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One-dimensional response of sandwich plates to underwater blast: Fluid-structure interaction experiments and simulations

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ABSTRACT

Fluid-structure interaction (FSI) experiments and finite element (FE) calculations are performed in order to examine the one-dimensional response of water-backed and air-backed sandwich plates subject to blast loading in either deep or shallow water. The sandwich plates comprise rigid face sheets and low-density foam cores. Experiments are conducted in a transparent shock tube, allowing measurements of both structural responses and cavitation processes in the fluid. Measurements are found in good agreement with predictions and allow concluding that the advantages of using the sandwich construction over the monolithic one are maximised for the case of water-backed sandwich plates in deep water.

1. Introduction

Underwater explosions give rise to spherical shock waves, travelling in water at approximately sonic speed [1] and impinging on surrounding structures. At sufficient distance from the point of detonation, such waves can be taken as planar and their shape can be described by an exponentially decaying pressure versus time pulse, with peak pressure and decay time depending on the mass and type of explosive as well as on the distance from the detonation point [2].

In order to design structural components against underwater blast, fluid-structure interaction (FSI) needs to be thoroughly understood. First studies on FSI date back to World War II; Taylor [3] theoretically investigated the response of a free-standing rigid plate loaded by an underwater shock wave and found that the momentum transmitted to the plate is decreased by reducing its mass, with the reductions attributed to the occurrence of cavitation at the fluid-structure interface.

Kennard [4] theoretically examined the one-dimensional phenomena consequent to shock-wave induced cavitation in elastic liquids. He found that when the pressure drops below the cavitation limit at a point in the fluid, two 'breaking fronts' emerge from this point and propagate in opposite directions, defining an expanding pool of cavitated liquid. Subsequently, such breaking fronts may arrest, invert their motion and become 'closing fronts', forcing contraction of the cavitation zone. The evolution of the cavitation process depends on the problem geometry, the structural response, the characteristics of the blast wave and on the hydrostatic pressure in the fluid prior to the blast event.

During the last decade extensive research was conducted to assess the advantage of replacing monolithic structures by sandwich panels of equivalent mass. Several numerical and theoretical studies have shown that sandwich constructions can outperform monolithic designs of equal mass for a large range of core topologies [5–9]. These studies concluded that upon loading a sandwich plate with an exponentially decaying pulse, cavitation initiates at a finite distance from the fluid-structure interface, as a consequence of the support offered by the sandwich core to the front face sheet.

Deshpande and Fleck [10] and Hutchinson and Xue [11] developed analytical models for the 1D response of sandwich plates subject to blast in shallow water and treated FSI subsequent to first cavitation by conjecturing the existence, as a consequence of FSI, of an attached layer of water to the front face sheet, increasing the momentum transmitted to the sandwich plate. Later, Liang et al. [5] and McMeeking et al. [12] provided more detailed analytical models for FSI in underwater blast loading of sandwich structures; in particular, the models of McMeeking et al. [12] assumed that the cavitated fluid, initially appearing at a finite distance from the fluid-structure interface and expanding by propagation of two breaking

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fronts, reaches the front face sheet of the sandwich, thus causing the interface pressure to vanish and giving rise to a reconstitution wave (closing front) which propagates away from the structure and creates a layer of attached water, hence providing additional momentum to the front face sheet. However, the latter analysis did not explicitly account for the interaction between pressure waves reflected from the advancing breaking front and the structural interface and neglected the effect of a non-vanishing initial hydrostatic fluid pressure on the structural and fluid response.

Recent theoretical work by Schiffer et al. [13] 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 and their predictions were found to be in excellent agreement with dynamic FE calculations.

Early experimental work in underwater blast loading was carried out during Second World War and an extensive part of this research is found in Ref. [14]. Several studies focused on dynamic deformation and failure modes of real-size naval structures consequent to blast loading in explosive test facilities [15–17]. In order to minimise the time and cost required for large-scale tests, experimental methods at laboratory scale have been developed. Deshpande et al. [18] designed an experimental apparatus able to simulate 1D underwater blast loading in a water-filled steel shock tube. The apparatus was employed to measure the momentum transmitted to foam-cored sandwich plates. The momentum transmitted to the sandwich plates was found to be substantially lower than that delivered to monolithic plates of equal mass, consistent with the findings of previous theoretical and numerical studies [5–9]. This underwater shock simulator [18] was then employed by McShane et al. [19] who probed the blast performance of free-standing sandwich plates with metallic lattice cores via measuring transmitted momentum and permanent core compression.

Espinosa et al. [20] followed a similar approach and designed a divergent shock tube to investigate dynamic deformation of circular clamped monolithic plates subject to underwater blast loading and used scaling rules to mimic the response of naval structures of realistic dimensions. Plate deformation histories were measured by observing shadow Moiré fringes with a high-speed camera. Subsequently, other authors [21–23] employed this experimental method [20] to study damage mechanisms and failure modes exhibited by monolithic plates and sandwich panels consequent to blast loading and provided further experimental evidence for the benefits of sandwich construction in terms of blast resistance. LeBlanc and Shukla [24] also used a water-filled conical shock tube to examine underwater blast loading of clamped composite plates but with the shock wave generated via internal detonation of an explosive charge. Wadley et al. [25] designed an underwater explosive test rig comprising a water-filled cardboard cylinder placed on a steel plate machined with a recess in which the sandwich specimen was located. Shock waves were generated in the water cylinder by detonation of an explosive sheet and the loads transmitted to the supports were deduced from load-cell measurements.

The experimental methods quoted above do not allow observation of cavitation fronts and of the effects of an initially applied static pressure in the fluid prior to blast loading. Recently, Schiffer and Tagarielli [26] developed an experimental probe capable of reproducing blast loading in initially pressurised water, in order to mimic blast in deep water. The apparatus consists of a shock tube made from a transparent material, which allows observing the structural response as well as cavitation processes in the fluid.

The studies above did not provide a complete understanding of the blast resistance of sandwich panels:

- They only considered blast loading of sandwich structures in contact with water on one side and with air on the opposite side (air-backed), but did not examine the case of sandwich plates wetted by water on both sides (water-backed); the latter is relevant to the response of fin-like structures exposed to the threat of underwater blast, and we shall examine it in this paper.
- They did not consider the effect of an initial hydrostatic pressure in the fluid, and are therefore only relevant to blast loading of surface vessels; the apparatus developed by Schiffer and Tagarielli [26] allows subjecting the fluid to an initial pressure superimposed to the blast wave and it will be used in this study to investigate the 1D response to blast in deep and shallow water, i.e. at high and low (atmospheric) initial static pressure.
- They reported measurements of the structural response but not of the response of the fluid. Theoretical models, consequently, had to rely on simplifying assumptions on the response of the fluid; the technique we are reporting in this study, allowing visualisation of cavitation fronts, will permit us to correct some of these assumptions and to provide experimental evidence for the findings of previous theoretical studies [5,10,11].

A combination of dynamic pressure measurements and analysis of high-speed photographs is employed in this study to deduce the sensitivity of the imparted impulse to all governing parameters. The outline of this paper is as follows: in Sections 2 and 3 we describe the experimental techniques, while details of the FE calculations are provided in Section 4. Results are presented in Section 5 and discussed in Section 6.

2. Specimen design and manufacture

Dimensional analysis dictates that the problem under investigation is governed by the following set of independent non-dimensional parameters

$$\psi = \frac{\rho_w c_w \theta}{m}; \quad \overline{m}_f = \frac{m_f}{m}; \quad \overline{p}^*_{st} = \frac{p_{st}}{\sigma_c}; \quad \overline{\sigma}_c = \frac{\sigma_c}{p_0}; \quad \overline{E} = \frac{E_c}{\sigma_c}; \quad \varepsilon_D, \tag{1}$$

where ρ_w, c_w are density and speed of sound in water (respectively), p_{st} is the initial hydrostatic pressure in the fluid, p_0, θ are the peak pressure and the decay time constant of the exponentially decaying blast wave, σ_c, E_c, ε_D are collapse stress, elastic modulus and densification strain of the core material, while m_f, m represent the areal masses of a single face sheet and the entire sandwich panel, respectively. While the choice of these non-dimensional parameters is not unique, in this study we shall employ the set defined in eq. (1), as this was adopted in previous investigations.

Assuming that the relevant properties of the materials employed are independent of size, the problem under investigation is scale-independent. This assumption is in line with that of other authors, and justified by the fact that the relevant length-scales associated with the response of cellular solids and water are at the micron scale and below. It follows that the response to blast of large naval structures can be measured at laboratory scale by adopting a scaled-down experimental setup, with a set of non-dimensional parameters (1) identical to that of full-size structures. In the case of military vessels such as warships and submarines, highly exposed to the risk of blast loading, typical ranges of the non-dimensional parameters (1) are

$$1 < \psi < 7; \quad \overline{m}_f \approx 0.5; \quad \overline{p}^*_{st} < 1; \quad \overline{\sigma}_c < 1 \tag{2}$$

In this study, the choice of specimen geometry and loading parameters will be such to thoroughly explore these ranges.