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Damage response of steel plate to underwater explosion: Effect of shaped charge liner

Zhifan Zhang[a,b], Longkan Wang[a], Vadim V. Silberschmidt[b,*]

[a] College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China
[b] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire LE11 3TU, UK

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ABSTRACT

A shape of charge liners has a great effect on formation of a metal jet and its penetration into a target. In this paper, three different shapes of a charge liner, namely, conical, hemispherical and spherical-segment, are chosen to investigate their effect on damage response of a plate to underwater explosion. A Smooth Particle Hydrodynamic (SPH) method based on mesh-free Lagrange formulation is applied to simulate an entire process of a shaped-charge detonation, formation of a metal jet as well as penetration on a steel plate. Initially, a SPH model of the shaped charge with a spherical-segment liner is developed, and its results are compared with experimental data to verify the effectiveness of this method. Then, numerical simulations of shaped charges with different liners are performed to study the damage characteristics of a steel plate subjected to underwater-explosion shock loading and the metal jet. It was found that for the shock wave the peak value of the radial pressure is larger than that of the axial pressure during the detonation process; the level of pressure in the spherical-segment case was higher than that of the other two cases. After the detonation, the metal jet was gradually produced under the effect of the detonation wave. Three types of the metal jet - a shaped charge jet (SCJ), a jetting projectile charge (JPC) and an explosive formed projectile (EFP) – were formed corresponding to three cases with conical, hemispherical and spherical-segment liners. The obtained results show that the velocity and length of the SCJ in the conical case are greater than that of the other cases, and it therefore may lead to a larger penetration depth. In addition, the EFP has a better motion stability for a velocity difference in the spherical case is lower than that of the other two cases. Subsequently, the shock wave arrives at the plate earlier than the metal jet, which will cause deformation of the plate. Due to higher pressure, the shock wave in the spherical-segment case has a stronger damaging effect on the plate than that in the other two cases. Finally, the metal jet reaches the plate causing a hole. Because of a wider jet head, the EFP results in a more serious damage to the plate. The suggested analysis and its results provide a reference for structural design of shaped charge warheads.

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1. Introduction

Naval structures can be severely damaged by a shock wave [1–4] and a metal jet [5–6] associated with underwater explosion. The metal jet can be classified into three main modes - Shaped Charge Jet (SCJ) [7–13], Jetting Projectile Charge (JPC) [14–20] and Explosive Formed Projectile (EFP) [21–27]. These three modes were studied by various researchers using experiments, theoretical analysis and numerical modelling. For the first mode, Green [8] gained a first successful x-ray radiograph of an aluminum SCJ in 1974. Masahide et al. [10] proposed numerical-analysis methods to investigate non-inhibited and inhibited conical shaped charges. Molinari [13] adopted a finite-element Lagrangian code to simulate formation, fragmentation and penetration in a plate of a shaped charge jet. In their research of the JPC, Liao et al. [14] combined numerical simulation and experiments to study properties of a shaped charge with a semi-spherical liner. Murphy [16] introduced a unified analytical approach to solve a problem of shaped-charge penetration in concrete. Wu et al. [19] utilized 3D LS-DYNA in their simulation of the entire process of collapse and break-up of the JCP. As for the research of the EFP, Yu et al. [22] carried out many penetration tests into rocks of different strengths. Johnson et al. [25] discussed some technical issues and showed results for 3D EFP computations. Lin

* Corresponding author.
E-mail addresses: V.Silberschmidt@lboro.ac.uk, v.silberschmidt@lboro.ac.uk (V.V. Silberschmidt).

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et al. [27] analysed distributions of velocity and pressure theoretically, and the obtained analytical results agreed well with the experimental data. However, most of these studies were focused on cases of air explosion, with few published papers discussing the processes associating with underwater explosion.

It was found that various parameters [28–35], such as initiation modes, a charge length and a liner material, affect significantly a cumulative effect of a shaped charge. Li et al. [29] focused on the influence of annular multi-point initiation on formation of the EFP. Bai et al. [31] discussed the effect of interaction mechanism between a jet and a target on penetration performance of a shaped charge liner. Ayisit et al. [32–33] studied the effect of off-axis initiation for shaped charges with different L/D ratios. Wang et al. [35] conducted experiments to investigate penetration of shaped charges with different cone angles and liner materials into concrete target. A shape of the liner has an important effect on formation of a metal jet and its penetration performance as well. Fu et al. [20] used LS-DYNA software to investigate formation, elongation and penetration processes of rod-like jets with three jetting penetrator charges (JPCs) - spherical cone, truncated wide-angle and spherical-segment liners. The use of traditional finite-element software is limited by computational difficulties caused by grid distortion related to high deformations in highly nonlinear problems of shaped charges. A Smoothed Particle Hydrodynamics (SPH) method [2,4,7,36–39] has natural advantages in simulating underwater explosions and metal-jet penetration, since, thanks to its mesh-less nature, it is suitable for solving problems with large deformations while its Lagrangian formulation makes it easy to capture material interfaces.

Therefore, the SPH method was used to simulate the entire process of metal-jet evolution associated with underwater explosion penetrating a plate in this paper. First, after a brief overview of the SPH theory a simulation of a shaped charge with a spherical segment liner was performed, and its numerical results were compared with the experimental data to verify the validity and feasibility of the presented SPH method. Second, SPH models for three cases of shaped charges with different liners - conical, hemispherical and spherical-segment - were developed to simulate the process starting with detonation to the jet penetration. Third, the effects of different liners on shock-wave propagation, formation of the metal jet and its penetration performance were analysed. The structure of the paper reflects this research process.

2. Theory and numerical verification

2.1. Basic SPH equations

In the SPH method, the state of a studied continuum volume can be represented by a system of arbitrarily distributed particles that can move according to external forces and internal interactions between them [40]. As a result, governing equations are transformed into corresponding integral forms by using a specially selected smoothing kernel function. A continuous function $f(x)$ and its derivative $\nabla \cdot f(x)$ can be discretized as [40]

$$f(\mathbf{x}_i) \approx \sum_j \frac{m_j}{\rho_j} f(\mathbf{x}_j) W_{ij} \tag{1}$$

$$\nabla \cdot f(\mathbf{x}_i) \approx \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(\mathbf{x}_j) \cdot \nabla_i W_{ij}, \tag{2}$$

where W_{ij} is the smoothed function of a pair of particles i and j (the cubic spline function is employed in this paper); ρ and m denote the density and mass, respectively.

The standard SPH method is characterised by poor performance in solving problems with a large density ratio [41]. Hence, a modified SPH method [42] based on volume approximation is applied to simulate evolution of a shaped-charge jet associated with underwater explosion. The conservation of mass, momentum and energy can be expressed as [42]:

$$\begin{bmatrix} \frac{d\rho_i}{dt} \\ \frac{dv_i^a}{dt} \\ \frac{de_i}{dt} \end{bmatrix} = \begin{bmatrix} \rho_i \sum_{j=1}^{N} m_j \cdot v_{ij}^b \\ -\sum_{j=1}^{N} \frac{m_j}{\rho_j} \left(\frac{\sigma_i^{ab} + \sigma_j^{ab}}{\rho_i} + \Pi_{ij} \right) \\ \frac{1}{2} \sum_{j=1}^{N} \frac{m_j}{\rho_j} \left(\frac{\sigma_i^{ab} + \sigma_j^{ab}}{\rho_i} + \Pi_{ij} \right) v_{ij}^b \end{bmatrix} \cdot \frac{\partial W_{ij}}{\partial x_i^b}, \tag{3}$$

where v, e, t, x denote the velocity, energy, time and coordinates, respectively; a and b indicate the directions along the axes; Π_{ij} is artificial viscosity [40]; σ is the stress and it can be obtained by solving the constitutive model.

2.2. Constitutive model

The stress σ for water and exploding gas is composed of isotropic pressure and viscous shear stress; since their viscosity is small, it can be ignored in analysis of strong impacts such as a case of a shaped-charge jet associating with underwater explosion. Therefore, the stress can be obtained by solving a problem with regard to pressure. Pressure of detonation products and water can be presented with the Jones–Wilkins–Lee (JWL) equation of state (EOS) [43] and the Mie–Gruneisen equation of state [44], respectively.

The JWL EOS [43] for explosive gas is expressed as

$$P = A\left(1 - \frac{\omega\eta}{R_1}\right) \exp\left(-\frac{R_1}{\eta}\right) + B\left(1 - \frac{\omega\eta}{R_2}\right) \exp\left(-\frac{R_2}{\eta}\right) + \omega\eta\rho_0 e, \tag{4}$$

where ρ_0 is initial density; A, B, R_1, R_2 and ω are the fitting coefficients obtained from experiments; e is detonation energy per unit mass; η is the ratio of the density of detonation products to the initial density of the original explosive. The values of these parameters used in simulations below are listed in Table 1.

The Mie–Gruneisen equation of state [44] for water is given by

$$P = \begin{cases} \dfrac{\rho_0 C_0^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{a}{2}\mu^2\right]}{\left[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu+1)^2}\right]^2} + (\gamma_0 + a\mu)e, \mu > 0 \\ \rho_0 {C_0}^2 \mu + (\gamma_0 + a\mu)e, \mu < 0 \end{cases} \tag{5}$$

where ρ_0, C_0, a, e and γ_0 are the initial density, sound velocity, volume correction coefficient, the specific internal energy per unit volume and Gruneisen coefficient, respectively; S_1, S_2 and S_3 are fitting coefficients; μ is the compression, $\mu = \eta - 1$, where η is the ratio of density before and after the explosion, Water is in a compressed state when $\mu > 0$ while in an expanded one when $\mu > 0$. The relevant parameters are shown in Table 2.

Apparently, for solids with high shear strength, contribution of

Table 1
Parameters in Jones–Wilkins–Lee EOS for explosive gas [43].

ρ_0 (kg/m^3)	A (Pa)	B (Pa)	R_1	R_2	ω	e (J/kg)
1630	3.74	3.75	4.15	0.90	0.35	6.0×10^6

Table 2
Parameters in Mie–Gruneisen EOS for water [44].

ρ_0 (kg/m^3)	C_0 (m/s)	γ_0	a	S_1	S_2	S_3	e (J/kg)
998	1480	0.5	0	2.56	1.986	1.2268	357.1

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