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Predict effective thickness of sacrificial cellular claddings to shallow/deep water blast

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ABSTRACT

The cellular materials are well known to mitigate shock loadings. However, they may attenuate or enhance the shock transmitted to the protected structures. This paper is devoted to derive an explicit expression of the effective foam thickness when subjected to deep underwater explosion. Hereinafter, the effective foam thickness represents the crushed foam when the shock energy is just completely absorbed, i.e. the attenuation/enhancement boundary. One-dimensional (1D) analytical model which can consider the core crushing, the fluid-structure interaction (FSI), the cavitation phenomenon and the initially applied static pressure is proposed to solve the problem. The analytical model is then used for the parametric study. Finally, the empirical formulae of the effective foam thickness is derived from the results of the parametric study. In practical applications, the empirical formulae for the effective foam thickness can guide the design of such cellular claddings to water blast.

1. Introduction

Warships and submarines can be severely damaged by underwater explosion shock loadings (Liang and Tai, 2006; Zhang et al., 2011; Ming et al., 2016). To enhance the shock resistance ability of such weapons, one method is to design effective surface shields to protect the warships (Kim and Shin, 2013). Cellular materials possess superior energy absorption capability and are widely used in resistance of shock/impact loadings (Liang et al., 2001; Fleck and Deshpande, 2004; Karagiozova et al., 2010; LeBlanc and Shukla, 2015; Schiffer and Tagarielli, 2014, Jin et al., 2016, 2017). However, some studies demonstrated that if the total energy of the blast impact loading is not effectively absorbed by the cellular material, it results in an enhancement of the transmitted force to the protective structure (Cooper et al., 1991; Ben-Dor et al., 1994; Li and Meng, 2002; Harrigan et al., 2010). This is an unwanted situation in practical applications. Motivated by this fact, we devote to derive an explicit expression of the effective foam thickness needed to fully absorb the underwater shock energy in this paper. Hereinafter, the effective foam thickness represents the thickness of the crushed foam when the underwater shock energy is just fully absorbed, i.e. the attenuation/enhancement boundary.

There has been several papers studying the attenuation/enhancement boundary of sandwich structures with cellular cores to air blast loading (Aleyaasin et al., 2015; Turkyilmazoglu, 2016). Most recently, Turkyilmazoglu (2016) has derived an analytical solution for the response of a sandwich composite with a cellular core to the air blast. However, to derive an analytical solution for the similar structures to water blast is more difficult or even impossible since the involved the fluid-structure interaction (FSI) and cavitation phenomena are complex. A considerable body of literature exists on investigating sandwich structures to underwater explosion. The one dimensional (1D) analyses of Fleck and Deshpande (2004), Xue and Hutchinson (2004), Deshpande and Fleck (2005), Liang et al. (2007) and McMeeking et al. (2008) paid attention to how to calculate the problem more accurately by considering the FSI effects and cavitation phenomena. The models are gradually improved from the original Taylor's model (Taylor, 1963) to a simplified analytical model proposed by McMeeking et al. (2008) which could consider cavitation effects. Taking the above analyses into account, Yin et al. (2016a) proposed a full theoretical model which can considering the cellular material compression, the FSI effects, and the initiation and closure of cavitation bubbles for the cellular cladding to water blast. For the two dimensional sandwich beams, Tilbrook et al., (2006, 2009) divided the response into different regimes according to the intensity of the shock impulse and properties of the sandwich beams. They also found that there exists an optimum core strength for a given blast impulse and sandwich beam geometry, and a sandwich beam designed to be optimal for a given impulse is suboptimal for the other shock loadings. Therefore, the design work of such protective structures will become more concise and convenient if we know when a designed cellular protective structure attenuates/

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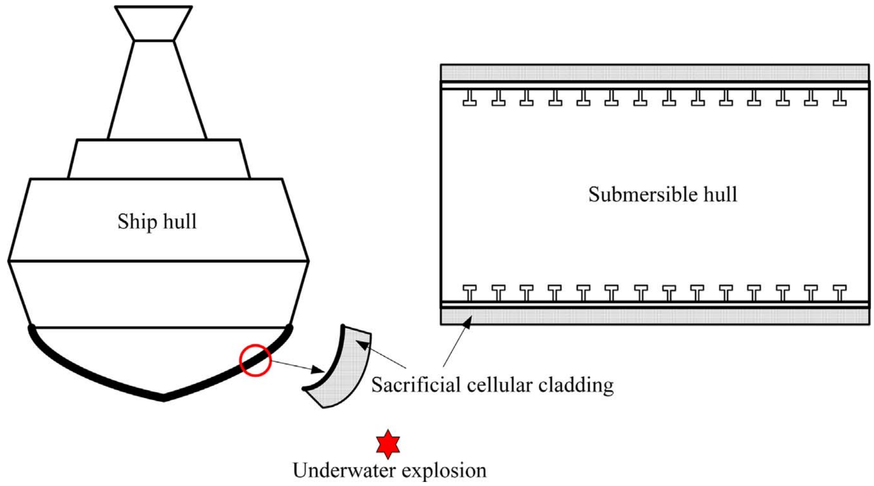

Fig. 1. The potential schematic map of using sacrificial cellular cladding as the protective structures of ship hulls or submersible structures.

enhances the underwater shock loading. Up to now, there is no study dealing with this problem. In this paper, we will analyze this problem from the simplest 1D case by calculating the effective foam thickness under different intensities of water blast.

There are two primary objectives in the present paper. First, the analytical model in Yin et al. (2016a) is modified by adding the initially applied static pressure to consider both shallow and deep water blast. Then, the sensitivity of the effective foam thickness to different parameters (including the intensity of the shock wave and the static pressure, and the properties of the cellular materials) is discussed using the analytical model to derive the explicit expression of the effective foam thickness. The derived explicit expression of the effective foam thickness is very useful for optimal designs of cellular claddings against underwater shock loadings.

2. Analytical model of cellular claddings under water blast loading

Fig. 1 gives the potential schematic map of using sacrificial cellular cladding as protective structures of ship hulls or submersible structures. Under water blast, the cellular materials will be sacrificed to absorb shock energy, thus decrease the energy and the stress transmitted to the ship hulls. If the cellular cladding is thin and cannot completely absorb the shock energy, the stress enhancement will take place in the ship hull and even enlarge the local hull response (Harrigan et al., 2010; Yin et al., 2016b). Therefore, the prediction of the effective thickness of the cellular cladding during the design is important. In this paper, we will analyze this problem from a 1D case, where the ship/submersible structure hulls are assumed to be clamped. When subjected to underwater explosion shock wave, the cellular cladding has been identified as the cellular material crushing phase and the FSI phase in a coupled way. In this section, we present the details of the analytical model, including the compaction mechanism of the cellular cladding, the FSI and cavitation phenomena.

2.1. Model description

The cladding is comprised of a rigid front face sheet with area density of m_f and a compressible cellular foam core, as shown in Fig. 2(a), where the rear end of the core is clamped. The foam core is modelled by an idealized rigid-perfectly plastic-locking (RPPL) material model. In the RPPL idealized material model presented by Reid and Peng (1997), two material parameters are used to define the material properties: the plateau stress σ_{pl} and the densification strain ε_D (Fig. 2(a)).

The initial static pressure in water is p_{st}, resulting in the initial stress in the foam before the blast loading. For a 1D problem, the initial stress in the foam equals to the initial static pressure. If the static pressure exceeds the yield strength of the foam, the cladding will be crushed before the arrival of the blast loading and cannot dissipate the shock energy anymore. Therefore, the static pressure analyzed in this paper is less than the yield strength of the foam. An underwater shock wave travelling in the positive x direction at a speed c_w impinges on the front face sheet. The origin of Eulerian coordinates locates at the wet face (static equilibrium position), and the water with density ρ_w occupies the region $x \le 0$. The exponentially decaying incident wave with time constant θ can be expressed by (Cole, 1948)

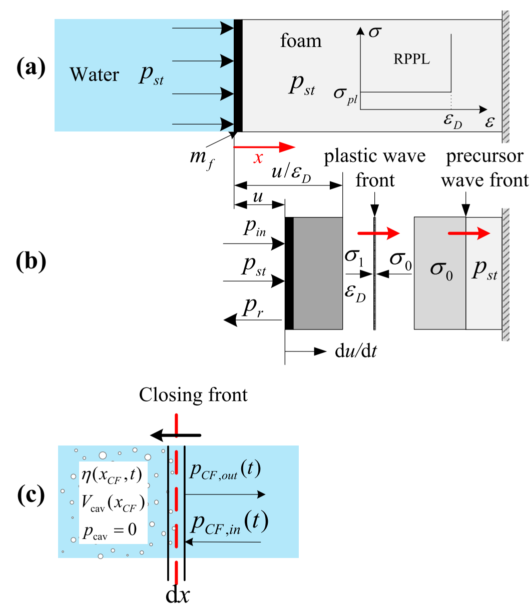

Fig. 2. (a) The sketch for a cellular cladding subjected to the shallow/deep water blast; (b) Compression of the cellular material to water blast loading; (c) The closure of cavitation bubbles.

$$p_{in}(x, t) = p_0 \exp[-(t - x/c_w)/\theta], \tag{1}$$

where p_0 is the peak pressure.

2.2. Compaction mechanism of cellular cladding

Under water blast, there are two waves, the elastic precursor wave and the compaction plastic wave, travelling through the cellular material (Fig. 2(b)). The latter is a plastic unloading wave with a