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The one-dimensional response of a water-filled double hull to underwater blast: Experiments and simulations

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ABSTRACT

Laboratory-scale fluid–structure interaction (FSI) experiments and finite element (FE) simulations are performed to examine the one-dimensional blast response of double-walled hulls, consisting of two skins sandwiching a layer of water. Both monolithic and sandwich designs are considered for the outer skin. Experiments are conducted in a transparent shock tube which allows measurements of water cavitation and hull response by high-speed photography. Experiments and FE predictions are found in good agreement and allow concluding that the impulse imparted to double hulls by underwater explosions can be dramatically reduced by employing the sandwich construction of the outer skin; such reductions are scarcely sensitive to the thickness of the water layer.

1. Introduction

Hulls of underwater vessels may consist of an inner pressure hull encapsulated in an outer skin structure; the gap between these hulls may be flooded with water to control buoyancy. Understanding the response of such structures to underwater explosions is of crucial importance in defence applications; the lack of scientific publications on this subject motivates the present work.

The detonation of an explosive charge in water gives rise to spherical shock waves, travelling in water at approximately sonic speed [1]. At sufficient distance from the point of detonation, such waves can be treated as planar and the pressure history associated to the passage of this wave at a fluid particle can be described by an exponentially decaying pressure versus time pulse

$$p(t) = p_0 \exp(-t/\theta), \tag{1}$$

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 analysed. Pioneering studies on FSI date back to World War II; Taylor [3] analysed the response of a rigid, free-standing plate loaded by an underwater shock wave (Eq. (1)) and concluded that the momentum transmitted to the plate can be reduced by decreasing the plate's mass, owing to the occurrence of cavitation in the water next to the fluid–structure interface. Valuable insight into the evolution of such cavitation phenomena is given in Kennard [4]. He found that when the pressure drops below the cavitation limit at a point in the fluid, two 'breaking fronts' start propagating from this point in opposite directions, forming an expanding pool of cavitated fluid. Subsequently, such breaking fronts can arrest, invert their motion and become 'closing fronts', reducing the volume of cavitated fluid. The evolution of such cavitation fronts depends on the hydrostatic fluid pressure and the characteristics of the blast wave, as well as on structural response.

During the last two decades extensive research was conducted to assess the advantage of replacing monolithic structures by sandwich constructions of equivalent mass. Several numerical studies have demonstrated that sandwich plates can outperform monolithic designs of equal mass [5–9]. The role of FSI in the response of sandwich plates subject to underwater blast has been investigated in more detail by Deshpande and Fleck [10] and Hutchinson and Xue [11]. They found that the onset of the cavitation process is located at a finite distance from the fluid–structure interface and therefore assumed that a layer of water attaches to the front face sheet, resulting in additional impulse imparted to the

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sandwich. Later, Liang et al. [5] and McMeeking et al. [12] developed more detailed models for underwater blast loading of sandwich plates by including the effects of the collapse of the cavitation zone.

Recently, Schiffer et al. [13] examined the effect of a non-vanishing initial hydrostatic pressure in the water upon the blast response of a rigid plate supported by a linear spring; they concluded that FSI is extremely sensitive to initial pressure in the fluid. These models accurately capture the emergence and propagation of breaking fronts and closing fronts, as outlined in Ref. [4], without using simplifying assumptions.

Early experimental work on underwater blast loading was published by the U.S. Office of Naval Research (ONR) [14]. Several studies focused on dynamic deformation and failure modes of real-size naval structures subject to blast loading in explosive test facilities [15–17]. In order to reduce the time and cost required for large-scale tests, experimental methods at laboratory scale have since been developed. Deshpande et al. [18] designed an experimental apparatus able to generate realistic underwater blast waves in a water-filled steel shock tube and used it to simulate 1D blast loading of monolithic plates and foam-cored sandwich panels. Subsequently, McShane et al. [19] employed this underwater shock simulator [18] to perform blast loading on free-standing sandwich plates with metallic lattice cores, measuring transmitted momentum and permanent core compression and providing experimental evidence for the benefits offered by the sandwich construction in terms of blast performance. Espinosa et al. [20] followed a similar approach and designed a divergent shock tube to measure dynamic deformation of clamped plates subject to underwater blast loading. This apparatus was then employed by Refs. [21–23] to study failure modes and damage mechanisms exhibited by monolithic plates and sandwich panels in an underwater blast event. Wadley et al. [24] performed underwater blast loading on sandwich specimens by using an underwater explosive test rig comprising a water-filled cardboard cylinder placed on a recessed steel plate in which the specimen was located, capable of measuring the loads transmitted to the supports in a blast event.

Recent experimental work on FSI in underwater blast was carried out by Schiffer and Tagarielli [25], who developed an experimental apparatus able to reproduce blast loading in initially pressurised water, in order to simulate blast loading in deep water. The apparatus consists of a shock tube similar to that used in Ref. [18] but made from a transparent material, to allow observation of specimen motion and cavitation phenomena in the water.

Subsequently, this apparatus [25] was used by Schiffer and Tagarielli [26] to examine the 1D response of water-backed and air-backed sandwich plates to blast in deep or shallow water, measuring the propagation velocity of cavitation fronts as well as core crush and impulse imparted to the sandwich, and providing experimental evidence for theoretical predictions [4,5,10,11] in the process.

Double-walled hull construction complicates the prediction of structural loading consequent to underwater blast, as pressure waves travelling in the water layer between the two hulls can significantly affect the ensuing cavitation process as well as the overall structural response; such phenomena need to be thoroughly understood. In this study we employ the apparatus developed in Ref. [25] in order to investigate the response of water-filled double hulls subject to underwater blast. In the process, we consider two practical design concepts: (i) double hulls with monolithic skins and (ii) double hulls with monolithic inner skin and sandwich outer skin. High-speed photography is employed to observe the dynamic structural response as well as cavitation processes in the water. Dynamic fluid pressure measurements serve to deduce the impulse imparted to the inner hull and to explore its sensitivity to the thickness of the water layer.

The outline of this paper is as follows: in Section 2 we define the problems under investigation; in Section 3 we briefly describe the laboratory setup, specimen manufacture and we outline the experimental programme, while details on the FE simulations are given in Section 4; results obtained from the experiments and FE calculations are presented and discussed in Section 5 and we summarise the main findings of this study in Section 6.

2. Problem definition

In this study, the response of double hulls subject to underwater blast is examined. Two different design concepts are considered and described below.

2.1. Monolithic double hull

The schematic in Fig. 1a illustrates the geometry of a double hull consisting of two rigid plates separated by a water layer of thickness D. We define as 'outer skin' the plate in contact with water on both sides while the underlying inner structure is termed as 'inner hull' and is in contact with water on the front face only. The outer skin (of mass per unit area m_F) is loaded on the outer surface by an exponentially decaying shock wave (Eq. (1)) of peak pressure p_0 and decay time θ. Subsequently, pressure waves transmitted into the water layer impinge on the inner hull (of mass per unit area m_B).

2.2. Sandwich double hull

The problem geometry for a sandwich double hull is sketched in Fig. 1b. It comprises of a monolithic inner hull (areal mass m_B) and an outer skin of sandwich construction (areal mass m_F), with a water layer (thickness D) located between outer skin and inner

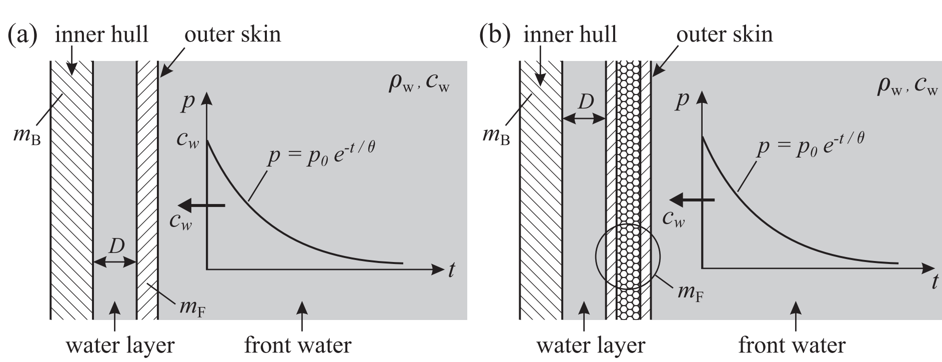

Fig. 1. Sketches of problem geometry and loading case for (a) monolithic design and (b) sandwich design.