Sympathetic underwater implosion in a confining environment

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Abstract

An experimental study is conducted to investigate the phenomenon of sympathetic underwater implosion of cylindrical metallic shells in a confining environment. Two aluminum 6061-T6 implodable volumes with different collapse pressures are placed inside a confining tube with one end open to the environment and are hydrostatically loaded upto the weaker implodable volumes' critical collapse pressure. Experiments show that implosion of the weaker implodable volume (critical pressure = P_c) inside the confining tube leads to the subsequent sympathetic implosion of the stronger implodable volume (critical pressure = $1.2P_c$). Implosion of the weaker implodable volume produces strong oscillating water hammer waves with $1.6P_c$ peak over-pressure, which initiates the implosion of the stronger implodable volume. Pressure histories recorded within the confining tube indicate that the sympathetic implosion of the stronger implodable volume generates low pressure high frequency implosion waves. The superposition of the low pressure waves with the high pressure water hammer waves mitigate to a great extent the later cyclic water hammer loading within the confining tube.

Keywords

Sympathetic Implosion, Implodable Volume, Collapse, Pressure Waves, Fluid Structure Interaction, Water Hammer, Confined Environment

1. Introduction

Thin walled structures are extensively used in underwater applications such as submarines, underwater remote operated vehicles, and underwater pipelines etc [1–3]. The presence of lower pressure, uncompensated gas inside the structure and the large external hydrostatic pressures lead to a net pressure differential across the walls of the structures. If the hydrostatic pressure exceeds a certain critical limit for a given structure [4,5], it becomes unstable and collapses/implodes onto itself. This implosion process is shown to be highly violent in nature with resulting high velocity water motion and strong shock waves [6]. There have been several investigations reported by researchers in naval and marine communities on the mechanics and fluid-structure interaction during an implosion process [2,7–19]. Although the evolution of implosion pressure waves and its relation to structure geometry has been widely studied, there is a little information on the interaction of these pressure waves with the adjacent structures and on the potential of damage/sympathetic implosion. Orr and Schoenberg conducted experiments with a pre-weakened glass sphere and a non-weakened glass sphere submerged together for the possibility of sympathetic implosion [12], although none was observed. Later, Harben and Boro bundled five glass spheres together and mechanically initiated one of them at a prescribed depth [20]. It was reported that sympathetic implosion did occur in these experiments. The accidental failure of 7000 photomultiplier tubes at the Super Kamiokande laboratory in a chain reaction is a classic example of sympathetic implosion of near-field structures [21].

The damage potential of an implosion pressure pulse is generally estimated by the pressure-impulse and the energy flux released during the implosion event. Since both the pressure-impulse and the energy flux released in an underwater free-field implosion decays in a spherical manner [2] (pressure-impulse as $1/r$ and energy flux as $1/r^2$), a structure located at a sufficient distance from an imploding structure can be considered safe from the design point of view. But in certain situations, there may exist a confining structure around the implodable volume. In the event of an implosion occurring in such situations, the confining environment significantly alters the implosion process due to strong fluid-structure interaction with the confining environment [14,19,22]. Hence, all the energy released during the implosion process focuses inside the confining structure. This phenomenon leads to generation of extremely strong water hammer waves with significant time period [22]. Therefore, implosion of the weakest implodable volume inside the confining tube may damage the adjacent stronger structures. In present study, an experimental investigation is conducted to understand the damage to the adjacent structures placed inside the confining tube with

a weaker implodable volume. Study reveals that the implosion of an implodable volume inside the confining tube can generate a large enough pressure pulse to initiate implosion of comparatively stronger structures.

2. Experimental setup

The implosion experiments are conducted inside an underwater pressure vessel facility at the University of Rhode Island. The implodable volumes chosen in this study are made out of commercially available aluminum 6061-T6 seamless extruded tubing with an outer diameter ($2a$) of 38.1 mm (1.50 in) and 0.870 mm (0.0343 in) nominal wall thickness (h). All the primary and secondary implodable volumes are cut out from single 1.8 m long (72 in) extruded tubing, thus there exists “no change in average wall thickness” between the implodable volumes* and implodable volumes with nearly identical and repeatable buckling pressures are manufactured as primary implodable volumes. Table 1 provides a summary of the experiments conducted and the details of the specimens used in this study. Ovality parameter ($\Delta_0 = (a_{\max} - a_{\min}) / (a_{\max} + a_{\min})$) and wall eccentricity parameter ($\Xi_0 = (h_{\max} - h_{\min}) / (h_{\max} + h_{\min})$) are measured for each specimen to quantify the initial imperfections present in the specimen prior to experiments [23] and are also shown in Table 1. Aluminum end-caps equipped with o-ring seals are press fitted at both the ends to avoid leakage of water into the implodable volume [14,15,19]. The theoretical buckling pressure (P_c) of the implodable volumes can be calculated from the following equation (derived by von-Mises [4]):

$$P_c = \frac{Eh}{a} \frac{1}{n^2 + \frac{1}{2} \left(\frac{\pi a}{l} \right)^2 - 1} \left\{ \frac{1}{\left[n^2 (l/\pi a)^2 + 1 \right]^2} + \frac{h^2}{12a^2 (1 - \nu^2)} \left[\left(n^2 + \left(\frac{\pi a}{l} \right)^2 \right)^2 - 2n^2 + 1 \right] \right\} \quad (1)$$

where the parameters are listed in Table 2.

The unsupported length of the primary (weaker) implodable volume is 302 mm, while the unsupported length for the secondary (stronger) implodable volume is $\sim 1/2$ of the primary implodable volume (163 mm), hence the theoretical buckling pressure of secondary implodable volume is 20% higher than primary implodable volume.

* Due to the extruded nature of the tube, the geometry along with imperfections is consistent in direction of extrusion (i.e. length direction). Thus the average wall thickness is identical for single extruded tubing at any longitudinal location. This fact can be observed in the author’s previous article [19], which shows three experiments of specimens cut from single extruded tubing. These experiments showed collapse pressure to be within 0.02 MPa (2 psi) for three different experiments.

The implodable volumes are placed concentrically inside a confining tube with one open end within the pressure vessel facility. The confining tube sits inside a 2.13 m diameter (84 in) underwater pressure vessel facility. (See [15] for detailed description of facility). A schematic of the confining tube with the implodable volumes is shown in Fig. 1. The confining tube has an inner diameter (D) of 178 mm (7.00 in) with 25.4 mm (1.00 in) wall thickness and is made out of aluminum 6061-T6. The total length (L) of the confining tube is 1.27 m (50.0 in). The bottom end of the confining tube is closed with an end-plate and the top end is open to the high pressure water environment of the underwater pressure vessel. High frequency dynamic pressure sensors (PCB-113B22) are installed in the inner wall of the confining tube at various locations. The signal from the pressure sensors is recorded using a 200 KHz bandwidth recorder at a sampling rate of 2 MHz.

To understand the evolution of water hammer pressure waves due to the primary implodable volume, an implosion experiment is first conducted with only the primary implodable volume. In this experiment (EXP-P in Table 1), the primary implodable volume is placed near the closed end of the confining tube (at Ch-3) as shown in Fig. 1(b) and the implosion occurs at 3.59 MPa (520 psi). In the second experiment (EXP-PS), the secondary implodable volume is placed just above the primary implodable volume (between Ch-4 and Ch-5) as shown in Fig. 1(c). In this experiment, the implosion of primary implodable volume occurs at 3.54 MPa (513 psi).

3. Experimental results and discussion

The pressure history observed in the confining tube for the experiment containing only the primary implodable volume (EXP-P) is shown in Fig. 2(a). In order to describe the overall behavior of pressure evolution throughout space, a time evolution of pressure is also shown in Fig. 2(a) indicating the various phases of primary implodable volume's implosion in the confining tube. The incompressible nature of water causes a sudden drop in the pressure at the nearest sensor (Ch-3) with the progress of implosion process, and these low pressure waves travel in both axial directions (Ch-3 $\rightarrow$ Ch-1 (downwards) and Ch-3 $\rightarrow$ Ch-7 (upwards)). These low pressure waves are indicated by P1 in Fig. 2(a). As the upward end is open to hydrostatic pressure, this wave reflects as a free boundary reflection and a reflected high pressure wave enters inside the confining tube (indicated by wave P2 in Fig. 2(a)). This generates high water velocity at the open end towards inside and compensates for the low pressure present in the confining tube. On the other hand, the low pressure waves reflect as a fixed boundary reflection from bottom end-plate and pressure is greatly reduced upto the cavitation pressure (see Ch-2 at ~ 1.0 ms). After the pressure reaches

zero near the end-plate, a cavitation bubble is formed due to separation of water from the end-plate. This bubble grows to its largest size and collapses onto itself generating a small local pressure pulse seen between 1.5 ms - 2.0 ms at Ch-2 [24].

When the high pressure wave P2 reaches the implodable volume, the ongoing collapse causes additional low pressure waves to release seen as pressure wave P3. At the completion of the collapse of the implodable volume, the water velocity at the open end is still in the downwards direction. This in-rushing water hits the end-plate and the velocity of the water at the end-plate abruptly vanishes. Thus the following in-rushing water over-compresses the water in front and a high pressure water hammer type wave forms inside the confining tube at the closed end-plate seen as P4 in Fig. 2(a). This can be seen by 5.0 MPa peak over-pressure achieved at ~ 3.1 ms in Fig. 2(a). The gradual reduction of water velocity throughout the tube generates high pressure wave at the other locations in the upper confining tube. These high pressure water hammer waves are oscillatory in nature. The confining tube is cyclically loaded with high pressure at a time period of ~ 3.7 ms (at ~ 270 Hz). It is important to note that due to their large time duration period, these waves accumulate large impulse during high pressure cycle, which can potentially implode other structures in the near-field.

The pressure history and time evolution of pressure observed for the experiment (EXP-PS) of primary implodable volume placed with a secondary implodable volume is shown in Fig. 2(b). Results show that the initial collapse of the primary implodable volume is unaffected by the presence of secondary volume and the description of P1 to P4 waves is similar as described earlier in this section. The low pressure phase until 2.5 ms is identical for both experiments (see pressure time evolution in both Fig. 2(a) and (b)).

After the generation of high pressure water hammer wave (P4) in the confining tube, the secondary implodable volume experiences much higher transient pressure loading than its critical buckling pressure, 4.24 MPa (615 psi). Pursuant to the arrival of first hammer wave (see Fig. 2(a)), starting from $t = 2.7$ ms, the peak pressure experienced by the secondary implodable volume is ~ 4.55 MPa higher than its own buckling pressure. *This is the primary cause of initiation of implosion of the secondary implodable volume.* This phenomenon is similar to a dynamic buckling problem (i.e. a structure subjected to a transient pressure load) earlier reported by Goodier and McIvor[25] and, Lindberg and Florence [26]. In such dynamic situations, the peak pressure along with the impulse of the pressure wave determines the onset of instability/buckling for a given implodable volume (or the adjacent structure) [25–27]. In this study, the high pressure water hammer wave acts as the impulsive loading and it causes the secondary

volume to start collapsing at $\sim t = 3.7$ ms indicated by a sharp decrease in pressure at the nearest sensor Ch-4. These low pressure waves (denoted by S1U- and S1D-) travel in both upwards and downwards direction exhibiting consecutive sharp pressure drop at every sensor location. The implosion event of secondary implodable volume is relatively faster than primary implodable and is indicated by the very sharp pressure drop (see strong blue region towards top side at ~ 4.25 ms following S1U-). The superposition of initial water hammer wave (P4) present in the lower confining tube with S1D- results into slowly decaying S1D-. The reflection from open-end of S1U- and its interaction with itself generates a high pressure wave indicated by S2+, while the reflection from the closed end-plate results into low pressure reflected wave indicated by S2-. Later, two upward travelling high pressure waves originate near the closed end-plate marked by ① and ②. The repeated reflection of these waves from the open-end of the confining tube and from the closed end-plate, along with their interference with each other results into high frequency pressure oscillations inside the confining tube.

Interestingly, as the onset of implosion occurs at the instant of highest pressure, these low pressure implosion waves of the secondary implodable volume superimpose over the high pressure hammer wave of primary implodable volume as a partially destructive interference (see Fig. 2(b)). It implies that the secondary implodable volume can effectively absorb the energy present in the first high pressure hammer wave, which is beneficial in reducing the repeated cyclic loading of the water hammer wave as seen in the case of primary implodable volume[†].

An inspection of the pressure time history shows differences in the frequency components of the pressure waves between the two experiments as seen in Fig. 3(a) and (b). From the water hammer theory [28,29], the frequency of the water hammer wave can be written as $f_1 = c/4L = 264\text{Hz}$ (where c = coupled longitudinal pressure wave speed in the confining tube (1341 m/s) [14,30,31]), therefore the peak at a frequency of 256 Hz in Fig. 3(a) indicates the cyclic water hammer wave due to primary implodable volume implosion (EXP-P). In the case of sympathetic implosion (EXP-PS), the collapse of the secondary implodable volume results into a high frequency oscillated wave travelling over a low frequency wave (see time history in Fig. 2(b) beyond 5.5 ms). A sequential evolution of these high frequency waves is also shown in Fig. 2(b). If we trace two high frequency waves (shown by no. 1 (solid line)

[†] Note that, although the experiments conducted in this study show a destructive interference of waves exhibiting mitigation of water hammer wave, it may not be necessarily true for all different variations in the configuration (such as varying collapse pressures between the two implodable volumes or their relative placement inside confining tube). Hence, a carefully chosen design would be needed to use sympathetic implosion as a mitigation tool. For example, an implodable volume equipped with an initiating mechanism at prescribed critical dynamic pressure can be used as an active mitigation device.

and 2 (dashed line) in Fig. 2(b)), it is seen that these waves oscillate in the entire length of the confining tube. Thus the frequency of the oscillation can be approximately written as $f_2 = c/L = 1055\text{Hz}$. Fourier transform of the sympathetic implosion pressure history signal shown in Fig. 3(b) shows a similar frequency peak (at $\sim 1200\text{ Hz}$), which corresponds to high frequency oscillations.

Although sympathetic implosion of a stronger implodable indicates the detrimental nature of water hammer wave, it can be desirable in certain situations to avoid the high magnitude cyclic hammer loading of a single implosion. In this way, a stronger implodable volume can act as a sacrificial implodable to mitigate the water hammer wave. In order to compare the effectiveness of such concept, the damage potential of the pressure wave generated between the two experiments is estimated by comparing the following parameters: (I) mean dynamic pressure inside the confining tube, (II) the pressure-impulse associated with the positive pressure cycle and (III) the total compressible potential energy present in the confining tube. Fig. 4(a) shows that the sympathetic implosion decreases the magnitude of mean dynamic pressure oscillations from 3.04 MPa to 1.72 MPa. Thus, a 43% reduction in the magnitude of cyclic pressure loading dramatically reduces the fatigue damage. The positive pressure impulse (shown in Fig. 4(b)) present in the water hammer pressure wave also decreases with the initiation of the sympathetic implosion. It causes the maximum pressure-impulse to decrease by 30% in the first water hammer cycle and the pressure-impulse present in the following cycles also decreases significantly.

The compressible potential energy ($E(t)$) present inside the confining tube can be written as,

$$E(t) = \int_0^L \frac{\pi D^2}{4} \frac{\Delta P(x,t)^2}{2K} dx \quad (2)$$

where K = bulk modulus of water, $\Delta P(x,t)$ = dynamic pressure as a function of axial location (x) and time (t).

The comparison of compressible potential energy shown in Fig. 4(c) suggests that sympathetic implosion absorbs upto 70% potential energy present in the 2nd and 3rd water hammer cycles. The confining tube contains $\sim 7\text{ J}$ of energy in the case of sympathetic implosion as compared to 22.5 J for the primary implodable implosion.

4. Conclusions

The problem of sympathetic implosion in the presence of a confining environment is experimentally investigated. The study shows that the implosion of a structure inside a confining environment leads to strong oscillating water hammer waves which can be potentially dangerous to the other near-field structures. To demonstrate such phenomenon, a 20% higher critical pressure structure is shown to be sympathetically imploded due to the water hammer waves generated by an implosion event. Thus the presence of a weaker structure inside a confining environment is a significant risk to other stronger structures. The peak dynamic pressure of the water hammer wave is found to be approximately 1.6 times the critical collapse pressure in these experiments. Results also indicate that the sympathetic implosion event superimposes to primary implosion's water hammer wave in a destructive manner in this study and it absorbs/mitigates most of the impulse and released energy. Hence, further cyclic pressure loading is highly reduced due to the sympathetic implosion. Thus, a carefully designed sacrificial implodable volume in the event of an implosion can act as an effective tool for hammer wave mitigation.

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Figure Captions

Figure 1 Schematic of the open-ended confining tube implosion facility. (a) Underwater pressure vessel facility at University of Rhode Island. The confining tube is placed at the center of pressure vessel. (b) A detailed schematic of open-ended confining tube indicating the exact sensor locations for EXP-P. The primary implodable volume is located such that the axial center is in front of Ch-3 pressure sensor. (c) Schematic for a sympathetic implosion experiment (EXP-PS). The secondary implodable volume is placed above the primary implodable volume. (2-column figure)

Figure 2(a) Left figure plots the evolution of dynamic pressure in the entire length of the confining tube for experiment EXP-P. The y-axis is the axial direction with zero being the closed end-plate and 1.27 m represents the open end of the confining tube. The color intensity indicates the pressure contour level. The right figure is the dynamic pressure history plot for three near-field pressure sensors, Ch-2, Ch-3 and Ch-4, for EXP-P experiment. The hashed region indicates the approximate over-pressure pulse experienced by the secondary implodable volume during the EXP-PS experiment. The bottom line in the hashed region represents the critical buckling pressure (4.24 MPa) of the secondary implodable volume. (b) Left figure plots the evolution of dynamic pressure for experiment EXP-PS. The right figure plots the dynamic pressure history inside the confining tube for EXP-PS experiment. Ch-2 and Ch-4 are clearly seen oscillating out-of-phase from each other with Ch-3 being the baseline. (2-column figure)

Figure 3(a) Frequency spectrum plot for experiment EXP-P. The inset figure shows the zoomed spectrum plot between 200 Hz and 300 Hz. (b) Frequency spectrum plot for experiment EXP-PS. The inset figure shows the zoomed spectrum plot between 1150 Hz and 1250 Hz. (2-column figure)

Figure 4 (a) Plot of mean dynamic pressure in the confining tube as function of time. The mean dynamic pressure is calculated by spatial averaging of the dynamic pressure. (b) Plot of positive pressure-impulse present in the each hammer wave loading. Initial three hammer wave cycles are shown in Fig. 2(a). (c) Plot of total compressible potential energy present in the water inside the confining tube as a function of time. (2-column figure)

Table Captions

Table 1 Details of the experiments conducted. The average wall thickness from weight are calculated by estimating the weight of the implodable volume using volume of the material multiplied by the density of aluminum (2700kg/m^3)

Table 2 Properties of implodable volume material and its dimensions

Experiment Name	Tube	Unsupported Length (l)	Experimental Collapse Pressure (P_c)	Ovality (Δ_0)	Wall Eccentricity Parameter (Ξ_0)	Average Wall Thickness from Micrometer (h_1)	Average Wall Thickness from Weight (h_2)
EXP-P	Primary Implodable Volume – I	302 mm	3.59 MPa (520 psi)	0.01%	2.53%	0.859 mm (0.0339 in)	0.870 mm (0.0343 in)
EXP-PS	Primary Implodable Volume – II	302 mm	3.54 MPa (513 psi)	0.05%	2.34%	0.868 mm (0.0342 in)	0.867 mm (0.0341 in)
	Secondary Implodable Volume	163 mm	4.24 MPa (615 psi) *	0.02%	1.78%	0.863 mm (0.0340 in)	0.871 mm (0.0343 in)

Table 1

* This is not the experimentally calculated value. It indicates an estimated value predicted by Eq. (1) by changing length from 302 mm to 163 mm. Primary EXP-PS is used as the reference experimental collapse pressure for this estimation.

Parameter	Value
E (elastic modulus)	70 GPa
ν (Poisson's ratio)	0.3
a (radius of middle surface of implodable volume)	15.44 mm
h (wall thickness)	~ 0.870 mm
l (unsupported length)	302 mm (primary) 163 mm (secondary)
n (circumferential mode number)	2

Table 2

(a)

2.13 m

0.51 m diameter access door

2.13 m

Nitrogen Gas Inlet

Nitrogen Gas Pocket

Confining Tube

Specimen

Water

Figure 2

Figure 3

Figure 4

Graphical Abstract

Implosion within an Open Ended
Confining Tube

Sympathetic Implosion of Stronger Tube
after Weaker Tube's Implosion