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The response of circular composite plates to underwater blast: Experiments and modelling

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ABSTRACT

We present a new experimental technique to allow laboratory-scale observation of underwater blast loading on circular plates, including dynamic deformation and failure of the plates as well as the sequence of cavitation events in water. The apparatus is used to measure and compare the responses of a quasi-isotropic glass/vinylester composite and of a woven carbon/epoxy plate. Dynamic explicit FE simulations are conducted and their predictions are found in good agreement with experiments. Measurements and FE predictions are used to validate a recently developed theoretical model for the response of elastic orthotropic plates to underwater blast.

1. Introduction

A major concern in the design of naval composite structures is their ability to withstand intense dynamic loading consequent to an explosion in water. Underwater explosions give rise to spherical pressure waves propagating in the water at approximately sonic speed (Cole, 1948); at sufficient distance from the detonation point, such shock waves[1] can be taken as planar and their history can be approximated by an exponentially decaying pressure versus time pulse

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

where peak pressure p_0 and decay time θ depend on the mass and type of explosive material as well as on the stand-off distance (Swisdak, 1978).

1.1. Review of theoretical and numerical work on underwater blast loading

The loading applied on submerged structures in the vicinity of the blast can cause severe deformation and failure and is strongly affected by fluid–structure interaction (FSI). The first theoretical studies on FSI in underwater blast date back to the early 1940s; Taylor (1963) first analysed the response of a free-standing rigid plate subject to loading by an underwater shock wave, as given in Eq. (1), and concluded that the momentum transmitted to the plate is reduced by decreasing the plate's mass, promoting early cavitation in water.

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[1] Shock waves are intended here as discontinuities in the pressure distribution, propagating at sonic speed.

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Great insight into the cavitation process triggered by pressure waves propagating in a bi-linear elastic fluid is given in Kennard (1943). He found that cavitation zones spread by propagation of a 'breaking front' (BF) emanating from the point of first cavitation and forming an expanding pool of cavitated fluid. Such breaking fronts can arrest and invert their direction of motion, thus becoming 'closing fronts' (CF) and reducing the volume of cavitated fluid.

Several numerical and theoretical studies on FSI have focused on the response of metallic monolithic and sandwich structures (Deshpande and Fleck, 2005; Hutchinson and Xue, 2005; Liang et al., 2007; McMeeking et al., 2007). Schiffer and Tagarielli (2014a) investigated theoretically the response of circular elastic composite plates subject to underwater blast, by extending previously developed one-dimensional FSI models (Schiffer et al., 2012). These predictions will be validated by the experiments reported in this study.

1.2. *Review of experimental work on underwater blast loading*

Early experimental research in underwater blast loading is published by the US Office of Naval Research (1950). During the last decades several studies focused on dynamic deformation and failure modes exhibited by real-size naval composite and steel structures consequent to blast loading in explosive test facilities (Hall, 1989; Mouritz et al., 1994; Ramajeyathilagam and Vendhan, 2004). However, such experiments are time-consuming, cost-intensive and require extensive control and safety measures. Because of these issues recent advances in experimental methods have focused on simulating underwater blast loading in a laboratory environment (Deshpande et al., 2006; Espinosa et al., 2006; Latourte et al., 2011; Mori et al., 2007, 2009; Wadley et al., 2008), Deshpande et al. (2006) developed an experimental apparatus able to simulate realistic underwater blast loading in a water-filled metallic shock tube, and used it to probe the 1D blast response of free-standing monolithic plates and sandwich panels, concluding that the sandwich construction offers remarkable benefits in terms of the impulse imparted to a structure in a blast event.

Due to their high specific stiffness and strength, composites are a candidate material to replace metallic alloys in blast-resistant components; this is due to FSI: These lighter and softer materials, deforming rapidly upon blast loading, promote early fluid cavitation and in general reduce the impulse transmitted to the structure. On the other hand, these materials possess a relatively low ductility when compared to metals, which limits their range of application.

The dynamic response of composite plates is dominated by elastic deformation up to catastrophic, brittle failure. It is necessary to measure this elastic response, which entails transient propagation of radial flexural waves. Only a few authors have provided detailed deflection histories for metallic or composite plates subjected to underwater blast, due to the complexity of the measurements. Espinosa et al. (2006) designed a divergent steel shock tube to investigate 3D dynamic deformation of circular clamped composite plates subject to underwater blast. Exponentially decaying shock waves were generated by firing a projectile at a sliding water piston, as in Deshpande et al. (2006). Plate deformation histories were measured by observing shadow Moiré fringes with a high-speed camera. LeBlanc and Shukla (2010) also used a water-filled shock tube to examine underwater blast loading of clamped composite plates but with the shock wave generated via internal detonation of an explosive charge. An alternative experimental method to perform blast loading on submerged sandwich plates was developed by Wadley et al. (2008). They designed an underwater explosive test rig comprising a water-filled cardboard cylinder placed on a recessed steel plate in which the sandwich specimen was located. Shock waves were generated in the water cylinder by detonation of a sheet of explosive and the load transmitted to the supports in the dynamic tests was measured.

The experimental techniques above did not allow observation of cavitation in water, which deeply affects the structural loading history. Specifically, cavitation breaking and closing fronts act as partially reflective interfaces for pressure waves; the structural response is highly sensitive to the location and time at which breaking fronts and closing fronts develop as well as to their speed of propagation. Recently, Schiffer and Tagarielli (2012) developed a transparent shock tube capable of reproducing blast loading in shallow or deep water and to allow simultaneous observation of structural motion and fluid cavitation. This apparatus was then employed to examine the 1D response of sandwich plates to blast in deep water (Schiffer and Tagarielli, 2014c) and to investigate the response of water-filled double hulls subject to underwater blast (Schiffer and Tagarielli, 2014b).

1.3. *Scope and outline of study*

In this study we employ a modified version of the apparatus developed by Schiffer and Tagarielli (2012) in order to examine the response of fully clamped circular composite plates subject to underwater blast. The main objectives of this paper are

- to present a new technique to measure the dynamic deformation of composite plates subject to underwater shock in a laboratory setting, while allowing, for the first time, the simultaneous direct observation of the sequence of cavitation events in the fluid;
- to perform fully-coupled, detailed 3D dynamic FE simulations of the plate response and compare to experiments;
- to validate the predictions of a recently developed theoretical model (Schiffer and Tagarielli, 2014a) by measurements and FE predictions; and