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Estimation of the underwater implosion pulse from cylindrical metal shells

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ABSTRACT

Underwater implosion, the rapid and catastrophic collapse of a structure caused by hydrostatic pressure, generates a short-duration, high-pressure pulse in the surrounding water that is potentially damaging to adjacent structures or personnel. This paper presents a method to estimate the energy in the pressure pulse as the difference between the known total potential energy and energy lost by plastic deformation. The implosion pulse energy is proportional to the maximum system kinetic energy developed during collapse. The pulse was approximated by considering only the first phase of collapse (up to the instant of first contact), because the maximum kinetic energy occurs very near that instant. The plastic energy dissipated by the structure during the initial phase of implosion was evaluated analytically, using the principle of virtual velocities. The solution for energy dissipation agreed with numerical simulation within 1% at the end of the initial collapse phase. It was found that for a representative aluminum cylinder, the implosion pulse represents only 15% of the total available energy.

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1. Introduction

Underwater implosion occurs when the hydrostatic pressure exceeds the critical buckling pressure of a structure, or through a combination of hydrostatic pressure less than critical buckling pressure and a triggering event, such as an underwater explosive load (UNDEX). The duration of a typical implosion event is on the order of milliseconds. Implosion of a structure generates a pressure pulse in the surrounding water, similar to the pressure pulse created by the collapse of a gas bubble from an UNDEX event. Fig. 1 shows a typical implosion dynamic pressure history, as measured at a point in the surrounding fluid [1]. The negative phase represents the decrease in pressure due to the collapsing cylinder walls and the associated in-rushing water. The large positive spike is caused by the rapid deceleration (and subsequent compression) of the water when the opposite walls impact one another. The details of the implosion phenomenon have been studied and well reported by Turner and Ambrico [1] and Farhat et al. [2].

The primary impetus for studying underwater implosion is the damaging effect that the implosion pressure pulse may have on an adjacent structure. Any pressure vessel containing a non-compensated compressible volume may implode [3]. Implosion can cause a cascade of secondary implosions. A dramatic example was the Super-Kamiokande Cherenkov detector facility in Japan in November 2001, where failure of a single photomultiplier tube triggered the subsequent implosion of 6777 more tubes [4]. The U.S. Navy has a strong interest in underwater implosion because of the danger that implosion poses to an adjacent submarine. Submarines carry a variety of potentially implodable devices and systems, such as drydeck shelters and unmanned underwater vehicles. For this reason, the U.S. Navy has funded a large portion of the recent research on the subject.

A comprehensive experimental implosion program was undertaken in a suitably constructed pressure vessel by Kyriakides et al. [2]. He tested a variety of circular cylindrical shells with diameters of 1.0–1.5 in, recording pressure in the surrounding water as well as high-speed photography of the implosion event. His data provide excellent correlation between the timing of the implosion event and the resulting fluid pressure. Fig. 2 shows Kyriakides' experimental setup and representative test samples.

To date, little has been reported on the effect that structural energy absorption has on the magnitude of the implosion pressure pulse. Cor and Miller [5,6] studied spherical and cylindrical implodable volumes and the effect that internal structure (i.e., bulkheads, equipment, etc.) has on the implosion pressure pulse.

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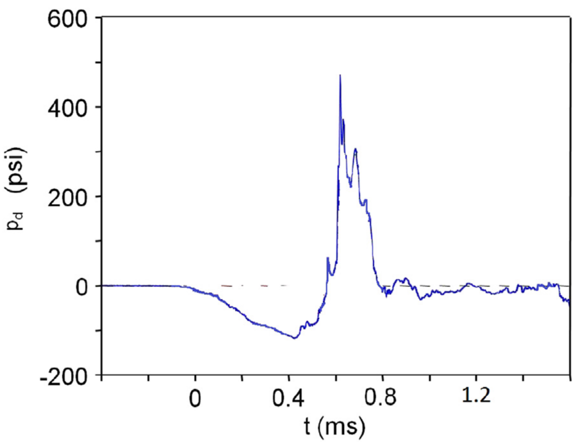


Fig. 1. Typical dynamic pressure history for an underwater implosion event.

They concluded that internal structure can significantly reduce the implosion pressure pulse, but did not quantify the energy absorbed by the outer shell.

The goal of the present work is to quantify the energy in the implosion pressure pulse, since this quantity is directly related to the damage potential. One method of calculating the pulse energy (presented by Chamberlin [7]) is to sample the fluid pressure (either experimentally or numerically) and integrate pressure squared over a surface (Eq. (1)). A limitation of this method is it requires detailed knowledge of the pressure field.

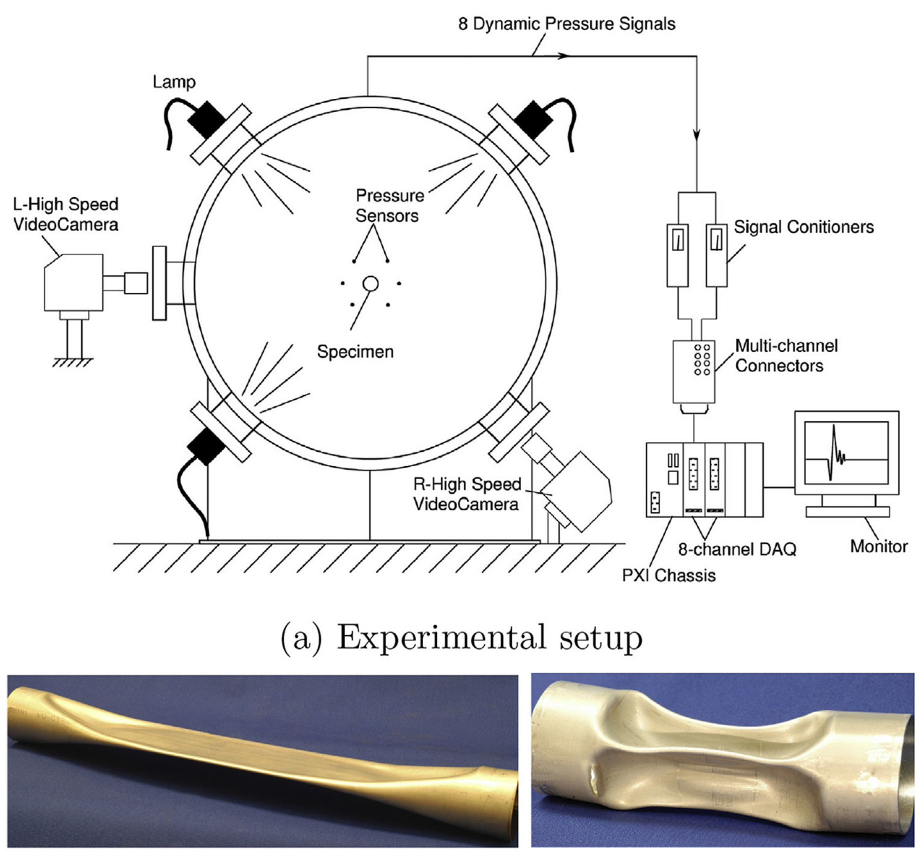
$$E = \int_S \int_{t1}^{t2} \frac{p^2}{\rho c} \mathrm{d}t\mathrm{d}S \tag{1}$$

An alternate method is to measure the velocity of the cylinder surface and surrounding water during collapse and thus calculate system kinetic energy. The maximum value of kinetic energy during collapse represents the energy available to be converted into the implosion pulse. However, data from experiments to date are insufficient to allow these calculations. A third method, presented in this paper, is to develop analytic solutions for the plastic strain energy dissipated by the structure and the energy to compress the air inside the cylinder. The results are then applied to the overall energy balance of the implosion problem to estimate the energy that will be transmitted in the pressure pulse.

2. Problem formulation and simplifying assumptions

A number of assumptions and simplifications were required to make the problem mathematically tractable.

1 The material was modeled as rigid-perfectly plastic, with flow stress σ_0.
2 The bending and membrane effects were separated by assuming a rectangular, limited interaction yield condition.
3 Shear energy dissipation was neglected.
4 The 3D kinematics of implosion were simplified into a single degree of freedom model.
5 The internal air compression was treated as adiabatic and uniform throughout the cylinder.



(a) Experimental setup

(b) Mode 2 collapse (c) Mode 4 collapse

Fig. 2. Experimental setup and representative samples from Kyriakides et al [2].