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Damage characteristics of ship structures subjected to shockwaves of underwater contact explosions

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ABSTRACT

The damage process of ship structures subjected to underwater contact explosions is characterized by strong nonlinearity, thus there are great challenges in solving such problems. Firstly, the full Smoothed Particle Hydrodynamics (SPH) method for the fluid and structure interaction (FSI) is established based on compressible SPH fluid dynamics and SPH shell. Furthermore, the normal flux method is introduced to treat the interface. However, given the immaturity of the SPH shell in dealing with the fracture of complex structures, an SPH-FEM (Finite Element Method) coupling method for FSI is proposed with the "glue" treatment applied at the interface. The above two methods are verified by an underwater contact explosion experiment. Afterwards, the pressure-time relationship within six charge radii is fitted based on the axisymmetric SPH simulation. On this basis, the flat plates subjected to underwater contact explosions are studied in detail with the application of a combined damage variable. Three stages in the damage process, namely localized bulging, discing and petaling, are observed, and the crack and deflection are found to be sensitive to the changes of peak pressure and impulse respectively. Finally, complex models of a stiffened plate and a ship are established to further study the damage characteristics.

1. Introduction

The process of an underwater explosion near a ship hull is typically accompanied with the impinging of water jet, the penetration of high-speed fragments, the propagation of shockwaves among multilayer structures, the interaction of stress waves in structures and other extremely complex phenomena. The fluid dynamics are usually strongly nonlinear such as discontinuity, saltation, etc., while the structure undergoes large-deformation, tearing and even breaking, thus the whole process is very complex. As the source of energy in underwater explosions, the charge properties are directly related to the energy release and subsequently the structural damage. At present, the understanding of underwater contact explosion loading is still relatively incomplete. Moreover, the hole size, damage mode, failure criteria and other factors related to the damage phenomenology are as yet unresolved, but widely studied.

For the shock loading of near-field underwater explosions, the earliest and classic empirical formula of shockwave load can be found in Cole (1948), in which the pressure was the function of charge weight and detonation distance. It was followed by the study of Zamyshlyayev (1973), who modified the formula using experiments by identifying two regions in the detonation distance: as 6–12 charge radii, and above 12 charge radii. Afterward, the above formulas are further verified by many scholars. Besides, the shock loading of underwater explosions was also obtained from theoretical derivations. Geers and Hunter (2002) drew the pressure-time relationship utilizing the volume acceleration model of a spherical bubble, but it only suits the pressure of a certain distance away from the bubble due to the assumption of acoustic approximations. These studies mostly focus on the loading over a certain detonation distance, but they are difficult to apply to the problems of underwater contact explosions due to the multiple interfaces between different phases.

For the hole size and the forms of damaged structures caused by underwater contact explosions, the hole is always assumed to be circular. Keil (1956) found the hole size had a quantitative relationship with the charge weight ϖ and the plate thickness d by statistical analyses, and finally the empirical formula of the hole radius R was given as:

$$R = 0.0704\sqrt{\varpi/d} \tag{1}$$

Obviously, this formula did not consider the effects of material parameters (e.g. the yield strength), the charge parameters (e.g. the charge types) as well as the material hardening. Subsequently,

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based on the energy principle, Rajendran and Narasimhan (2001) had derived an estimation formula as follows:

$$R = \sqrt{2\beta\varpi_{TNT}E_{TNT}/\pi d\bar{\sigma}_s\bar{\varepsilon}_f} \tag{2}$$

where β is the ratio of effective work, E_{TNT} is the inner energy of a unit mass, $\bar{\sigma}_s$ and $\bar{\varepsilon}_f$ are the constant yield stress and fracture strain. The formula was confined to the rigid-plastic material and assumed the absorbed energy was only used for the membrane strain but not the bending strain. Though the material and charge properties were concerned in the above formula, there were also some deviations due to the material hardening and the strain rate effects during underwater contact explosions. Besides, in analytical ways, Wierzbicki (1999) studied the radial cracking and petaling of a rigid-plastic plate subjected to a local explosion loading by means of the velocity and displacement field and finally the relationships among the loading, the petaling number and the petaling curvature were drawn. Lee and Wierzbicki (2005a, 2005b) obtained the process of localized bulging, discing and petaling of a plate subjected to a local pulse loading with analytical and numerical approaches, which revealed the damage characteristics of such load but there are still some differences from the actual underwater explosions because of the coupling effects between the fluid and structure.

For the damage mode and failure criteria of structures caused by underwater contact explosions, Teeling-Smith and Nurick (1991), Wierzbicki and Nurick (1996) and Cloete et al. (2005) carried out many experiments on the square, circular and stiffened plates under the pulse load. The damage mode was divided into three types, namely large ductile deformation, tensile-tearing and deformation, along with transverse shear failure. Subsequently, the tensile-tearing and deformation mode was refined as the partial tearing, the complete tearing with an increasing mid-point deformation, and the complete tearing with a decreasing mid-point deformation. Ramajeyathilagam and Vendhan (2004) carried out the experimental studies of a rectangular plate subjected to the explosion load from different charge weights and different distances, thus the above damage modes were also observed. Moreover, they found when the total strain (including the membrane strain and bending strain) and the shear stress were used as the failure criteria, the results were more desirable than those obtained from the single criterion, i.e., the equivalent plastic strain. Gupta et al. (2010) simulated the damage modes of stiffened and unstiffened plates subjected to underwater explosions with the software ABAQUS considering the effects of strain rate and material hardening. The Johnson-Cook failure criterion was used in the simulation. Zong et al. (2013) conducted the studies of damage modes with an acoustic-structure coupling method and the constant fracture strain was used as the failure criteria. Though many understandings of the damage mode and failure criteria had been made, they are still unclear for the problems of the near-field underwater explosions. Accordingly, more effective technical routes are still desperately needed.

For the influencing factors of structural damages in near-field underwater explosions, Wierzbicki and Nurick (1996) studied the effects of loading areas and pulse amplitudes on the damage modes of circular plates with 40 groups of experimental data. Ramajeyathilagam et al. (2001) found the numerical results were closer to the experiment data when considering the strain rate effect for the near-field explosion of a cylindrical shell. Jacob et al. (2004) conducted many experimental studies and pointed out the temporal and spatial variations of the shock loading should be concerned. Gupta et al. (2010) found the peak pressure played an important part in the structural damage during numerical studies.

To sum up, the above scholars had done lots of work on the shock loading and structural damages. Meanwhile, some key parameters were highlighted, such as the shock loadings (including the peak pressure and impulse) and their temporal and spatial variations, structural damage modes and corresponding failure criteria, strain rate effects and so on. These issues are the cores of the studies of underwater contact explosions. They show great differences in the far-field underwater explosions, so new approaches and ideas should be proposed, which is the very motivation of the present study. It is because the process of underwater contact explosions always accompanies with the phenomena of large-deformation, tearing, moving interface, multiphase mixing and so on that the traditional algorithms are always incompetent to solve such problems due to the mesh distortion. In this paper, the meshfree SPH method which has the advantage of dealing with such problems will be introduced (Liu and Liu, 2003). Firstly the FSI methods for dealing with underwater contact explosions, including full SPH approach and SPH-FEM coupling approach, will be established followed by the verification with experimental data, then based on the studies of load distributions near the charge, the damage characteristics of a flat plate, a stiffened plate and a complex ship will be studied. It is worth mentioning that the experimental data is so expensive that only some simple model tests are carried out now. More validations are eager to be conducted in the future.

2. Fluid-structure interaction methods for underwater contact explosions

The process of underwater contact explosions always accompanies with strong nonlinearity, such as the discontinuity and jump of fluid dynamics, the large-deformation and fracture of structures. A full SPH method is adopted to deal with the nonlinear problems of underwater contact explosions in this paper. The three-dimensional compressible SPH is used to simulate the processes of charge detonation and shockwave propagation, while the nonlinear responses of ship structures are obtained by the damage and fracture models of SPH shell. Besides, given the immaturity of the present SPH shell for treating the dynamic fracture of complex ship structures, the SPH-FEM coupling method for FSI is proposed. The fluid (including the explosive gas and water) dynamics are also simulated from the SPH model, but the dynamic responses of complex ship structures will be solved with FEM. In the following, the three-dimensional compressible SPH for fluid dynamics, the meshfree SPH shell and the SPH-FEM coupling method will be presented.

2.1. Three-dimensional SPH for the compressible fluid dynamics

Due to the characteristics of drastic deformation, strong flowability, splashing, breaking and so on, the SPH method in the updated Lagrangian form is adopted for fluid dynamics, i.e., the updated Lagrangian SPH method (ULSPH). Because the instantaneous pressure of underwater explosions can be the order of GPa, the consideration of fluid compressibility is necessary. In addition, the viscosity and body force are so small that they can be ignored when compared with the instantaneous pressure. Thus, the three-dimensional SPH governing equations for the compressible fluid are (Liu and Liu, 2003):

$$\frac{D\rho_I}{Dt} = \rho_I \sum_{J=1}^{\text{sum}} \mathbf{v}_{IJ}\mathcal{V}_J\nabla_I W_{IJ} \tag{3}$$

$$\frac{D\mathbf{v}_I}{Dt} = -\sum_{J=1}^{\text{sum}} \rho_I^{-1}(p_J + p_I)\mathcal{V}_J\nabla_I W_{IJ} + \mathbf{G}_\text{V} \tag{4}$$