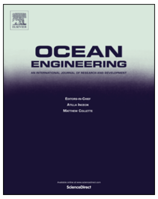
Ocean Engineering 117 (2016) 221–237

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



# Shock mitigation effects of cellular cladding on submersible hull subjected to deep underwater explosion

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ARTICLE INFO

*Article history:*
Received 11 November 2015
Received in revised form
19 February 2016
Accepted 13 March 2016
Available online 31 March 2016

*Keywords:*
Underwater explosion
Fluid–structure interaction
Static pressure
Submersible hull
Cellular cladding

ABSTRACT

Warships and submarines can be severely damaged by underwater explosion (UNDEX) shock loadings, so improving shock resistance ability of such weapons is of great importance. However, studies on the shock resistance ability of submersible hull subjected to deep UNDEX shock wave are rare. In this paper, the transient response of bare/coated submersible hull subjected to combined loads of hydrostatic pressure and shock wave is analyzed numerically by Abaqus, with special attention on shock mitigation capability of cellular cladding coated on the pressure hull. The local cavitation in water and transient response of bare and coated hulls are obtained. Additionally, the effects of the initially applied hydrostatic pressure on the system response are discussed. The results indicate that the cellular cladding coated on the pressure hull is very effective on reducing hull deformation, velocity and acceleration response, and the soft cladding is more effective than the strong cladding if the cladding is not fully densified. Otherwise, the stress enhancement appears which can amplify the local response of coated hull. The research results are useful in designing surface shields for submersible hull so as to enhance its resistance to underwater shock damage.

## 1. Introduction

Surface ships and submarines are routinely exposed to threats of underwater explosion (UNDEX). The transient response of ships/submarines subjected to UNDEX is a very complicated problem since it involves shock wave propagation, cavitation, fluid–structure interaction and nonlinear dynamic behavior of structure. To enhance shock resistance ability of such structures, we need to accurately predict the transient response of ships/submarines subjected to underwater shock loading and improve the strength of ship hull or design effective surface shields to protect the warships. In the past, there have been many studies to investigate the dynamic response of warships subjected to primary shock wave (Gong and Lam, 1999; Liang and Tai, 2006), bubble pulse load (Zhang et al., 2011, 2014) and the combined loads of these two (Hung et al., 2009; Jin and Ding, 2011; Wang et al., 2014). Their studies demonstrated that such explosive loads can lead to large plastic deformation, overall damage of the ship and even break offs.

In recent years, researches on how to enhance naval vessels' shock resistance ability attract more and more researchers' interests. Two possible methods exist to enhance the shock resistance ability of warships: one is to improve the strength of the ship hull itself and the other is to design effective surface shields. Improving material or adding stiffeners can strengthen the ship hull. Kalavalapally et al. (2009) demonstrated that the stiffened torpedo performed better than the unstiffened torpedo under explosive pressure loads. Gong and Lam (1998) found that the composite hull surpassed over the steel hull in amortizing the effects of underwater shock wave. Recently, Gong and Khoo (2015) studied the transient response of composite and steel hull subjected to the bubble pulse and revealed that composite hull outperformed the steel hull. Fathallah et al. (2015) investigated the dynamic behavior of optimized composite elliptical submersible pressure hull to non-contact UNDEX. Surface shields are also proved to be effective in attenuating shock wave. Chen et al. (2009) experimentally demonstrated that a rubber sandwich layer coated on the metal box was efficient in mitigating water blast. Kim and Shin (2013) researched different surface shields and verified their shock resistance ability. LeBlanc et al. (2013) and LeBlanc and Shukla (2014) used a conical shock tube facility to explore the underwater blast response of polyurea coated composite plates. They found that the shock resistance ability of the composite plates is improved when coated by polyurea. Later, LeBlanc et al. (2015) experimentally studied the same structure subjected to near field underwater explosion and drew similar

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http://dx.doi.org/10.1016/j.oceaneng.2016.03.037
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conclusions. Additionally, sandwich structures with cellular material cores possess a superior energy absorption capability and are widely used in resistance of shock/impact loadings (Xue and Hutchinson, 2004; Deshpande and Fleck, 2005; Liang et al., 2007; Schiffer and Tagarielli, 2014; Avachat and Zhou, 2015a, 2015b, 2013). Both mentioned above dealt with only the shock resistance ability of the shield itself or for simple structures, such as beam and plate. Literatures dealt with transient response of a submersible hull as well as shock resistance ability of sacrificial claddings coated on the pressure hull subjected to combined loads of hydrostatic pressure and shock wave, however, are limited.

Due to complicated physical phenomena involved in UNDEX, analytical method is extremely difficult and full-ship trials are costly and limited by environment. Therefore, numerical simulation is unavoidable for practical structures. The present paper aims to numerically study the transient response of bare/coated submersible hull subjected to deep UNDEX. The local cavitation in water, deformation mode of hull, pressure at the fluid–structure interface, velocity and plastic deformation of hull are presented. Specially, the shock mitigation effects of cellular cladding coated on the pressure hull are discussed in detail. In addition, the effects of initially applied hydrostatic pressure on the response of system is examined. The results are useful for designing effective surface shields for submersible hull to enhance its resistance to underwater shock damage. All analyses are performed by the non-linear finite element code Abaqus. The incident pressure from the explosive charge is obtained from the empirical equation of Cole (1948). Both initially applied hydrostatic pressure and UNDEX shock wave are taken into consideration.

An outline of this paper is as follows. In Section 2, the formulations of UNDEX load and fluid–structure interaction equations are described. Then the numerical model is validated in Section 3. In Section 4, the geometry characteristics, material properties and loading conditions of bare/coated submersible hull analyzed in this paper are presented. Section 5 provides comparisons and discussions on the typical transient response and shock resistance ability of bare/coated submersible hull subjected to the combined loads of hydrostatic pressure and shock loading. Finally, conclusions are presented in Section 6.

## 2. Underwater shock analysis

### 2.1. Shock wave parameter

According to Cole (1948), marine structures are exposed to two types of loads, shock wave and bubble pulsation. During underwater explosion, the charge instantly converts into a hot explosion gas and induces a shock pressure up to 5000 MPa. The shock wave propagates spherically in the surrounding water and is superimposed on the hydrostatic pressure. Most cases demonstrated that the damage done on marine structures occurs early and is due to the strikes of the shock wave (Liang and Tai, 2006). This paper only considers the effects of the shock wave. The explosion energy is a function of the charge weight and stand-off distance. The pressure time history at any location has an instantaneous pressure increase followed by a decay and can be approximated by an exponential function

$$p_{in}(t) = p_0 e^{(-(t-t_0)/\theta)} \quad (\mathrm{MPa}), \tag{1}$$

where $t$ is the time elapsed after the detonation of charge in (ms), $t_0$ is the arrival time of shock wave to the target after the detonation of charge in (ms), $p_0$ is the peak pressure at the shock wave front in (MPa) and $\theta$ is the time decay constant in (ms). The peak pressure, $p_0$, and the decay constant, $\theta$, are given by

$$p_0 = K_1 (W/R)^{A_1} \quad (\mathrm{MPa}), \quad \theta = K_2 W^{1/3} (W/R)^{A_2} \quad (\mathrm{ms}), \tag{2}$$

where $W$ is the weight of the explosive charge in (kg), $R$ is the distance between the explosive charge and target in (m), $K_1$, $K_2$ and $A_1$, $A_2$ are constants depended on explosive charge type. In case of TNT charge, these constants are $K_1 = 53.4$, $K_2 = 0.0925$ and $A_1 = 1.13$, $A_2 = -0.22$.

### 2.2. Local cavitation

During UNDEX events, two types of cavitation may occur: bulk cavitation and local cavitation. The former is caused by reflection of shock wave at a free surface and cannot be ignored during analysis of surface ship. When the underwater shock wave impinges upon a flexible structure, the total pressure at the fluid–structure interface can be expressed by

$$p_{wet}(t) = p_{in}(t) + p_c(t) + p_{st}, \tag{3}$$

where $p_{in}$ is the incident shock wave, $p_{st}$ is the hydrostatic pressure, and $p_c$ is the scattered pressure which can be negative. Consequently, the total pressure may be negative as well. However, the water cannot sustain tension. Local cavitation will occur in water as the pressure drops to vapor pressure (about 0.3 psi) (Shin, 2004). Then, the cavitation will collapse and reload the structure (Rajendran, 2008; Jin et al., 2015; Yin et al., 2016). In this paper, a submersible hull is analyzed and only local cavitation is considered.

### 2.3. Fluid–structure interaction

The submerged structure subjected to shock loading involves responses of the structure, the surrounding fluid and interaction between the two. Under water blast, the structure deforms and displaces the fluid around it, thus affecting the pressure distribution in water surrounding the structure. These pressures influence the deformations of structure which, in turn, influence the hydrodynamic pressure again. Therefore, the fluid–structure interaction is very important to the system response. The governing equation of structural response can be expressed by

$$[M_s]\{\ddot{u}\} + [C_s]\{\dot{u}\} + [K_s]\{u\} = \{f_{out}\}, \tag{4}$$

where $M_s$ is the structural mass matrix, $C_s$ is the structural damping matrix, $K_s$ is the structural stiffness matrix, $f_{out}$ is the external force vector and $u$ is the structural displacement vector. When the submersible hull impinged by shock wave, the external forcing function can be given by

$$\{f_{out}\} = -[T][A_f](\{p_{in}\} + \{p_c\} + \{p_{st}\}). \tag{5}$$

The matrix $A_f$ denotes the diagonal area matrix associated with an element in the fluid mesh, and $T$ represents the transformation matrix relating the structural and fluid nodal surface forces.

## 3. Validation of the numerical model

In this section, two experimental tests are employed to verify the numerical model. The first test is the UNDEX experiment of Kwon and Fox (1993) in which a submerged test cylinder is exposed to a pressure shock wave. The second test deals with the response of one-dimensional cellular cladding with foam core under combined loads of water blast and initially applied hydrostatic pressure.

### 3.1. UNDEX response of cylindrical shell

In the first test, the cylinder is made of aluminum and has an overall length of 1.067 m, an outside diameter of 0.305 m, a wall