Original Article

High velocity projectile impact of a composite rubber/aluminium fluid-filled container

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A B S T R A C T

When penetrated by a high-velocity projectile, a fluid-filled container can be severely damaged and ruptured due to the intense impact loading from Hydrodynamic Ram (HRAM), which causes a primary shock wave, and then a subsequent loading phase when a cavity evolves in the fluid. In the design of fuel tanks for aircraft, and other transport vehicles, the HRAM pressure is a major concern for the reliability of the structure. In this paper, experiments of high-velocity projectiles impacting two different types of fluid-filled containers, including an aluminium wall and a composite aluminium/rubber wall, were performed to study the mitigation effect of the rubber layer on the damage of the structure and the impact loading from Hydrodynamic Ram. A high-speed camera was employed to record the formation process of the cavity, and the shock wave pressure-time histories in the fluid were also obtained by pressure transducers. By comparing and analysing the experimental results, it is shown that the rubber layer of the composite wall container was able to reduce the reflected shock pressure and the deformation of the structure.

1. Introduction

The Hydrodynamic Ram (HRAM) loadings was induced when a high-speed projectile penetrates through a fluid-filled container. The projectile transfers its kinetic energy to the surrounding fluid whilst it travels through the fluid and induces a primary shock pressure and then a subsequent loading when a cavity evolves resulting in intense impact loads that could possibly damage the entire structure of the fluid-filled container [1]. A fuel tank of an aircraft, can be impacted by high velocity fragments, e.g. tyre and runway debris, and the loss of contained fuel and the possibility of ignition can cause a catastrophic failure. There have been very

serious accidents in the past, such as the Concorde accident and the Qantas A-380 accident [2]. However, the HRAM phenomenon occurs not only in the aerospace industry but also in ground-based vehicles and marine vessels industry that transporting fuel or other fluids [3,4]. This case can be particularly dangerous if the liquid inside the container is a kind of hazardous material.

The process of HRAM mainly includes four particular phases: shock, drag, cavitation and exit. The loading from each phase contributes to structural damage in a different form and to a varied degree [5,6]. In the shock phase, the projectile initially impacts or penetrates the wall of the fluid-filled container, causing the primary pressure impulse propagating rapidly in the liquid. Then, in the drag phase, the projectile travels through the fluid, and as projectile velocity is attenuated, its kinetic energy is converted into shock wave in the liquid and the movement of the fluid and later into plastic deformation and rapture of the walls of the container. For the cavitation phase, as the projectile travels through the fluid, the pressure behind the projectile drops below the fluid's vapour pressure resulting in cavitation or the kinetic energy of the projectile can set the fluid in motion forming a cavity. Finally, for the

exit phase, if the projectile has enough kinetic energy, it will exit the container.

The HRAM event is particularly harmful for structures with lightweight designs. It should be specially considered in the design phase of fluid-filled containers. Several researchers and designers [7—14] were particularly interested in the projectile velocity prediction, the cavity evolution process, the damage mechanism of the structure and the counter-measures for alleviating the impact loads from HRAM and protecting the container structure. Based on the findings and conclusions from previous research, some approaches of reducing the vulnerability of fluid-filled tanks subjected to the HRAM phenomenon have been proposed. Townsend et al. [15] employed two different techniques to reduce the damage to the container by alleviating the shock pressure in the fluid. The results showed that an approximately 40%—60% reduction of shock pressure can be achieved by placing air filled baffles or bubbling air through the fluid in the tank. Disimile et al. [16] installed four different geometries of triangular bars inside the water-filled container to reduce the shock pressure wave by disturbing the interaction between the initial shock wave and its reflections. Experimental results showed that the pressure in the rear wall decreased dramatically.

Due to the highly elastic, low sound-speed and density properties of the rubber material, it was commonly used in laminate panels to affect the wave propagation in different materials and the consequent anti-ballistic performance of the armour plates. Sarlin et al. [17] investigated the effect of impact energy and rubber thickness on the impact properties of layered steel/rubber/composite hybrid structures, the results showed that the rubber layer absorbs the impact energy and decreases the interfacial and internal damage in the hybrid structure and in its components. The area of permanent damage showed a decrease of nearly 50% with the use of rubber when comparing a structure without rubber to a structure with 1.5 mm rubber. The research of Tasdemirci et al. [18] showed that the interface rubber material can have a strong effect on the fragmentation behaviour of the ceramic layer and decreases the subsequent damage, caused mainly by the reflection of the compressive waves at the ceramic-interlayer interface due to the impedance mismatch. The results indicated that the rubber layer was capable of mitigating the dynamic response of the fluid-filled container significantly [19]. In addition, the excellent nonlinear elastic properties would be helpful in avoiding the spray or leakage of the hazardous liquid in the container. However, in practical scenarios, both the effectiveness and the feasibility of the deployment of the protective measures should be considered. In this paper, a series of experiments employing an aluminium wall and a composite aluminium/rubber wall for fluid-filled containers were conducted. This is when they are subjected to impact from high-speed projectiles to study the mitigation effect of the rubber layer on the impact load caused by the HRAM and the subsequent dynamic response and damage of the container.

2. Experimental setup

The tests were performed by employing a propellant gun, the velocity of the projectile was determined directly by the mass of propellant, as shown in Fig. 1. The steel projectiles used in the experiments were flattened cylinders with diameter 13.8 mm, length 19 mm and mass of 22.2 g. The schematic of the experimental arrangement is shown in Fig. 1. In the experiments, the velocities of projectiles were in the range from 700 to 900 m/s.

The main structure of the fluid-filled container was manufactured by using 12 mm steel plates. The inner dimensions of the container are 200 mm, 780 mm and 368 mm for the width, length and depth directions, respectively. In order to capture the trace of the projectile and the evolution process of the cavity, 30 mm thick PMMA plates were installed on the both lateral walls of the container, while a PMMA window with size of 300 × 195 mm was set on the top wall to receive the supplementary lighting. A replaceable target panel, 200 mm × 200 mm, made of 2024-T3 aluminium, was located in the centre of front and rear walls of the container, allowing for multiple tests to be performed, as shown in Fig. 2.

The pressure pulse in the fluid was recorded by a PCB 138A06 pressure transducer with a maximum value of the measurement range of 34.4 MPa and a resolution of 0.07 kPa. A hole was drilled in the top wall of the container to place the sensors inside the water, as shown in Fig. 3. The GEN7t data-acquisition device was used to record all the signals.

In order to record the trace of the projectile penetrating the fluid and the evolution of the cavity, a digital high-speed camera was employed. The frame rate was set to 30,000 fps, the time interval between the two sequence frames is 0.033 ms, which was short enough to capture the detailed penetration process of the projectile and capable of recording images with acceptable quality. In order to improve the image quality, three LED lights were set close to the top and side walls of the fluid-filled container to provide enough light intensity to meet the requirements of clear measurements.

As mentioned previously, this research proposed a new scheme of countermeasure to attenuate the effects of the HRAM phenomenon, protect the structure of fluid-filled container and avoid the possible leakage of the hazardous liquid. In this paper, rubber layer, of thickness 4 mm, was placed between walls of container and fluid, as shown in Fig. 4. Six tests were performed in this study, including 1 mm, 2 mm and 4 mm aluminium wall containers and corresponding composite rubber/aluminium wall containers.

3. Results and discussions

Six different experiments were conducted and the initial and residual velocities of these experiments were recorded and summarized in Table 1. It is worth noting that the initial velocities were different in each test, but their difference was small, less than 5%, whilst the residual velocities are closer to each other, in the same
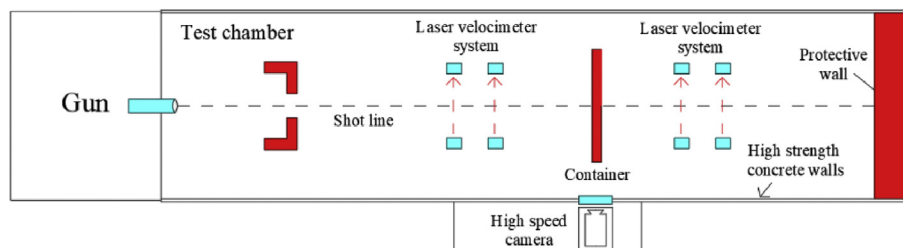

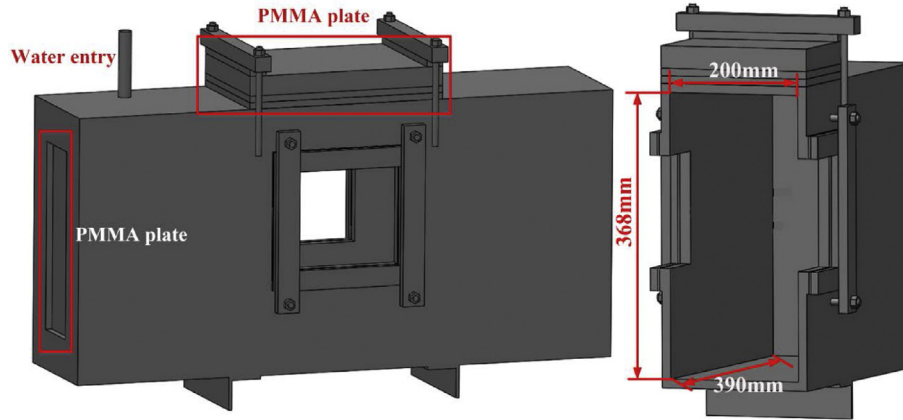**Fig. 1.** Schematic of the experimental configuration.

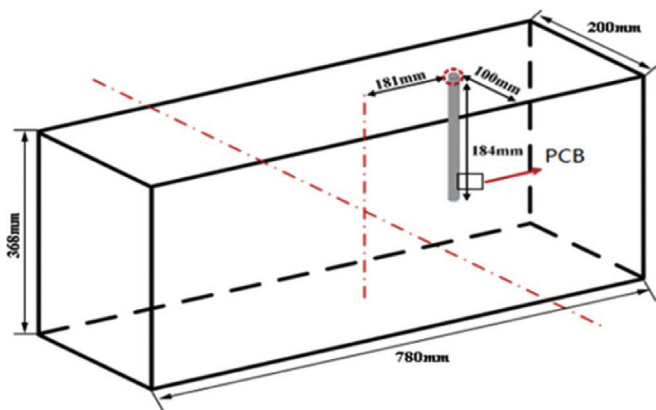**Fig. 2.** Schematic of the liquid container

Fig. 3. Location of the pressure transducer.

series of tests. It showed that the rubber layer, with thickness 4 mm, had slight influence on the velocity decay when the projectile penetrated through the inner liquid and walls of the fluid-filled container.

In addition, the images recorded by the high-speed camera were employed to compare the HRAM phenomenon induced cavitation in the fluid between the aluminium wall and composite rubber/aluminium wall containers. Fig. 5 shows the formation and growth of the cavity when the projectile penetrating through the fluid-filled container. By comparing the recorded images, it shows that

Fig. 4. Configuration of the composite rubber/aluminium wall container.

the shape and growth sizes of cavity were similar in the conditions of the projectiles impacting the aluminium wall and composite rubber/aluminium wall containers. The data in Table 1 shows that the projectile velocity attenuation in the conditions of containers with rubber layer is close to that of the containers without rubber layer. In addition, as the growth rate of the cavity was mainly determined by the velocity of the projectile [20], the similar shape and sizes of cavity means that the 4 mm rubber hardly affect the velocity decay of the projectile, due to that the rubber has much lower modulus and density than aluminium.

Fig. 6 shows the comparison of permanent deflection and damage between the aluminium wall and composite rubber/aluminium containers, in which the thickness of the entry and exit aluminium plates of container were all 1 mm. When subjected to the intense impact load from HRAM effect, both the entry and exit walls of the fluid-filled container were severely damaged and totally ruptured. Meanwhile, the comparison showed that damage level of the composite rubber/aluminium wall container was significantly decreased. Except for large deflection and the holes punched by the projectile, no obvious rupture occurred on the entry and exit walls. The reason is that the existence of the rubber layer, which has comparatively lower density and modulus, attenuated the shock wave applied on the aluminium wall due to the impedance mismatch effect.

The comparison of damage mode of the two different containers with 4 mm aluminium was shown in Fig. 7. The thicker walls of the container were capable of resisting the impact load due to the HRAM effect. In the exit wall of the container without rubber, the petalling cracks around the punch hole caused by the projectile can be found, while the punch hole in the exit wall of the composite rubber/aluminium container was smaller and smooth. In addition, the residual deflection of the entry and exit walls was measured by employing a 3D laser scanner. It is worth noted that the entry and exit wall deformed to opposite directions when subjected to the HRAM pressure. For the entry wall, the impact from the high-speed projectile only caused localized deformation around the impact point along the flying direction, in which the back fluid in the container restrained the entry wall deformed further. As soon as the projectile contacted the fluid, the kinetic energy transferred to the fluid and caused intense shock wave, and subsequently the dynamic response of the container walls were induced by the moving shock wave and then deformed outwards. The deflections of the cross-sections of the entry and exit plates were measured and shown in Fig. 8. It is found that the exit plate deformed more significant than that of the entry, as not only the initial shock wave but also the drag force continuously acted on the exit plate until the
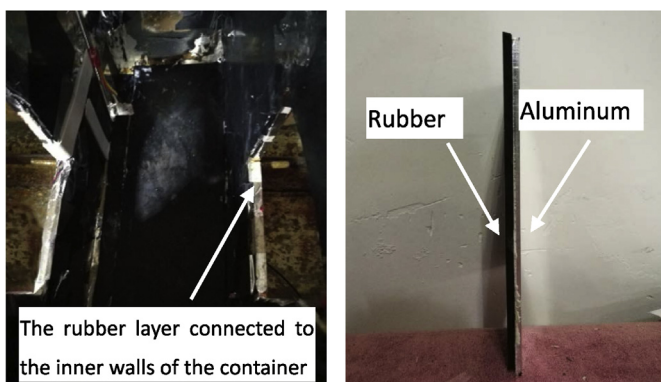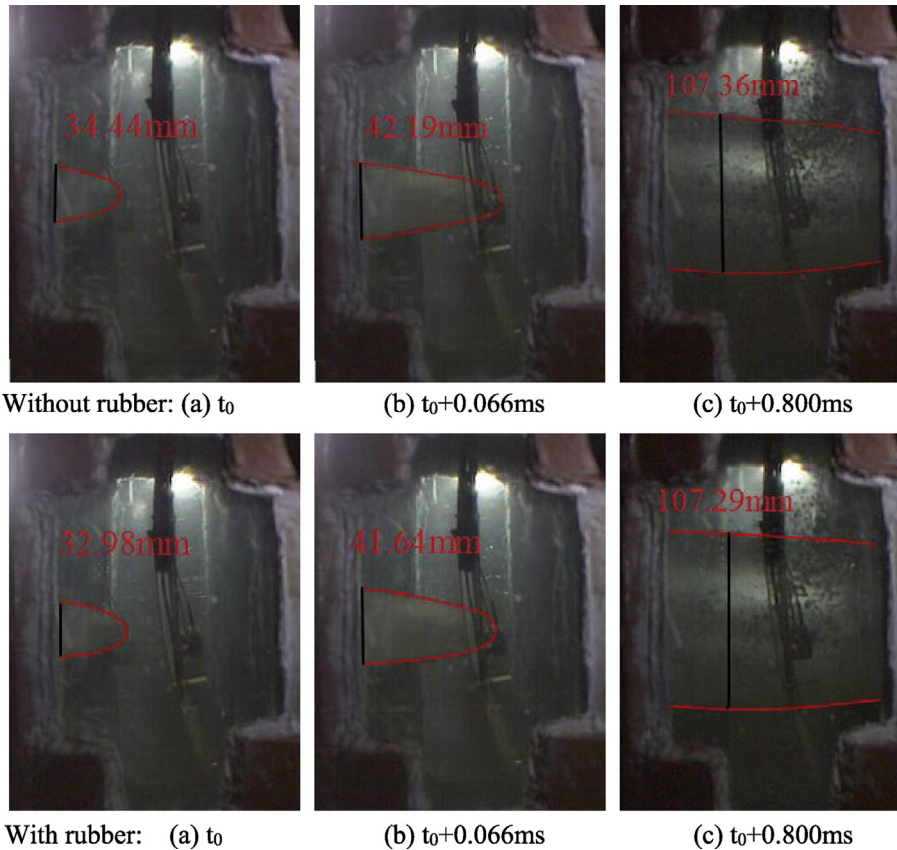
Table 1
The results of the container, with and without rubber layers.

Test number	entry/exit plates (mm)	Type	Impact velocity (m/s)	Residual velocity (m/s)
1	1/1	With rubber	768.2	352.4
2	1/1	No rubber	754.7	346.9
3	2/2	With rubber	807.4	379.3
4	2/2	No rubber	781.81	391.5
5	4/4	With rubber	788.1	275.0
6	4/4	No rubber	826.0	290.3

Without rubber: (a) t_0 (b) $t_0+0.066$ms   (c) $t_0+0.800$ms

With rubber: (a) t_0 (b) $t_0+0.066$ms   (c) $t_0+0.800$ms

Fig. 5. Growth of the cavity in the process of the projectile penetrating the container (the red lines show the boundary of the cavity).

projectile pierced it [19]. In addition, the deflections of entry and exit plates of the composite rubber/aluminium container decreased significantly than those of the aluminium wall container. Due to the mitigation effect of the rubber layer, the maximum deflections of the entry and exit wall decreased by 21.8% and 24.1%, respectively.

It is interesting to observe that the rubber layer of the composite wall bounced back without any tear after the projectile pierced the container. The experimental results indicated that the composite rubber/aluminium wall container had the ability of self-sealing. It means that the rubber layer can not only alleviate the damage level, but also slow down the subsequent leakage of the toxic or combustible liquid from the container. Experiments of high-velocity tungsten alloy burning-fragment impacting fuel tank with rubber layer in Refs. [21]. Compared with the ordinary fuel

a. Entry plate with rubber   b. Exit plate with rubber   c. Entry plate without rubber   d. Exit plate without rubber
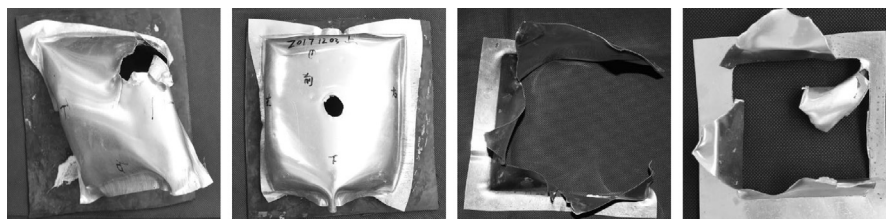
Fig. 6. Damage and deformation of the container (1 mm).

a. Entry plate with rubber b. Exit plate with rubber c. Entry plate without rubber d. Exit plate without rubber
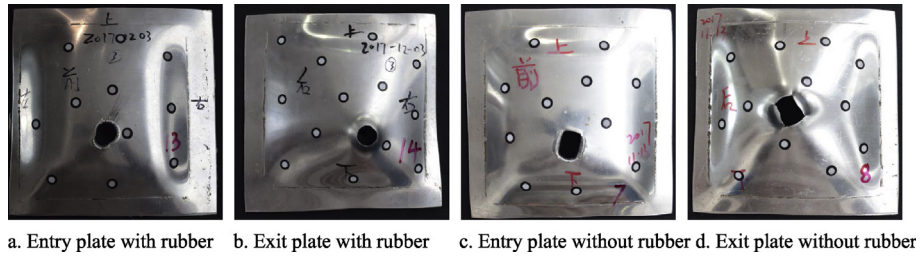
Fig. 7. Damage mode of the containers (4 mm).

tank, the results indicated that the fuel tank with rubber layer were unignited and unexploded. From the experiments, it can be seen that only small amount of fuel ejected from the tank. So, the rubber layer cannot completely prevent the leakage of the liquid but can slow down the leakage of the liquid. The punched holes in the aluminium and rubber layer caused by the high-speed projectile was shown in Fig. 9. The size of the perforation in rubber layer was much smaller than that in 2024-T3 aluminium plate.

In this series of tests, the pressure sensor was employed to record the pressure-time history of the HRAM phenomenon. The sensor was placed in the middle position along the width and depth of the container, 181 mm away from the projectile trajectory (central line). The pressure-time histories in the conditions of the two different fluid-filled container with wall thicknesses of 2 mm and 4 mm were measured and displayed in Fig. 10. It is found that the typical pressure history can be split into three sequential stages, including the initial shock wave, the projectile drag induced pressure and the reflected shock wave, as marked in Fig. 10. According to the research in Ref. [9], the magnitude value of the initial shock wave was mainly determined by the projectile velocity when it impacted the fluid. By comparing the detailed data of the aluminium and the composite rubber/aluminium wall containers, it is found that the reflected shock wave took more time to reach the sensor location and the peak dropped significantly. The main reasons are that the relatively low modulus of the rubber layer decreased the shock wave velocity and the impedance mismatch effect between the different materials of water and rubber affected

the reflected shock wave from the interfaces. Chou et al. [22] proposed a theoretical analysis model to predict the shock wave velocity in the water:

$$u_s = 1442.2 + \frac{500.4(0.738K_e)^{1/3}}{1000t + 1} \tag{1}$$

where u_s is the shock wave velocity in water, K_e is the initial kinetic energy of projectile.

By taking the specific values related in the experiments, including the initial velocity projectile as listed in Table 1, the container width 200 mm, the thickness of the rubber layer 4 mm, the velocity of sound in the fluid 1465 m/s, the sound velocity in the rubber layer 300 m/s, then the propagation of the shock wave can be determined. When the projectile travels close to the exit wall, the initial shock velocity propagated at approximate sonic velocity and calculate by Eq. (1) is 1458 m/s. Taking both the incident and reflected waves into consideration, the duration required for the travelling shock wave in 4 mm rubber layer and water can be calculated respectively, as follows:

$$t_1 = \frac{2 \times 4}{1458} = 0.005ms, \ t_2 = \frac{2 \times 4}{300} = 0.0267ms$$

By subtracting t_1 from t_2, the difference of time interval of the initial and reflected shock waves between the aluminium wall and composite rubber/aluminium wall container is 0.0217 ms, whilst this value obtained from test data is about 0.03 ms. It is revealed
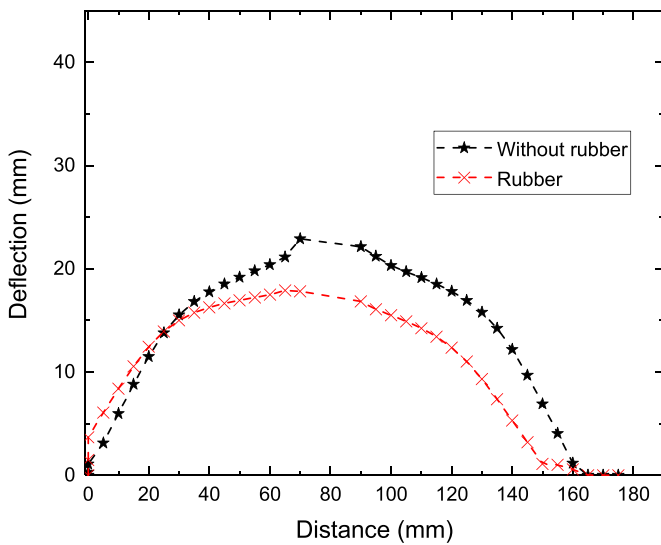
(a) Deformation of entry plate.
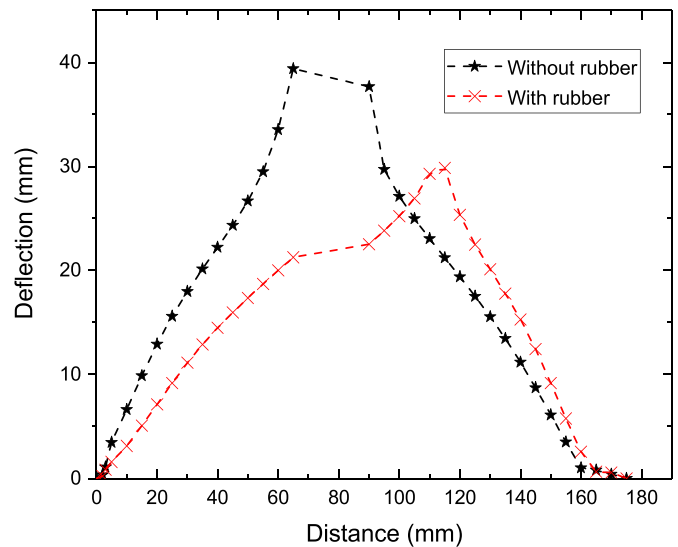
(b) Deformation of exit plate.

Fig. 8. Deflection of entry and exit wall of the containers (4 mm).

(a) Hole in the aluminium plate.
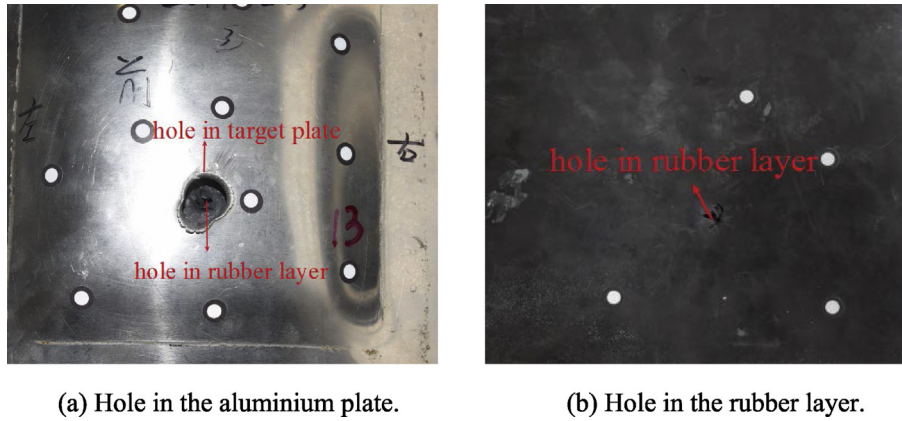

(b) Hole in the rubber layer.

Fig. 9. The punched holes in the aluminium and rubber layer.

that the lower velocity of shock wave in the rubber layer delayed the arrival time of the reflected wave.

The initial impact wave was initially a shock wave, created due to the geometry of blunt body impact as described by Korobkin, and the initial wave pressure was vary with the initial velocity of the projectile [9]. The pressure time histories depicted in Fig. 10 shows that the peaks of the initial shock waves are determined by the initial velocity of the projectile shown in Table 1 and therefore implies that this magnitude is independent of the rubber layer. After the initial shock wave, it is clearly shown that for the composite rubber/aluminium wall container, the peaks of the reflected shock waves are much lower than that values of the aluminium wall container. It is mainly due to the high elasticity and low modulus properties of the rubber as well as the impedance mismatch effect occurred at the interface between water and rubber that affected the reflected shock waves. The mechanism behind this phenomenon could be analysed by employing the 1D wave propagation theory. When a stress wave travels from one into another materials, the transmission and reflection of the wave would occur at the interface. By introducing the momentum conservation condition, the relationship among incident wave, reflected wave and transmitted wave is as follows:

$$\frac{\sigma_I}{\rho_w c_w} - \frac{\sigma_R}{\rho_w c_w} = \frac{\sigma_T}{\rho_a c_a} \tag{2}$$

$$\sigma_I + \sigma_R = \sigma_T \tag{3}$$

where σ_I, σ_R and σ_T are the incident wave pressure, the reflected wave pressure and the transmitted wave pressure, respectively. ρ_w and ρ_α are the density of water and material α. c_w and c_α are the sound speed in water and material, α.

By substituting Eq. (2) into Eq. (3), the following relational expression could be obtained:

$$\sigma_T = T\sigma_I, \ \sigma_R = F\sigma_I, \ T = \frac{2}{1+n}, \ F = \frac{1-n}{1+n}, \ n = \frac{\rho_w c_w}{\rho_a c_a} \tag{4}$$

where T, F and n are the transmission factor, the reflection factor, and the wave impedance ratio, respectively.

Due to the significant differences between the density and the sound speed of these two materials, by analysing Eq. (4), it is clear that at the time when the shock wave propagates from water into aluminium, the wave impedance ratio n is a relatively small
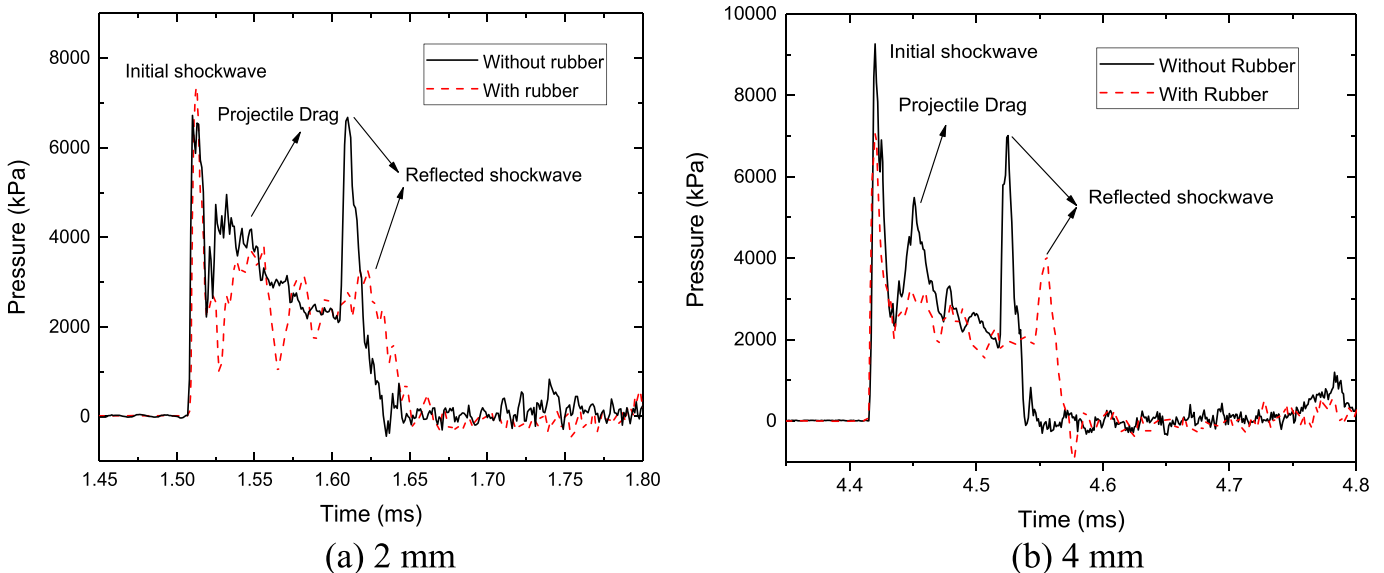

(a) 2 mm

(b) 4 mm

Fig. 10. Pressure-time histories of the HRAM load in the fluid.

Table 2
The peaks pressure of the initial and reflected shock waves with rubber layers.

Test number	entry/exit plates (mm)	Type	Initial pressure (kPa)	Reflected pressure (kPa)
3	2/2	rubber layers	7346	3247
5	4/4	rubber layers	7063	4061

number. It means that the intensity of the reflected shock wave is close to that of the initial shock wave, and attenuation effect on the reflected shock wave between water and aluminium is not obvious. However, for the composite rubber/aluminium wall container, the initial shock wave caused by projectile firstly propagating from water into rubber. The density of the rubber is very close to that of the water, about 1000 kg/m^3, but the sound speed in rubber is much less than that of water, which leads to a high wave impedance ratio and a negative value of the reflection factor. For the materials in this series tests, the speed of sound in rubber, c_{rubber}, and in water, c_w, are 300 m/s and 1465 m/s, respectively. According to Eq (4), the wave impedance ratio $n = 4.9$ and the final calculation result of the projection pressure of shock wave propagating from water into rubber is $\sigma_R = -0.66\sigma_I$. The presence of the rubber layer between the water and aluminium wall can effectively mitigate the shock wave applied on the container wall and the subsequent reflected shock wave. In the two test conditions, the peak pressures of the initial and reflected shock waves with rubber layers were recorded by a PCB 138A06 pressure transducer, as shown in Table 2, and the results showed the reflected shock wave in the composite rubber/aluminium wall containers decreased by 51.4% and 42.0% than the initial shock wave.

4. Conclusions

In order to reduce the vulnerability of the container structure, a composite rubber/aluminium wall container was designed and manufactured. In addition, experiments of high-velocity projectiles impacting two different types of containers, including aluminium wall and composite aluminium/rubber wall, were performed to investigate the mitigation effect of the rubber layer on the damage of the structure and the impact load from the Hydrodynamic Ram event. The results obtained were compared and analysed and the following conclusions are drawn as follows:

(1) By comparing with the experimental data of the aluminium wall container, the rubber layer of the composite rubber/aluminium wall container does not modify appreciably the velocity decay of the projectile and the growth of the cavity from HRAM event. However, as an impedance mismatch effect occurs at the interfaces between different materials, the transmission and reflection waves of the initial shock wave, induced by the high-speed projectile, were significantly reduced. The maximum deflections of the entry and exit walls of the 4 mm aluminium plates decreased by 21.8% and 24.1%, and the measured reflected shock wave in the fluid decreased by 51.4% and 42.0%, respectively.

(2) The experimental results also indicated that the composite rubber/aluminium wall container had the ability of self-sealing to some extent. The rubber layer can not only alleviate the dynamic response of the structure, but also slow down the subsequent leakage of the toxic or combustible liquid from the container. In the design of fuel tanks with respect to HRAM pressure, the scheme presented in this paper would be a good option to reduce the vulnerability of the fluid-filled container.

It is considered that these experiments, and careful analysis of the impact events, have shown that a rubber layer of the composite wall container was able to reduce the reflected shock pressure and the deformation of the structure. In so doing, the container with rubber layers can provide a safer structure for containing fuel or other hazardous fluid than the ordinary container which may be subject to penetrating impact.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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