The Response of Rigid Plates to Blast in Deep Water: Fluid-Structure Interaction Experiments

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Abstract

Laboratory-scale dynamic experiments are performed in order to explore the one-dimensional response of unsupported rigid plates to loading by exponentially decaying planar shock waves in deep water. Experiments are conducted in a transparent shock tube allowing measurements of plate motion and imparted impulse, as well as observation of cavitation in water, including motion of breaking fronts and closing fronts. Loading of both air-backed and water-backed rigid plates is examined, and the sensitivity of plate motion and imparted impulse to the structural mass and to the initial hydrostatic pressure in the water is measured. Experiments also serve to validate recently developed theoretical models, whose predictions are found in agreement with measurements.

Keywords: fluid-structure interaction, underwater blast, cavitation, shock-wave

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1. INTRODUCTION

The design of structures against underwater blast is of great interest to the defence and oil industries. Underwater blast events result in intense pressure waves propagating in water at the speed of sound and impinging on surrounding structures. The pressure associated with such waves decays exponentially in a short time, with peak pressure and decay time depending upon the mass and type of explosive, as well as on the distance from the detonation point (Swisdak (1978)); at sufficient distance from this point, blast waves can be considered planar.

In order to design submerged structures against blast loading, fluid-structure interaction need to be understood. An extensive body of literature exists on the subject; early theoretical work dates back to World War II: Taylor (1941) investigated the response of a rigid, unsupported plate loaded by exponentially decaying pressure waves in shallow water (i.e., in water at a negligible initial hydrostatic pressure, compared with the amplitude of blast waves); he found that the impulse transmitted to the plates can be reduced by decreasing their mass: lighter plates respond to blast loading with higher acceleration, promoting cavitation of water at the fluid-structure interface and forcing the loading at this interface to cease. Understanding of cavitation is paramount when studying FSI in underwater blast events. Theoretical work by Kennard (1943) provided great insight into this; he found that when the pressure drops below the cavitation limit at a point in a liquid, 'breaking fronts' emerge from this point and propagate outwards, forming an expanding region of cavitated liquid. Subsequently, subject to certain conditions, such breaking fronts can arrest, invert their motion and become 'closing fronts', reducing the volume of cavitated fluid.

The evolution of cavitation fronts (breaking and closing fronts) strongly depends on the details of the problem investigated. Several authors have explored numerically the blast mitigation capacity of sandwich plates subject to underwater blast in shallow water (Liang e*t al.* (2007), Qiu *et al.* (2003), Tilbrook *et al.* (2009), Xue & Hutchinson (2004)) and found that sandwich plates can outperform monolithic plates of equivalent mass. In addition, they noted that the evolution of cavitation fronts is different for sandwich plates and rigid plates: in the case of a sandwich plate cavitation initiates at a finite distance from the fluid structure interface, due to the support offered by the sandwich core. Deshpande & Fleck (2005) and Hutchinson & Xue (2005) constructed approximate models assuming that the occurrence of cavitation at a finite distance from the structure results in a layer of water that attaches to the structure, effectively increasing its mass. Liang *et al.* (2007) and McMeeking *et al.* (2007) subsequently improved these theoretical models by explicitly modelling the propagation of cavitation fronts in water.

The above authors did not consider the effects of a non-negligible hydrostatic pressure in water prior to the blast event. Recently, Schiffer *et al.* (2011) demonstrated that the impulse imparted by blast waves to submerged structures, as well as the details of water cavitation, are strongly dependent on the initial hydrostatic pressure. This was done by explicitly modelling (theoretically and via FE simulations) the propagation of cavitation fronts, for the case of a one-dimensional, exponentially decaying pressure wave loading a rigid plate supported by a linear spring and in contact with pressurised water on either one side or both sides. Excellent agreement was found between the theoretical and numerical predictions of Schiffer *et al.* (2011); one of the objectives of this study is to provide experimental evidence in support of these predictions.

The response of structures to underwater blast is difficult to observe at laboratory scale and for this reason experimental studies have appeared only in the last decade. The pioneering work of Deshpande *et al.* (2006) provided experimental evidence for the findings of Taylor; these authors developed an apparatus able to produce one-dimensional, exponentially decaying blast waves in a metallic tube in a controlled manner, and used it to explore the sensitivity of the impulse imparted to monolithic and sandwich plates to the structural mass and the characteristic of the incident blast wave. Espinosa *et al.* (2006) followed a similar approach and designed a divergent shock tube to investigate the three-dimensional, dynamic response of clamped circular plates subjected to underwater blast in shallow water. Mori *et al.* (2007), Latourte *et al.* (2011) and Mori *et al.* (2009) employed the apparatus developed by Espinosa *et al.* (2006) to explore the failure modes of monolithic and sandwich plates. Wadley *et al.* (2008) employed explosive sheets in order to explore, at a laboratory scale, the response of different plates to one-dimensional blast waves, measuring the imparted impulse and its sensitivity to the characteristics of the incident shock.

The existing experimental techniques are capable of reproducing, at a laboratory scale, the dynamic response of structural components; on the other hand, none of them allows measuring the effects of an initially applied hydrostatic pressure in the fluid, which is fundamental in order to design structural components loaded by blast waves in deep water. In addition, while growth and collapse of cavitation bubbles in proximity of solid surfaces has been observed by several authors (for example: Benjamin & Ellis (1966), Lauterborn & Bolle (1975), Tomita & Kodama (2003)) in order to explore cavitation-induced erosion, no studies so far report direct observation of the propagation of cavitation fronts subsequent to structural loading by underwater blast.

In this study we shall fill these gaps in the literature by developing an apparatus to generate one-dimensional, exponentially decaying blast waves in initially pressurised water; we shall use this apparatus to study the response of both air-backed and water-backed unsupported rigid specimens and its sensitivity to initial static pressure and structural mass. In doing so we shall also provide experimental evidence supporting the theoretical findings of Kennard (1943) in case of blast loading; this will be achieved by direct observation of the cavitation processes and structural response by high speed photography. The experimental results will also be used to validate the predictions of the theoretical models by Schiffer *et al.* (2011).

The outline of the paper is as follows: in Sections 2 and 3 we define the problem under investigation and describe the experimental apparatus; experimental results are presented in and discussed in Section 4.

2. PROBLEM DEFINITION

The two one-dimensional problems under investigation are sketched in Fig.1 and briefly described below.

(i) *Loading of an air-backed rigid plate:* An unsupported rigid plate of mass per unit area m is in contact on one side (front face) with water at initially uniform hydrostatic pressure p_{st} and on the opposite side (back face) with air at the same pressure p_{st} in order to ensure initial equilibrium prior to dynamic loading by an exponentially decaying, planar blast wave impinging on the front face at $t = 0$ (Fig. 1a). The problem is equivalent to that of a rigid plate supported by a perfectly plastic foundation with compressive yield stress equal to p_{st}.

(ii) *Loading of a water-backed rigid plate:* A rigid plate of mass per unit area *m* is initially in contact with water at initially uniform hydrostatic pressure p_{st} on both sides. The plate is loaded by an exponentially decaying blast wave on one side (Fig. 1b).

3. EXPERIMENTAL APPARATUS

3.1 Transparent shock tube and instrumentation

The experimental technique developed in this study is an extension of that established by Deshpande *et al.* (2006); this technique is modified here in order to permit initial pressurization of the water and to allow direct observation of cavitation. The apparatus, sketched in Fig. 2, consists of a transparent shock tube of inner diameter $d = 27\,\text{mm}$ and length $L = 2\,\text{m}$. The tube was machined from a cast acrylic rod of density $\rho = 1190\,\text{kgm}^{-3}$, Young's modulus $E = 3.3\,\text{GPa}$ and tensile strength of approximately 80 MPa; honing of the bore provided a glossy finish to ensure clear observation of fluid and plate by high-speed photography. The wall thickness of the tube was chosen to guarantee no failure or plastic deformation upon loading by an internal pressure of 20 MPa, while the length was chosen to ensure sufficient time of observation of specimens placed inside the tube, prior to secondary loading due to reflections of pressure waves at the tube's ends. The same tube was used in two different configurations to explore the response of air-backed and water-backed plates, as described below.

Air-backed configuration: Cylindrical monolithic specimens were machined from stainless steel rods, fitted with two O-rings and inserted in the shock tube at a short distance from its distal end, as illustrated in Fig 2a. The shock tube was then filled, in a vertical position, with filtered tap water and closed by a sliding nylon piston, fitted with O-rings, at the opposite end (front end); the front piston included a bleed valve to evacuate air bubbles trapped in the water column prior to the experiments. The front end of the tube was provided with an anvil to avoid the front piston from being ejected when the water was pressurised.

In order to mimic the idealised problem sketched in Fig. 1a it is necessary to apply a constant, uniform pressure p_{st} at the specimen's back face and to pressurise the water column to the same hydrostatic pressure p_{st}. This was achieved by placing a foam cylinder in contact with the specimen’s back face and compressing this cylinder by quasi-static application of a force *F* (measured via a resistive load cell) immediately before the experiment; the force was increased until the desired pressure p_{st} was reached and an initial plastic strain of around 5% was induced in the foam cylinder. During the dynamic experiment, specimen motion induces additional plastic strain in the foam cylinder; however the plastic collapse of the foam occurs at constant stress during the plateau response of this compressible solid; the length of the foam cylinder was chosen to obtain a strain below the densification strain ε_D, thereby guaranteeing a constant back pressure p_{st}. Different Rohacell foams were employed to manufacture the foam cylinders and the cylinder’s cross-section was varied in order to adjust p_{st}. For experiments with air at atmospheric condition (i.e. approximately $p_{st} = 0.1\text{MPa}$) the supporting foam cylinder was not employed.

Note that if the plate is actually in contact with air on the back face, motion of the specimen induces an increase in back pressure proportional to the velocity of the plate; this velocity was small in our tests (< 15 ms^{-1}) and therefore such pressure increase was negligible compared to the initial pressure p_{st} and to the dynamic pressure induced by the blast wave. Compression of the foam during the dynamic experiments conducted in this study occurred at strain rates of the order of 10s^{-1}; the Rohacell foams employed in this study possess negligible strain rate sensitivity in the range $\dot{\varepsilon} = 10^{-3} \div 10^{3}\,\text{s}^{-1}$ (Arezoo *et al.* (2012)) and we therefore assume that the foams yield stress can be treated as a constant.

Water-backed configuration: In order to reproduce the problem sketched in Fig. 1b, the steel specimen was placed at the centre of the shock tube, separating the bore into two sections. Both front and back sections were filled with filtered tap water and both tube ends were closed with sliding nylon pistons as described above. To induce a hydrostatic pressure p_{st} in the water the sliding piston at the distal end of the tube was loaded with a compressive force *F* until the desired pressure was attained. Such force was not applied in experiments with $p_{st} = 0.1\text{MPa}$.

A Phantom 'Vision Research' (V7.1) high-speed camera was used to observe the motion of the specimen and the details of water cavitation. The pressure in the water columns was measured by piezoelectric pressure transducers manufactured by PCB Piezoelectronics Inc. (of type 113B23) and mounted flush to the inner surface of the tube; one of such transducers was placed at a distance of 120 mm from the front end of the tube in order to record the incident pressure versus time history. A second transducer was placed at a distance of 120 mm from the centre of the tube (on the distal side) in order to measure pressure waves emanating from the specimen's back-face during the dynamic experiments. Hoop resistance strain gauges were adhered to the external surface of the tube in order to provide triggering signals and additional readings of the pressure versus time history in the tube, as well as to measure the speed of wave propagation in the tube.

3.2 Generation of the shock wave

When a blast event takes place in deep water at initial pressure p_{st}, an exponentially decaying pressure wave is generated. At sufficient distance from the detonation point, the pressure versus time history associated with the passage of the pressure wave at a point can be written

$$p(t) = p_{st} + p_0 e^{-t/\theta} \tag{1}$$

where the peak overpressure p_0 and the decay time θ depend upon the mass and type of explosive material as well as the distance from the point of detonation.

The above pressure history (eq. (1)) was generated by impacting the nylon piston placed at the front end of the shock tube with a high-speed compound projectile made from a combination of stainless steel and a compressible foam. The reasons for using this setup, rather than a simpler steel cylinder as in Deshpande *et al.* (2006) are explained below. Prior to the loading phase, the nylon piston at the front end of the shock tube, of mass M_P, is subject to a static pressure p_{st}, whose action is equilibrated by the reaction force exerted by the anvil placed at the tube's end (Fig. 3a); such anvil imposes a unilateral constraint to motion of the nylon piston in the negative x direction. Now consider the inelastic impact of a cylindrical steel striker of mass M_S and velocity v_S on the nylon piston; treating both piston and striker as rigid bodies, and employing the acoustic approximation for the response of water, dynamic equilibrium of the combined striker-piston system can be written as

$$m_{S,P}\dot{v} = -p_{st} - \rho_w c_w v \tag{2}$$

where $m_{S,P}$ is the total mass of the striker-piston system divided by the cross section of the piston A_P, $m_{S,P} = \left(M_S + M_P\right)/A_P$, v is the system velocity, ρ_w and c_w are the density and speed of sound of water, respectively. The initial velocity of the striker-piston system is dictated by conservation of linear momentum and given by

$$v_0 = \frac{M_S\, v_S}{M_S + M_P}\,. \tag{3}$$

Equation (2) can be solved with the initial condition $v\left(t=0\right) = v_0$, giving the interface pressure $p\left(x=0,t\right) = p_{st} + \rho_w c_w v\left(t\right)$ as

$$p\left(x=0,t\right) = \left(p_{st} + p_0\right)e^{-t/\theta} \tag{4}$$

where the peak pressure p_0 and the decay time θ are given by

$$p_0 = \rho_w c_w v_0 \quad , \quad \theta = \frac{m_{S,P}}{\rho_w c_w}\,. \tag{5}$$

It follows from eq. (4) that impact of the nylon piston by a rigid projectile generates a pressure pulse whose amplitude decays exponentially to zero, rather than to a finite value p_{st} as desired and prescribed by eq. (1). This is due to the fact that, subsequent to impact, the nylon piston loses contact with the supporting anvil (Fig. 3a) and sends into the water column a pressure wave of magnitude $-p_{st}$. To avoid this problem, it is necessary to apply an additional constant pressure p_{st} to the dry face of the piston during the impact event.

In order to overcome this problem, we employ the compound striker sketched in Fig. 3b, made from steel and polymeric foams, which allows generation of the desired pressure pulse (eq. (1)) in the water column. A cylindrical steel projectile is placed in series with a foam cylinder, followed by a foam crusher. Impact of the steel projectile generates an exponentially decaying pressure pulse in water while the plastic collapse of the foam exerts the necessary constant force on the piston; the function of the 'foam crusher' is to provide sufficient kinetic energy to drive the plastic collapse of the foam. The geometry of this compound striker induces a delay between the application of the exponentially decaying pressure pulse and that of the constant pressure associated with the plastic collapse of the foam; on the other hand such delay is of the order of nanoseconds, therefore negligible compared to the decay time of the exponential pulse (in this study it was typically $\theta \approx 0.12\,\mathrm{ms}$).

An alternative striker capable of generating the pressure pulses given by (eq. (1)) was also developed in this study. In this second striker a steel projectile is coupled to a hollow foam cylinder, free to slide along the steel projectile; such cylinder is backed by a hollow metallic striker ('foam crusher'). This compound projectile is accelerated in such a way that the steel projectile and the hollow foam cylinder make contact with the piston simultaneously; the plastic collapse of the foam exerts the necessary constant force on the piston, while impact of the steel projectile generates an exponentially decaying pressure pulse in water. The first striker (Fig. 3b) was used in this study due to its relative simplicity.

Rohacell foams of different densities were employed to construct the compound strikers sketched in Fig. 3b and their cross-section A_F was chosen to guarantee a contact pressure at the foam-piston interface equal to the desired p_{st}, i.e. $A_F = A_P\left(p_{st} / \sigma_c\right)$, where σ_c is the plastic collapse stress of the foam employed. In first approximation such collapse stress relates to the quasi-static yield stress of the foam σ_Y and to the impact velocity v_S as $\sigma_c = \sigma_Y + \rho_F v_S{}^2 / \varepsilon_D$ (Deshpande & Fleck (2005)). In the present study impact velocities were low ($v_S < 20\,\mathrm{ms}^{-1}$) and $\sigma_c \approx \sigma_Y$. The quasi-static collapse strength of the different foams used was taken from Arezoo *et al.* (2011) and the strain rate sensitivity of the foam was neglected, as reported by Arezoo *et al.* (2012).

For the case of experiments at atmospheric pressure, i.e. $p_{st} = 0.1\mathrm{MPa}$, the loading pulse was generated in the water column by simply impacting the nylon piston by a cylindrical steel projectile, as in Deshpande *et al.* (2006).

Examples of the pressure waves generated in the water column are plotted in Fig. 4; dynamic pressure histories measured by the piezoelectric transducer placed at the left-hand side of the nylon piston are compared with the desired pulse (eq. (1)). Figure 4a shows pressure histories generated by firing steel strikers of different mass at similar velocities, for the case $p_{st} = 0.1\mathrm{MPa}$; the pressure decays exponentially to 0.1 MPa as expected, and the decay time can be precisely adjusted by using strikers of different mass. Figure 4b shows two measurements (and corresponding predictions) for $p_{st} >> 0.1$ MPa; in this case loading was induced by impact of a compound striker as sketched in Fig. 3b. The generated pressure pulses have initial amplitude of $p_{st} + p_0$ and decay exponentially to the initial pressure p_{st}, as required. Although measured peak pressures are slightly lower than theoretical predictions, the agreement between experiments and predictions is satisfactory.

3.3 Propagation of shock waves in the compliant tube

The exponentially decaying pressure wave radiated by the nylon piston travels in the water column towards the specimen. The speed at which waves propagate in the tube depends on the density, geometry and stiffness of the acrylic tube employed. For the case of a rigid tube, waves propagate at the sonic speed of water ($c_w \approx 1498\, ms^{-1}$); in contrast, if the tube undergoes significant hoop deformation and consequent change in diameter due to the passage of the pressure wave, pressure pulses propagate at lower speeds than the speed of sound in water; in addition, the pressure pulses progressively attenuate and distort as they propagate along the tube (Korteweg (1878)).

Due to the relatively low Young's modulus of the acrylic tube ($E = 3.3\,\mathrm{GPa}$), the wave speed in the tube was expected to be lower than the speed of sound in water; measurements of the wave speed, by the two pressure transducers fitted on the tube (at relative distance of 1 m, Fig. 2), confirmed this. Measurements provided $c_w = 1000\,\mathrm{ms}^{-1}$, significantly lower than sonic speed in water and in agreement with the predictions of Korteweg (1878); the observed amplitude attenuation of the pressure pulses after 1 m was of approximately 5%, and the initial rise time of the pressure pulse was also observed to increase by around 5%; the decay time of the exponential pulse also increased by approximately 15%.

Note that the mechanical coupling between the tube and the water column, by reducing the speed at which waves propagate, affects the calculation of the peak pressure p_0 and decay time θ of the generated pressure wave (eq. (5)). For this reason all calculations in this study were performed by using the measured wave speed $c_w = 1000\,\mathrm{ms}^{-1}$.

4. RESULTS AND DISCUSSION

We proceed to present observations and results obtained with the apparatus described above. First we describe the response of water to pressure wave loading, with emphasis on the process of cavitation; then, we examine specimens' motion and we deduce the impulse imparted to these by the underwater shock.

4.1 Response of fluid

High-speed photography was employed to measure the position and time at which cavitation in water first occurs, and the subsequent propagation of breaking fronts and closing fronts. We present photographic sequences from four selected experiments; experiments 1 and 2 are performed in air-backed configuration while tests 3 and 4 are conducted with a water-backed arrangement, as described in Section 2.

Details of the masses of strikers and specimens, as well as impact velocities and corresponding characteristic of the loading pulses used in each experiment are reported in Table 1. We include in this table the calculated fluid-structure interaction parameter $\psi = \rho_w c_w \theta / m$ (Taylor (1941)) which is a non-dimensional measure of the mass, for a given loading pulse. The values of ψ were chosen to match those associated to typical blast events on large-scale structures.

Air-backed specimens.

Experiment 1 was conducted in air-backed configuration, with $p_{st} = 0.1\,\mathrm{MPa}$, $\psi = 1.13$, $p_{st} = 14.9\,\mathrm{MPa}$. Figure 5 presents the high-speed photographs obtained from this experiment; Figure 5a shows the air-backed specimen in contact with water at the instant when the pressure wave, travelling from right to left, reaches the specimen ($t = 0$). In Fig. 5b we observe that soon after the specimen has been set in motion, bubbles form in the water; initially these appear very close to the fluid-specimen interface but subsequently, they also form on the walls of the transparent tube. This indicates that cavitation initiates near the specimen's wet face and subsequently extends towards the right into the fluid column by propagation of a breaking front, as predicted theoretically by Kennard (1943) and Schiffer *et al.* (2011). In Fig. 5c we note that while the specimen accelerates further, the breaking front propagates towards the blast event and the bubbles have increased in size, as a result of the increased strain in the liquid. As time elapses (Fig. 5d) the specimen decelerates due to air resistance; it can be predicted theoretically that a closing front must emerge from the fluid-structure interface and propagate towards the blast event, forcing collapse of the bubbles and leaving uncavitated water behind, as observed in the test. This closing front continues to propagate and after a sufficiently long time the cavitated region completely disappears, as shown in Fig. 5e.

The high-speed photographs in Fig. 6 refer to experiment 2, which was conducted in air-backed configuration with $\psi = 1.13$, $p_{st} = 2.7\,\mathrm{MPa}$, $p_0 = 11.9\,\mathrm{MPa}$, in order to explore the effect of an increased hydrostatic pressure in the water. Note that the specimen is now supported on the left-hand side by a Rohacell foam cylinder of diameter $d_F = 25\,\mathrm{mm}$ and collapse strength $\sigma_c = 2.6\,\mathrm{MPa}$.

Figure 6a illustrates the configuration of the specimen at the instant when the incident pressure wave reaches the fluid-structure interface. For $p_{st} >> 0.1$ MPa the theoretical models of Schiffer *et al.* (2011) predict onset of cavitation at a finite distance from the fluid-structure interface, rather than very close to this interface. Figure 6b shows that this is the case; cavitation initiates at a distance of approximately 45 mm from the specimen's wet face, and two breaking fronts emerge and propagate in two opposite directions at speeds in excess of the speed of sound, as predicted by Kennard (1943), creating an extending pool of cavitated water. In Fig. 6c we observe that the breaking front travelling towards the specimen arrests before reaching the fluid-structure interface and inverts its motion, becoming a closing front, and the strain in water increases. In Fig. 6d the closing front continues propagating and forcing collapse of the cavitation bubbles, and the cavitation zone completely disappears from the field of observation in Fig. 6e. The size of the bubbles (and hence the strain in the cavitated water) is significantly lower in this experiment, compared to experiment 1; this is due to the reduced displacement of the specimen, consequent to the higher initial pressure p_{st} applied on the left-hand side.

We now proceed to a quantitative comparison of the measurements conducted in this study with the theoretical predictions of Schiffer *et al.* (2011), with focus on the cavitation processes in the liquid and for the case of air-backed specimens. A convenient way to perform this comparison is to plot the measured and predicted trajectories of breaking fronts and closing fronts as shown in Fig. 7a. High-speed photographs such as those shown in Figs. 5 and 6 were used to measure the distance of the cavitation boundaries from the fluid-structure interface, as a function of time. The position of the breaking and closing fronts are determined from the horizontal coordinate of the edge of the first bubble visible in high-speed photographs. The limited temporal and spatial resolution of the high-speed camera used in the experiments introduces finite errors in the measurements of time and distance (on the order of the inter-frame time, $28\,\mu\text{s}$, and pixel size, $500\,\mu\text{m}$; this uncertainty in measurements is graphically indicated by a grey ellipse in Fig. 7a). However, it is clear from Fig. 7a that the theoretical predictions are in good agreement with the measurements.

Figure 7 shows the onset of cavitation and the trajectories of breaking fronts and closing fronts for experiments conducted in air-backed configuration at different initial static pressures. For the case of experiment 1 ($p_{st} = 0.1\,\text{MPa}$) both measurements and predictions give onset of cavitation very close to the interface ($x = 0.5\,\text{mm}$) and propagation of breaking fronts and a closing front. Measurements and predictions for experiment 3 ($p_{st} = 0.9\,\text{MPa}$, $\psi = 1.13$ and $p_0 = 12.5\,\text{MPa}$; the high-speed photographs associated with this test are not presented for the sake of brevity) indicate that cavitation initiates near the interface ($x = 6\,\text{mm}$) and is followed by propagation of two breaking fronts; one of these subsequently inverts its motion becoming a closing front. For the case of experiment 2, conducted at a higher initial static pressure ($p_{st} = 2.7\,\text{MPa}$), the onset of cavitation occurs at a much greater distance from the fluid-structure interface (x = 45 mm, see also Fig. 6), in line with theoretical predictions; such predictions also capture accurately the velocity of the propagating cavitation fronts; in particular, the velocity of the closing front increases with increased initial pressure.

Water-backed specimens.

High-speed photographs for experiment 4 are presented in Fig. 8. In frame (a), a shock wave reaches the water-backed specimen, in contact with water at $p_{st} = 0.1\text{MPa}$ on both sides. The ensuing response of the fluid is similar to that observed for experiment 2 and presented in Fig. 6. In Fig. 8b cavitation occurs at a distance $x = 23\,\text{mm}$ from the specimen and causes the propagation of two supersonic breaking fronts in two opposite directions. The breaking front travelling away from the interface continues advancing further into the water column while the other breaking front arrests before reaching the specimen and inverts its motion becoming a closing front, propagating away from the specimen and causing collapse of the bubbles in the cavitation zone (Fig. 8c). Cavitation occurs in the water column in contact with the specimen's back face (Fig. 8d), as predicted by Schiffer *et al.* (2011).

Experiment 5 is conducted in the same conditions as experiment 4 but with a higher initial hydrostatic pressure in the water ($p_{st} = 1.1\text{MPa}$). The fluid and specimen responses are presented in the high-speed photographs of Fig. 9. The sequence of events is similar to that observed in experiment 4; however in this test the onset of cavitation occurs at increased distance from the fluid-structure interface ($x = 59\,\text{mm}$); in addition, the strain in water is remarkably lower than in experiment 4, due to the reduced displacement of the specimen. Such observations are again in agreement with the predictions of Schiffer *et al.* (2011).

The trajectories of breaking fronts and closing fronts measured in experiments 4 and 5 ($p_{st} = 0.1\text{MPa}$ and $p_{st} = 1.1\text{MPa}$, respectively) are compared in Fig. 7b with the theoretical predictions of Schiffer *et al.* (2011). Excellent agreement between observations and analytical predictions is found. Schiffer *et al.* (2011) also predicted that in the case of water-backed specimens a limit value $\bar{p}_{st}^* = p_{st} / p_0$ exists beyond which cavitation in water is completely suppressed; this critical value is a function of the only parameter $\psi = \rho_w c_w \theta / m$ for the experiments reported here, and is included in Table 1. In order to verify this prediction, an additional test was conducted at $\psi = 1.13$, $p_0 = 12.4\text{MPa}$ and $p_{st} = 2.1\text{MPa}$, giving $p_{st} / p_0 = 0.169 > \bar{p}_{st}^* = 0.121$ (experiment 6 in Table 1). The high-speed photographs for this test are omitted for the sake of brevity; however, no cavitation was observed in the experiment, in line with theoretical predictions.

Volumetric strain field in water.

High-speed photographs have been used to estimate the volumetric strain field in water. Figure 10 presents an example of these measurements, together with predictions by Schiffer *et al.* (2011), for experiment 7 in Table 1 ($\psi = 1.94$, $p_{st} = 0.1\,\text{MPa}$, $p_0 = 14.7\,\text{MPa}$). The insert of Fig. 10 shows three high-speed photographs recorded in this experiment at three specific times. Each of the photographs was subdivided in three regions as indicated by the numbers 1, 2 and 3 in the figure (each of equal volume V_w), and the average volumetric strain in each of these regions was calculated as a function of time. The calculation performed relies on the assumption that the observed bubbles can be idealised as hemispheres with centre on the internal surface of the tube, consistent with the notion that nucleation of cavitation bubbles occurs at this surface, driven by surface roughness; this is also consistent with observations by other authors (Benjamin & Ellis (1966)). The diameter of all bubbles in each of the regions was measured, and both geometric and optical corrections were made to these measurements in order to account for the fact that the tube was cylindrical. This allowed calculating the volume of bubbles V_c in each region, thereby obtaining the average true volumetric strain in water as

$$\eta = \ln\left(1 + V_c / V_w\right) \tag{6}$$

upon neglecting the small elastic contribution to this volumetric strain.

Figure 10 shows that strain measurements are about 15% lower than the theoretical predictions of Schiffer *et al.* (2011), however they show a similar trend; such discrepancy can be justified by the fact that not all bubbles emerging in the cavitated water can be seen in the high-speed photographs, since (i) some of these bubbles are hidden behind other bubbles and (ii) some bubbles are too small to be observed.

4.2 Response of the specimen

Air-backed plates.

High-speed photographs allowed measuring the displacement versus time histories of the steel specimens consequent to blast loading. The intensity of the load imparted to an air-backed specimen, as quantified by the specific impulse (impulse per unit area) imparted to the specimen front face $I_f(t)$, can be deduced my measuring the specimens' velocity histories. Upon neglecting friction between O-rings and tube wall (frictional forces were measured to be $<10\,\mathrm{N}$), conservation of linear momentum dictates

$$I_f(t) = \int_0^t \left[p_f(\tau) - p_{st} \right] \mathrm{d}\tau = mv(t) \qquad (7)$$

where $p_f(t)$ is the time history of the pressure applied at the specimen front face. The velocity histories $v(t)$ were extracted from the high-speed photographs. Note that eq. (7) is valid for any choice of p_{st}.

Figure 11a presents the indirectly measured non-dimensional time histories $\overline{I}_f(t) = I_f(t)/(2p_0\theta)$ for experiments 1 and 2 (Table 1), together with the predictions of the analytical models by Schiffer *et al.* (2011). These models predict a greater impulse than measured, with the difference being of the order of 15%; this can be justified recalling that while analytical models assume a perfectly sharp incident shock wave, in the experiments a finite rise time of such wave was observed, together with a 5% attenuation of the incident peak pressure and an increase in decay time, due to propagation in the compliant shock tube. However, the agreement between measurements and predictions is more than satisfactory. Both analytical predictions and experiments show that an increase in static pressure results in lower displacement (displacement of the specimen is proportional to the area under the $\overline{I}_f(t)$ curves); on the other hand, the peak value of $\overline{I}_f(t)$ is independent of the initial hydrostatic pressure p_{st}.

Water-backed plates.

When a water-backed specimen is set in motion by the incident shock wave, a pressure wave is radiated into the water column in contact with the specimen’s back face. Given the low specimen velocity observed in our experiments, the acoustic approximation can be employed and the pressure at the specimen's back face can be written as

$$p_b(t) = p_{st} + \rho_w c_w v(t). \tag{8}$$

(measurements of the pressure history at the specimen back face combined with high-speed photography allowed validation of eq. (8)). Now write conservation of linear momentum for the specimen to obtain the specific impulse applied to the front face as a function of the specimen's velocity history

$$\begin{aligned} & mv(t) = \int_0^t \left[p_f(\tau) - p_b(\tau) \right] d\tau = I_f(t) - \rho_w c_w \int_0^t v(\tau) d\tau \Rightarrow \\ & \Rightarrow I_f(t) = mv(t) + \rho_w c_w \int_0^t v(\tau) d\tau \end{aligned} \tag{9}$$

Equation (9) was employed in order to plot the non-dimensional specific impulse applied to the front face $\overline{I}_f(t)$ in experiments 4 and 5 (see Table 1), as shown in Fig. 11b. This figure includes analytical predictions by Schiffer *et al.* (2011), which are in good agreement with the measurements. Contrary to what observed for air-backed plates, both measurements and predictions suggest that the maximum value of $\overline{I}_f(t)$ can be decreased by increasing the static pressure $\overline{p}_{st}$.

4.3 Sensitivity of impulse to mass and initial static pressure

The peak value $\overline{I}_{f,\max} = \max\left[\overline{I}_f(t)\right]$ can be considered as a measure of the severity of the structural loading induced by an underwater blast event on a rigid plate. A large series of experiments was performed in this study in order to measure the sensitivity of $\overline{I}_{f,\max}$ to (i) the specimen mass, quantified by the non-dimensional fluid-structure interaction parameter $\psi = \rho_w c_w \theta / m$ and (ii) the initial hydrostatic pressure, expressed in non-dimensional terms by $\overline{p}_{st} = p_{st} / p_0$. In the following, the measured sensitivity is compared to that predicted by Schiffer *et al.* (2011), for both air-backed and water-backed specimens.

Figure 12a presents the dependence of $\overline{I}_{f,\max}$ upon ψ, for a hydrostatic pressure of $p_{st} = 0.1\text{MPa}$ and both air-backed and water-backed plates. Different values of ψ were obtained in the experiments by varying either the areal mass of the specimen *m* or the combined areal mass of the striker and piston $m_{S,P}$ (thereby varying the decay time θ, eq.(5)). For both problems the maximum impulse $\bar{I}_{f,\max}$ decreases by increasing ψ, and experiments are in excellent agreement with theoretical predictions.

Water-backed plates are subject to higher impulse than air-backed plates, for a given mass, and the reduction in applied impulse with decreasing plate mass is less pronounced if the structure is in contact with water on both sides. The experimental scatter is higher in tests on water-backed plates due to the small displacements of these plates, leading to less accurate measurements of $v(t)$.

We now examine the sensitivity of $\bar{I}_{f,\max}$ to $\bar{p}_{st}$, for two selected values of ψ and for both air-backed and water-backed rigid plates. In Fig. 12b measurements and predictions by Schiffer *et al.* (2011) are shown and are found in good agreement. As discussed above and shown in Fig. 11a, both experiments and theoretical models show that $\bar{I}_{f,\max}$ is insensitive to the initial static pressure for the case of air-backed plates and a reduction in applied impulse of more than 50% is achieved if the parameter ψ is increased from 1.13 to 4.25, in line with what shown in Fig. 12b.

In contrast, the impulse imparted on water-backed plates is only mildly sensitive to ψ and $\bar{I}_{f,\max}$ gradually decreases as $\bar{p}_{st}$ increases, stabilising at $\bar{I}_{f,\max} = 0.5$ for non-dimensional static pressures $\bar{p}_{st}$ beyond a critical value $\bar{p}^{*}_{st}(\psi)$. This was predicted by Schiffer *et al.* (2011), who showed that when $\bar{p}_{st} \geq \bar{p}^{*}_{st}(\psi)$ cavitation in the fluid is completely suppressed and $\bar{I}_{f,\max} = 0.5$ irrespective of ψ. It is clear from what has been shown above that the theoretical predictions of Schiffer *et al.* (2011) are accurate.

5. CONCLUDING REMARKS

We have presented a novel experimental technique to produce controlled blast loading in liquids subject to an initial hydrostatic pressure, in order to mimic, at laboratory-scale, the structural loading consequent to explosions in deep water. This technique has been employed to investigate the response to exponentially decaying underwater shock waves of both air-backed and water-backed unsupported rigid plates, and to measure the effects of the initial hydrostatic pressure on the cavitation process in water and on the response of the plates.

The probe developed in this study allowed visualising for the first time the nucleation and propagation of cavitation fronts initiated by fluid-structure interaction in a blast event and their interaction with the loaded structure; it also allowed measuring the strain field in cavitated water regions consequent to fluid-structure interaction, providing experimental evidence for the theoretical predictions of Kennard (1943). Experimental results were compared to the predictions of theoretical models recently developed by Schiffer *et al.* (2011) and we concluded that these models are accurate and capable of capturing all details of the response of both fluid and structure to underwater blast in deep water.

The main conclusions from this study are the following:

- for both air-backed and water-backed rigid plates loaded by exponentially decaying blast waves, an increase in initial hydrostatic pressure causes first cavitation in the fluid to occur at increasing distance from the fluid-structure interface; breaking fronts emerge from the point of first cavitation and propagate at supersonic speeds. The breaking front travelling towards the structure can arrest and invert its motion, becoming a closing front and moving at subsonic speed.
- for given incident blast wave and initial static pressure, air-backed plates are imparted less impulse than water-backed plates; the impulse imparted to air-backed plates can be greatly reduced by reducing the mass of the plate, while a smaller reduction in imparted impulse is observed by reducing the mass of water-backed plates.
- the peak impulse imparted to air-backed plates is insensitive to the initial hydrostatic pressure while that imparted to water-backed plates decreases with increasing static pressure.

The experimental technique presented in this study is suitable to investigate the blast response of different types of structures, e.g. monolithic and sandwich plates, in which both deformation and fluid-structure interaction are two-dimensional or three-dimensional in nature; it can also be employed to reproduce and understand the performance of blast-mitigators and their effect on fluid-structure interaction. We shall examine these problems in our following studies.

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Figure and Table captions

Table 1: Details of selected experiments performed in this study.

Fig. 1 Free body diagram of rigid plates in the two problems under investigation: (a) air-backed plate and (b) water-backed plate. Plates are loaded by exponentially decaying pressure waves in initially pressurised water.

Fig. 2 Sketch of the apparatus employed in this study to explore the response of (a) air-backed unsupported rigid plates and (b) water-backed unsupported rigid plates.

Fig. 3 Impact of the striker on a piston in contact with pressurised water (a); sketches of the compound steel-foam striker employed in this study (b).

Fig. 4 Comparison between theoretical predictions and experimental measurements of the incident pressure versus time histories in water at (a) atmospheric pressure and (b) higher initial static pressure.

Fig. 5 High-speed photographs for experiment 1 ($p_{st} = 0.1\text{MPa}$, $\psi = 1.13$, $p_0 = 14.9\text{MPa}$): (a) shock wave reaches the specimen; (b) onset of cavitation and propagation of a breaking front (BF); (c) propagation of the breaking front and increase of strain in the liquid; (d) emergence of a closing front (CF) at the fluid-structure interface; (e) complete collapse of the cavitation zone.

Fig. 6 High-speed photographs for experiment 2 ($p_{st} = 2.7\text{MPa}$, $\psi = 1.13$, $p_0 = 11.9\text{MPa}$): (a) shock wave reaches the specimen; (b) onset of cavitation and propagation of two breaking fronts (BF); (c) propagation of one of the breaking fronts and emergence of a closing front; (d) further propagation of the closing front (CF); (e) complete collapse of the cavitation zone.

Fig. 7 (a) Measured trajectories of the closing fronts and breaking fronts in a time versus distance chart for experiments 1 ($p_{st} = 0.1\text{MPa}$, $\psi = 1.13$), experiment 2 ($p_{st} = 2.7\text{MPa}$, $\psi = 1.13$) and experiment 3 ($p_{st} = 0.9\text{MPa}$, $\psi = 1.13$). (b) Same information for experiment 4 ($p_{st} = 0.1\text{MPa}$, $\psi = 0.91$) and experiment 5 ($p_{st} = 1.1\text{MPa}$, $\psi = 0.91$); analytical predictions are included for comparison.

Fig. 8 High-speed photographs for experiment 4 ($p_{st} = 0.1\text{MPa}$, $\psi = 0.91$, $p_0 = 15.1\text{MPa}$): (a) shock wave reaches the specimen; (b) onset of cavitation and propagation of two breaking fronts (BF); (c) propagation of one of the breaking fronts and emergence of a closing front; (d) further propagation of the closing front (CF) and cavitation at the specimen back face; (e) complete collapse of the cavitation zone.

Fig. 9 High-speed photographs for experiment 5 ($p_{st} = 1.1\text{MPa}$, $\psi = 0.91$, $p_0 = 13.1\text{MPa}$): (a) shock wave reaches the specimen; (b) onset of cavitation and propagation of two breaking fronts; (c) emergence of a closing front; (d) further propagation of the closing front; (e) complete collapse of the cavitation zone.

Fig. 10 Volumetric strain field in the water adjacent to the air-backed specimen in experiment 7 ($\psi = 1.94$, $p_{st} = 0.1\text{MPa}$, $p_0 = 14.7\,\text{MPa}$) measured at 3 specific times corresponding to the high-speed photographs; the continuous lines represent analytical predictions.

Fig. 11 (a) Time histories of the non-dimensional impulse $\bar{I}_f = I_f / (2 p_0 \theta)$ for experiment 1 ($p_{st} = 0.1\text{MPa}$, $\psi = 1.13$) and experiment 2 ($p_{st} = 2.7\,\text{MPa}$, $\psi = 1.13$) conducted in air-backed configuration. (b) Same information for experiment 4 ($p_{st} = 0.1\text{MPa}$, $\psi = 0.91$) and experiment 5 ($p_{st} = 1.1\text{MPa}$, $\psi = 0.91$) conducted in water-backed configuration; analytical predictions are compared to measurements..

Fig. 12 Sensitivity of the non-dimensional specific impulse $\bar{I}_{f,\max} = \max\left[\bar{I}_f\left(t\right)\right]$ to (a) ψ and (b) $\bar{p}_{st} = p_{st} / p_0$, for experiments performed with both air-backed and water-backed plates; analytical predictions are included for comparison.