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Numerical investigation of the dynamic response of optimized composite elliptical submersible pressure hull subjected to non-contact underwater explosion

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ABSTRACT

Predicting the dynamic response of a floating and submerged structure subjected to underwater explosion is greatly complicated by the explosion of a high explosive, propagation of shock wave, bubble-pulse and complex fluid–structure interaction (FSI) phenomena. A numerical simulation has been carried out to examine the behavior of optimized composite elliptical submersible pressure hull to non-contact underwater explosion (UNDEX) and take the effect of bubble-pulse. Various explosive weights and explosion distances were explored to determine the critical weights and safe distance. The optimization process is performed using ANSYS parametric design language (APDL). After that the finite element package ABAQUS was used to model the UNDEX and the FSI phenomena. Time histories of the wet-surface displacement, velocity and Tsai–Hill failure index are presented for different composite plies. All of these results can be a valuable reference for designing underwater vehicles to resist UNDEX.

1. Introduction

Many structural elements made of fiber reinforced composites are increasingly utilized in naval applications such as advanced ship hull designs, unmanned underwater vehicles, and submarine components [1]. The most important benefits from using such advanced materials are high stiffness-to-weight ratio, reducing the weight of the structure, long fatigue life, improved corrosion resistance, and reduced maintenance costs. When a naval ship is attacked by an underwater explosion (UNDEX), the ship can be severely damaged by shock waves and gas bubble pulse. The design and analysis of structure subjected to UNDEX require a detailed understanding of explosion phenomena and the dynamic response of various structural elements [2]. LeBlanc et al. [3], studied the response of curved E-Glass/Vinyl ester composite panels subjected to underwater shock loading. Schiffer et al. [4], developed analytical models to predict the response of circular, fully clamped, orthotropic elastic composite plates loading by a planar, exponentially decaying shock wave in water. Kalavalapally et al. [5], investigated the lightweight torpedo subjected to an UNDEX. Panahi et al. [6], investigated the transient dynamic response of a submerged cylindrical foam core sandwich panel subjected to shock loading. Chirica et al. [7], presented the effects of explosion on ship structure made of composite materials. From the results, the proposal of a composite structure with damping system can help the structure to sustain blast load. Kalavalapally et al. [8], obtained the response for both a composite and stiffened metallic torpedo model. The results showed that, the composite torpedo model is stronger and lighter than the metallic design, when subjected to an UNDEX. Zhang et al. [9], developed a procedure which coupled the finite element method with doubly asymptotic approximation (DAA) method to study the problem of transient responses of a ship hull structure subjected to an underwater explosion bubble. Chen et al. [10], investigated experimentally the dynamic performance of rubber coated ship body and discussed the protective effects of rubber layer on its blast resistance. Amana et al. [11], studied the dynamic response of the shipboard equipment to the shock wave load, taken into account the coupling elastic effect between equipment and hull structure. Schiffer [12], investigated the response of double-walled hulls to underwater blast loading. Kwon and Fox [13], studied the nonlinear dynamic response of a cylinder subjected to side-on UNDEX. Shin and Hooker [14], studied the damage response of

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submerged imperfect cylindrical structures to UNDEX. Qiankun and Gangyi [15], predicting the response of a ship section subjected to non-contact UNDEX and found that the size of fluid mesh and the fluid thickness from the wetted surface to the outer boundary of fluid are of great importance for improving numerical accuracy. Gong [16], investigated the transient response of a floating composite ship section subjected to underwater shock. Kumar et al. [17], conducted an experiments to study the effect of plate curvature on the blast response of thirty two layered carbon composite panels. Zhang et al. [18], calculated the dynamic bending moment of bubble acting on hulls. And found that, underwater explosion bubble will cause general longitudinal bending of ship and lead to hogging and sagging damage of ship. In this study, a composite submarine pressure hull in the form of elliptical cylinder subjected to hydrostatic pressure as shown in Fig. 1 is optimized using nonlinear finite element analysis software ANSYS. According to the optimum design results, the finite element model will build using the finite element package ABAQUS to examine the behavior of composite elliptical submersible pressure hull to non-contact UNDEX.

2. Analysis of underwater shock loading and bubble pulse

In an underwater explosion event, the structure is exposed to the effect of two types of time dependent loads, shock wave and bubble pulsation. Both types of loads have great damages on the ship hull structures. The shock wave has very high peak pressure with extremely short duration. It usually induces local structure damage. The energy in the bubble pulsation is nearly 47% of the total explosion energy [19]. Fig. 2 shows the different events occurring during the UNDEX event in a pressure against time history plot [20,21]. The loading mechanisms due to underwater explosion include incident shock wave, free surface reflection wave, bottom reflection wave, gas bubble oscillation, bubble-pulse loading and bulk and hull cavitations [22].

The pressure history $P(t)$, of the shockwave at a fixed location starts with an instantaneous pressure peak, P_{max}, followed by a decline which is usually approximated by an exponential function. The empirically determined equation of the pressure profile [19,23–25] has the following form:

$$P(t) = P_{max} e^{-\left(\frac{t-t_1}{\theta}\right)} \quad (\text{MPa}) \quad t \geq t_1 \tag{1}$$

where t is the time elapsed after the detonation of charge in (ms); t_1 is the arrival time of shock wave to the target after the detonation of charge in (ms), P_{max} is the peak pressure magnitude (MPa) at the shock wave front and θ is the time decay constant which describes the exponential decay in (ms). The peak pressure P_{max} and decay constant θ, can be expressed as follows [26]:

$$P_{max} = K_1\left(\frac{W^{\frac{1}{3}}}{R}\right)^{A_1} \quad (\text{MPa}), \quad \theta = K_2 W^{1/3}\left(\frac{W^{\frac{1}{3}}}{R}\right)^{A_2} \quad (\text{ms}) \tag{2}$$

In case of TNT charge, the maximum bubble radii of explosive gas, R_{max}, and first pulsation periods, T, are expressed as [27]:

$$T = 3.38\left(\frac{W^{\frac{1}{3}}}{(D+33)^{5/6}}\right) \quad (s),$$
$$R_{max} = 2.1\left(\frac{W}{(D+33)}\right)^{1/3} \quad (\text{m}) \tag{3}$$

where K_1, K_2, and A_1, A_2 are constants that depend on explosive charge type when different explosives are used. These input constants are as stated in Table 1 [28]. W is the weight of the explosive charge in (kg); D is a charge depth in (m) and R is the distance between the explosive charge and target in (m).

A shock factor (SF), which is proportional to the energy density of the shockwave arriving at a structure, due to various combinations of charge weight and standoff distance is derived by:

$$SF = 0.45\sqrt{w}/R \ (\text{Kg}^{1/2}/\text{m}). \tag{4}$$

3. Failure criteria of composite materials

3.1. Maximum stress failure theory

In this case, the principal stresses in each ply are compared with their corresponding strength values X_t, X_c, Y_t, Y_c, and S. Where X_t and X_c are the longitudinal tensile and compressive strengths, respectively, Y_t and Y_c are those in the transverse direction, S is the ultimate in-plane shear strength. According to this criterion, failure is predicted whenever one of the principal stress components exceeds its corresponding strength. The failure index is defined as [29]:

$$I_F = \max\begin{cases} \sigma_{11}/X_t & \text{if} \quad \sigma_{11} > 0 \quad \text{or} \quad -\sigma_{11}/X_c \quad \text{if} \quad \sigma_{11} < 0 \\ \sigma_{22}/Y_t & \text{if} \quad \sigma_{22} > 0 \quad or \quad -\sigma_{22}/Y_c \quad \text{if} \quad \sigma_{22} < 0 \\ |\tau_{12}|/S \end{cases} \tag{5}$$

3.2. Tsai–Hill failure criteria

Tsai–Hill failure criterion is one of the most practicable criterions for the prediction of damage progress in laminates, which assumed that there is an important connection between longitude strength, traverse strength and shear strength in the damage progress. The criterion can be expressed as [30]:

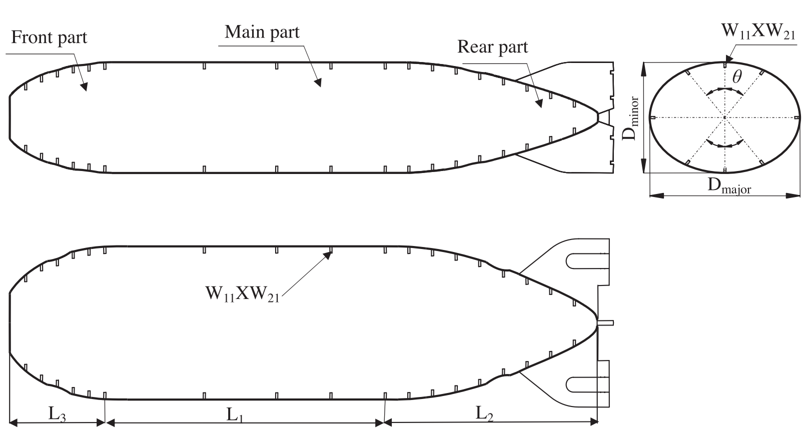

Fig. 1. Geometry of elliptical submersible pressure hulls.