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Underwater blast loading of water-backed sandwich plates with elastic cores: Theoretical modelling and simulations

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ABSTRACT

Analytical predictions and finite element (FE) calculations are performed to predict the 1D response to underwater blast loading of sandwich plates with elastic cores, in contact with water on both sides and loaded by an exponentially decaying shock wave on one side. The theoretical models explicitly account for cavitation processes and effects of deep water, and their formulation helps identifying the governing parameters of the problem. Three characteristic regimes of behaviour are identified and regime maps are constructed. The analytical models are validated by FE simulations and used to explore the sensitivity of the predictions to the governing non-dimensional parameters. It is shown that, in the absence of plastic core deformation, sandwich plates with stiff cores are imparted higher blast impulses compared to those with softer cores and equivalent areal mass.

1. Introduction

A major consideration in the design of naval components is their resistance to withstand blast loading in water. In the last decades, sandwich panels have found increasing engineering use in commercial and military marine vehicles because they combine high stiffness, low mass and the capability to absorb kinetic energy by plastic core crushing. However, if the intensity of blast loading is relatively low (e.g. in case of a large stand-off distance from the detonation point) and the collapse strength of the core is sufficiently high (e.g. metal honeycomb cores), core crushing does not occur and the sandwich undergoes a linear elastic response. A detailed examination of this latter case is necessary if sandwich plates are to be designed to sustain blast loading with negligible plastic deformations.

The loading applied to a structure in an underwater blast event is highly sensitive to the details of the ensuing fluid–structure interaction (FSI) processes taking place during the early stage of the loading phase. A profound understanding of these processes is crucial to achieve optimal design against underwater blast. Early studies on FSI in underwater blast date back to World War II and were published in the 1950s by the Office of Naval Research [1]. The pioneering work of Taylor [2] examined the response of a free-standing rigid plate loaded by an underwater shock wave in water and found that the transmitted momentum is highly sensitive to the plate's mass. He showed theoretically that the reductions in momentum are a consequence of the occurrence of cavitation spreading at the fluid-structure interface.

The underlying physical phenomena of shock-wave induced cavitation in water were first studied by Kennard [3]. He found that the cavitated liquid expands by propagation of two *breaking fronts* (BF) emerging from a single nucleation point and propagating in opposite directions at supersonic speed. Subject to the conditions in the water, a propagating BF may turn into a *closing front* (CF) forcing contraction of the cavitation zone.

Later, it was shown that Kennard's theory can be used to predict the underwater blast response of submerged structures [4], concluding that the propagation of BFs and CFs (and hence, the loading on the structure) depend on the problem geometry, material properties, the characteristics of the shock wave and on the hydrostatic pressure in the fluid prior to the blast.

Recent literature in underwater blast loading focused on the benefits of replacing monolithic structures with crushable sandwich plates. Several studies have shown that sandwich panels widely outperform monolithic designs of equal mass if the core material and geometry are adequately selected [5–9]. It was found that sandwich plates exhibit a different FSI mechanism compared to that of monolithic plates [5,10]: for a sandwich plate with crushable core, cavitation initiates at a finite distance from the fluid-structure interface due to the resistance offered by the core. On the other hand, if the core response is purely elastic, two cavitation zones may initially appear in the water, as reported by Mäkinen [11]. Experimental evidence for these findings was provided by other researchers [12–14] who measured the propagation of cavitation fronts using a

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transparent shock tube. Other authors used steel shock tubes or explosive devices to measure the underwater blast resistance of sandwich plates [15–18] but did not visualise the cavitation process.

The underwater blast response of sandwich plates does not only entail complex FSI processes, it may also result in structural damage and failure if the loading intensity is sufficiently high. Wei et al. [19] developed detailed 3D FE models to examine deformation and failure of monolithic composite plates and sandwich panels, concluding that core crushing and face sheet failure are highly sensitive to the details of the cavitation process. Avachat and Zhou [20] followed a similar approach to examine damage and failure mechanisms in both air-backed and water-backed sandwich plates, concluding that low-density cores consistently outperform those with higher densities in terms of face sheet deflection and sustained blast impulse.

Other authors developed simplified analytical models to study the details of the cavitation process, and its effect on the structural response. For example, Deshpande and Fleck [10] and Hutchinson and Xue [21] developed analytical models for the 1D underwater blast response of sandwich plates with crushable cores and accounted for the FSI effect by assigning an *attached water layer* to the front face sheet, as a consequence of cavitation occurring at a finite distance. McMeeking et al. [22] modelled the cavitation process in more detail, assuming that the cavitated fluid spreads by propagation of two BFs, and considering the possibility of the emergence of a reconstitution wave (equivalent to the notion of a *closing front*). On the other hand, the analysis of McMeeking et al. [22] did not explicitly account for the reflection of pressure waves at the propagating cavitation front and the effect of a non-vanishing initial hydrostatic fluid pressure. Theoretical work by Schiffer et al. [4] analysed such effects for the case of underwater blast loading of a rigid plate supported by a linear spring, concluding that FSI is extremely sensitive to initial pressure in the fluid. These models capture propagation of breaking fronts and closing fronts as well as their interactions with the structure in a blast event. Later, the latter approach [4] was used by other authors to assess the performance of different types of claddings in terms of underwater blast mitigation [23,24].

In this study we examine the 1D response to underwater blast loading of a sandwich plate with an elastic core and rigid face sheets; both face sheets are considered to be in contact with water. Following the approach of Schiffer et al. [4], we construct analytical models capable of replicating the details of the cavitation process, including propagation of breaking fronts and closing fronts in the fluid, and its effect on the response of the sandwich plate. Theoretical predictions are compared to results obtained from fully-coupled dynamic FE calculations, and the effect of face sheet mass, spring stiffness and initial fluid pressure on the impulse imparted to the sandwich are explored. Non-dimensional regime maps and performance charts are constructed to provide guidelines for blast resistant design.

The outline of the paper is as follows: in Section 2 we derive the governing equations of the analytical model, identify characteristic regimes of behaviour and present non-dimensional regime maps; a description of the FE scheme is presented in Section 3; we compare analytical and FE predictions in Section 4; in Section 5, we explore the sensitivity of the structural response to the governing non-dimensional parameters, and finally, in Section 6, we summarise the main findings of this study.

2. Analytical modelling

2.1. Wave propagation and fluid–structure interaction

In this section we present the governing equations for the propagation of blast waves in water and their interaction with surrounding structural interfaces. We assume that the explosive charge is sufficiently far away from the structure, resulting in a nearly planar shock front travelling at approximately sonic speed in water. According to Cole [25], the primary shock wave can be expressed as an exponentially decaying pressure versus time pulse

$$p_{pos}(x,t)=p_0 e^{-(t-x/c_w)/\theta}, \tag{1}$$

for a wave travelling in the positive x direction at an arbitrary time t. The peak pressure p_0 and the decay time θ are set by the characteristics of the blast [25]. At time $t = 0$, the shock-wave (1) reaches the fluid-structure interface located at $x = 0$, and reflects back into the fluid column. The reflected wave, travelling in the negative x direction, is given by

$$p_{neg}(x,t)=p_0 e^{-(t+x/c_w)/\theta}. \tag{2}$$

In case of a rigid, stationary interface the total interface pressure is given by $p_{pos}(0,t)+p_{neg}(0,t)$ and results in an imparted impulse

$$I_0=2\int_0^\infty p_0 e^{-t/\theta}dt=2p_0\theta. \tag{3}$$

Now, instead of a stationary interface, assume that the loaded structure is an unsupported rigid plate free to move in the x direction. Then, upon arrival of the pressure wave (1) at the fluid-structure interface, the plate is set in motion and compatibility dictates that the plate and the fluid at the interface must have equal velocity $v_f(t)$; plate motion in the positive x direction gives rise to a rarefaction wave of magnitude

$$p_{rare}(x,t)=-\rho_w c_w v_f(t+x/c_w) \tag{4}$$

emanating from the fluid-structure interface and travelling in the negative x direction, away from the plate. The total fluid pressure at an arbitrary point x in the front water column is then given by superposition of Eqs. (1), (2), (4) and the initial hydrostatic fluid pressure p_{st}:

$$\begin{aligned}p(x,t)&=p_{st}+p_{pos}+p_{neg}+p_{rare}=p_{st}+p_0 e^{-(t-x/c_w)/\theta}\\&\quad+p_0 e^{-(t+x/c_w)/\theta}-\rho_w c_w v_f(t+x/c_w).\end{aligned} \tag{5}$$

Similarly, the particle velocity field in the water $v_w(x, t)$ is obtained by superimposing the particle velocity fields associated with incident, reflected and rarefaction waves. This gives

$$v_w(x,t)=\frac{p_{pos}}{\rho_w c_w}+\frac{p_{neg}}{\rho_w c_w}+\rho_w c_w v_f(x,t+x/c_w). \tag{6}$$

The tensile rarefaction wave can cause the pressure to drop to the value of the cavitation pressure of the fluid p_c, at location x_c and time t_c. In typical underwater blast events ($p_0 \approx 100$ - 200 MPa), the value of the cavitation pressure can be neglected; hence, we assume $p_c = 0$ in all calculations, consistent with assumptions of previous studies in this field [12–16].

The cavitation process is manifested by an expanding zone of cavitated water bounded by propagating cavitation fronts, acting as reflecting interfaces and affecting the pressure fields in the fluid. Hence, Eq. (5) needs to be modified to account for these effects. Accordingly, we define as 'Stage-I' the response prior to the onset of cavitation, while we denote as 'Stage-II' the response subsequent to this event.

2.2. Response prior to cavitation (Stage-I)

With reference to Fig. 1, we proceed to derive the governing equations for the Stage-I response of a sandwich plate comprising of an elastic core (stiffness k per unit area) and two rigid face sheets of equal mass per unit area m; both face sheets are in contact with water (density ρ_w, speed of sound c_w) at uniform initial pressure p_{st}. The sandwich is loaded at the front face by