the shock response and strain-time history.
(4) In Section 5, the synergistic effect of blast and fragment loadings was discussed. Some conclusions were drawn and