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Mitigating performance of elastic graded polymer foam coating subjected to underwater shock

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ABSTRACT

The possible mitigating effect of elastic Density Graded Polymer Foam (DGPF) coating on the marine structure subjected to underwater shock is investigated. A 1-D unified nonlinear finite element model based on the updated Lagrangian frame is built to solve both the transient response of foam coated structure and dynamic cavitation of water near fluid–structure interface. The mitigating effect of DGPF coating with respect to design parameters such as average density, density difference (uneven density), gradient functions and load intensity is explored. It is illustrated that DGPF is superior in underwater shock protection to the equivalent uniform foam if the foam density is properly distributed while load density is not so high. Lower density foam in the water side is helpful to reduce the total impulse transmitted from water. But the total energy absorption capability may be discounted as the coating enters densification phase earlier.

1. Introduction

Sandwich structures with foam core are capable of increasing the total anti-blast resistance. Their dynamic performance subjected to air and underwater shocks becomes a hot topic in recent years [1–9]. The good anti-blast resistance capability lies in two aspects. Firstly, the good deflection capabilities provide volume to expand explosion gases and decrease the shock wave pressure; secondly, the progressive damage mode and energy absorbing mechanism of core permit relative small deformation of inner face plate. If the blast medium is water, the first merit may be more prominent. Deshpande and Fleck [10] made a deeply investigation on the one-dimensional shock response of sandwich plates subjected to an underwater pressure pulse. The analysis concluded that: (a) the momentum transmitted into the sandwich plates is substantially lower than that into a monolithic plate with same mass. (b) For a given core relative density, a smaller fraction of the shock impulse is transmitted into the sandwich plates with the cores that have lower compressive strength. Some earlier works by the authors also reveal that the soft rubber foam coated onto the hull of floating structures can remarkably reduce its transient response and enhance the shock environment [11,12].

Compared with common homogeneous foam, Functionally Graded Foam Material (FGFM) contains micro-scale cells varied continuously in a predefined manner and often improves its energy absorbing characteristics under impact conditions. Avalle et al. [13] characterized compressive impact loading of polymeric foams over a range of densities using energy absorption diagrams. They showed that it may be possible to combine a large range of densities to improve the energy absorbing efficiency over a wider range of stress levels by means of functionally graded foam. Cui et al. [14] studied the influence of material distribution, controlled by various explicit gradient functions, material density range, and material average density, on energy absorption under the influence of various impact energies. It showed that density-graded foam can exhibit superior energy absorption over equivalent uniform foams under low energy impacts. Some more related research works on the impact characteristics of functionally graded foam can be found in [15–18].

Up till now, research on functionally graded foam using as the energy absorbing material is mainly concentrated on its applications ranging from packaging, to automotive components, helmets and head protection systems. Its application on the underwater explosion protection scenario is seldom dealt with. In this paper, the potential application of DGPF on the marine structures as a protective coating subjected to underwater shock wave is studied. Our motivation originates from two prospective merits of DGPF coating: (i) the fluid–structure interaction mechanism may be

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Nomenclature

DGPF	Density Graded Polymer Foam
ε_b	a critical strain value for the elastic foam. When strain greater than ε_b, the cell wall of foam begin to buckling and a stress plateau forms
ε_D	the densification strain for the foam
ρ_s, E_s	the density and elastic modulus of the solid cell wall material
ρ^*, E^*	the density and elastic modulus of the foam itself
ε^*_{el}	the elastic buckling strain of elastic foam
σ^*_{el}	the elastic buckling stress of elastic foam
C_1, D, m	material constants related to the specific foam
h	the thickness coordinate of foam core measured from the center of foam
h_c	the total thickness of the foam core
$\bar{h}$	the dimensionless thickness measured from the center of foam
$\rho^*(\bar{h})$	the density distribution functions of the foam core along the thickness
ρ^*_f, ρ^*_s and ρ^*_c	the density of the foam core at the fluid side, solid side and center of the foam respectively
$\bar{\rho}^*$	the average density of the whole DGPF core
χ_1, χ_2	the density gradient index of the DGPF, respectively for style 1, 2 and 3, 4
n	exponential constant of the density distribution function
M	the mass matrix
$f^{\text{int}}, f^{\text{ext}}$	the nodal force vector related to internal and external force
N^T	the polynomial interpolation functions
A	the section area of the domain
$\delta v(x), \delta v_{,x}$	the test function and its differential to the space coordinate
Ω, Ω_0	the current and reference configuration of the analyzed domain
Γ_t	the boundary of the analyzed domain
η	the nominal volumetric compressive strain
U_s	the linear shock velocity
U_p	the particle velocity U_p
P_o, θ	the peak pressure and decay constant of the shock wave pressure in the exponential form
W	the weight of TNT in kilograms
R	the stand-off in meters
A_1, K_1 and K_2	the coefficients related to specific explosive
m_f, m_b	the mass of front and back face of foam coating
$p_{\text{int}}(t)$	the pressure time history monitored at the fluid–structure interface
I_t	the impulse transmitted from water to the front face
I_0	the impulse achieved in the stationary rigid plate limit
I_0	$\int_0^\infty 2P_0 e^{-t/\theta} dt = 2P_0\theta$
$F_r(t)$	the reaction force acted on the main structure from the supporting spring
$\bar{F}_r^{\max}$	the maximum reaction force in the dimensionless form
HSF	Hull Shock Factor
$diff(\bar{F}_r^{\max})$	the difference of the maximum reaction force between the DGPF and uniform foam coating
$diff(\bar{I})$	the difference of the transmitted impulse between the DGPF and uniform foam coating

altered if the density distribution is rearranged, which may reduce the total impulse transmitted from water to the structure. (ii) The energy absorption or buffering capability of coating may be enhanced by optimizing the density distribution of the foam core.

2. Elastic DGPF coating

2.1. Basic scheme

The basic scheme using elastic foam as protective coating for ship hull or other marine structures is shown in Fig. 1. Once an underwater explosion takes place nearby, the transient shock wave will be transmitted from water around to the hull structure. If a layer of foam coating added, the hull plate and the equipment on board may be protected by the sacrifice of outer coating. The elastic foam is selected considering the fact that it can be easily shaped and coated onto metal hull by adhesive [12]. Unlike discussions on the common uniform foam in earlier work, this paper is mainly focusing on the DGPF coating. The difference between the DGPF and uniform foam is that the density of the former can be changed along the thickness direction. The density distribution function can be discontinuous such as arranging uniform foam with different density. It also can be continuous by controlling the foaming technology during manufacturing.

2.2. Constitutive model for the cellular elastic foam

The typical stress–strain curve for an elastic cellular foam in compression is characterized by three regimes [19]: a linear elastic regime, corresponding to cell edge bending or face stretching; a stress plateau, corresponding to progressive cell collapse by elastic or plastic buckling; and densification, corresponding to collapse of the cells throughout the material and subsequent loading of the cell edges and faces against one another. To ensure consistency, the proposed method for common macromolecular foam is briefly reviewed as follows:

(a) Linear elastic regime: $0 < \varepsilon < \varepsilon_b$.

In this regime, for loading along the prism axis, in the out-of-plane direction, the cell walls of a honeycomb initially compress

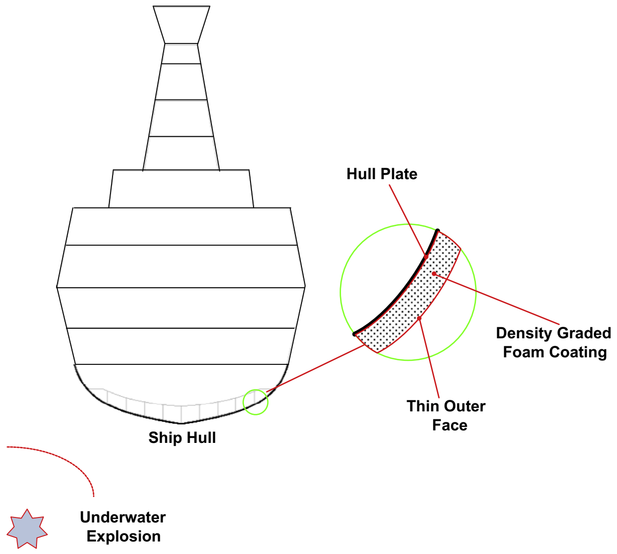

Fig. 1. The schematic map of using elastic DGPF as the protective coating for ship hull or other marine structures.