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Experimental and numerical investigation of ship structure subjected to close-in underwater shock wave and following gas bubble pulse

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ABSTRACT

One of the major topics confronted by the designers of naval vessels is to qualify the ship integrity exposed to underwater explosions (UNDEX). The far-field UNDEX & contact UNDEX problems are investigated by a few researchers previously. However, when a ship is subjected to close-in non-contact UNDEX environment, the failure mechanism of structures under the combined effect of shock wave load and bubble pulsations is rarely discussed. Thus, the dynamic response of ship structures subjected to close-in non-contact UNDEX is mainly concerned in this paper. Four UNDEX experimental tests of ship-type box structure (STBS, which can be fundamentally viewed as surface ships) are conducted in the study by using charge explosion. With reasonable finite element models, the coupled acoustic-structure algorithm in ABAQUS/Explicit code is utilized for the simulations. The wet vibration modes, accelerations, acoustic fluid pressure, and velocities from simulation results are compared with experimental data. The numerical simulation results agree well with those of experimental tests. Then, the detailed discussions are given to explore the damage processes of STBS subjected to the shock wave and bubble integrated loadings. The experiment and numerical simulation results reveal that global longitudinal strength collapse combined with the local wrinkling, the plastic deformation of hull between bulkheads and the plastic deformation of local bottom hull are the mainly three failure modes. And if the UNDEX bubble effects are not incorporated in the analysis, the damage severity

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will be underestimated. Moreover, other two practical numerical simulation examples are also discussed to illustrate the failure modes in depth.

1. Introduction

According to the statistical data of surface combatants and submarines severely crippled in the World Wars, the primary threatens to the vulnerability of a ship come from typical weapons (such as torpedo and mine) detonated near a ship which can damage the vessel in the form of dished hull plating [1–4]. The underwater explosion (UNDEX) phenomenon is characterized by the emission of a shock wave followed by a series of pressure pulses caused by subsequent oscillations of gas globes containing the product of detonation. The explosion results in the rapid liberation of energy, and the dissipation of detonation energy can be divided into three parts. The major part is the shock wave which is about 57% of total energy. And the second part is the secondary-wave pulse generated by UNDEX bubble, which is about 37% of total energy [5]. The remaining third part of energy (~6%) transferred from explosive is dissipated by heat.

To improve the vulnerability resistance of a naval vessel, engineers must evaluate the damage of a ship and the ability to perform the ship's mission capability in UNDEX environment. But the responses of ship structures subjected to UNDEX is quite complex involving fluid-structure interaction (FSI), high strain rate constitution equations, material and geometric nonlinearities, tensile tearing and rupture et al. Only limited experiment results can be obtained from previous studies. Harres and Cheneau [6] analyzed the acceleration and velocity responses of frigate, cruiser and submarine in different positions from the shock trial data of France Navy. And they also discussed the fitness of measuring equipments adopted in the experiments. The measurement velocity response characteristics of large surface naval vessels, such as an aircraft carrier, were reported by Oleson and Belsheim [7]. Recently, systemic experimental investigations on flat plates UNDEX problems were conducted by Rajendran et al. [8–13]. Based on Scanning Electron Microscopic (SEM) fractography of the failed sample, the ductile failure is the major damage mode for circular and rectangular flat plates. Presented in Ref. [14] were experiments to study the elastic–plastic dynamic responses and failure mode of the submerged stiffened plate. Nonlinear finite element analysis (by using the ESPA code) was also conducted and the results were compared with experimental data. It is found that the effect of FSI is not significant when UNDEX Shock wave propagates immediately through the water-backed thin plates [14]. Hung et al. [15] proposed an experimental study to investigate the transient dynamic responses of three types cylindrical shell structure subjected to UNDEX. Brett and Yiannakopoulos [16,17] also conducted a series of experiments nearby cylinders to reveal the dominance of bubble collapse loading for UNDEX in close proximity to a submerged cylindrical shell. Recorded acceleration and velocity responses showed the importance of bubble effects on structure damage.

Although the peak pressure of UNDEX bubble pulsation is usually 10%–20% of shock wave pressure, the total impulse of bubble secondary pressure has the same level as that of shock wave. Especially, the bubble pulsation and collapse jet force onto the structures may be the most severe structural load, generating high accelerations and causing significant plastic deformations when the bubble pulsation approaches the eigenfrequency of structures. Based on the hydroelastic theory and Timoshenko beam model, Hicks [18] analyzed the elastic responses of hull girder under a UNDX bubble pulse. Applied in Ref. [19] is the potential flow theory to predict the whipping displacements of a typical warship subjected to UNDEX bubble pulse.

Most of these discussions are limited to the far-field and contact UNDEX scopes. Few discussions are related to a close-in non-contact UNDEX problem. Wardlaw and Luton [20] discussed the FSI mechanism for a close-in explosion by adopting the DYSMAS/L (Lagrange method) and GEMINI (high order Godunov method) codes. Compared with explosion experiments on water filled cylinders, they pointed out that the cavitation and the cavitation collapse play an important role in cylinder flow field. But their experiments and simulations did not focus on typical ship structures. Webster [21]