Research on damage of typical water-containing composite structure under different types of charge

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Abstract. The damage of the water-containing composite structure subjected to underwater explosion is caused by multiple damage elements, such as charge structures, water-containing composite structure, experimental mode and so on. The underwater explosion experiments and the numerical calculations have been performed to study the damage of water-containing composite structure under the different kinds of charge underwater explosion and under different experimental mode. The result shows that the damage of structure under the action of shaped charge is more serious than that of blasting charge in the case of the same charge equivalent. The combined action of shaped penetrator and shock wave can cause perforation and plastic deformation of the rear plate and target of the water-containing composite structure. The tearing hole on the front board is 2~3 times of the shaped charge diameter. The damage of the rear plate is the penetration of the penetrator which is about 1/3 times of the shaped charge diameter. When shaped charge explodes in air or underwater, the plastic deformation of the rear plate is very different.

1. Introduction
There are two main forms of damage to water-containing composite structure by underwater contact explosion: one is that the explosive product directly acts on the water-containing composite structure to produce a break, while the explosive shock wave enlarges the break and causes serious deformation of the structure; the other is that the shaped charge has a cutting and armor piercing effect on the water-containing composite structure, causing a certain diameter of perforation damage to the water-containing composite structure [1][2].

The main damage elements produced by underwater explosion of shaped charge are the shaped charge penetrator and underwater explosion shock wave. The main effect of steel/water/steel is the impact of shaped charge on molten steel and explosion shock wave. The damage of structure caused by multiple damage elements, which are related to the water-containing composite structure (water layer thickness, material and thickness of target plate) and the experimental method (air or underwater), the vegetable is closely related.

2. Research model

2.1. Model building
Typical water-containing composite structure is shown in figure 1, including front plate, water tank, rear plate and aftereffect target. There is a certain thickness of water between front plate and rear plate.
The aftereffect target is placed in the sealed box, and the surrounding medium is air. Different water-containing composite structures have different thickness of water layer and target plate [3–5].

![Figure 1. Water-containing composite structure.](image)

Since the calculation of the water-containing composite structure under the action of the shaped charge requires the introduction of more material models and structural models, the number of grids required for numerical calculation and the amount of calculation are large. The process of forming the energy into the body and the penetration of the target are large deformation movements of multi-media interaction. The numerical calculation is mainly using by ALE method. At the same time, the CEL method is used to calculate the penetrating damage effect of the shaped energy penetrating body on the target.

The numerical calculation model is shown in figure 2; the shaped charge is coated with aluminum crucible, which is equivalent to the aluminum target, the front plate, the water, the rear plate and the aftereffect target from front to back. The brown region is air and other fluid regions are water. All fluid outer boundaries are set to non-reflective boundary conditions, eliminating the influence of the fluid outer boundary on the inner region; the target plate adopts the solid boundary condition.

![Figure 2. Numerical calculation model of water-containing composite structure under the action of shaped charge.](image)

2.2. Model validation
In the studies, the different types explosive sources (explosive charge and shaped charge) and the different experimental environments (air and underwater) where the explosive sources are located are calculated respectively for the composite structures of water layers with different thickness of 667mm and 250mm. The numerical calculation model is verified by experiment.

The comparison of the penetration of the multi-layer aftereffect target is shown in figure 3. From the comparison, the plastic deformation, the diameter of preformation and the number of layers penetrating the aftereffect target are basically the same. In underwater explosion experiment, the penetration thickness of 667mm water layer structure target is 13.5mm rear plate plus 3 layers of 6mm steel plate, while the numerical calculation results is 13.5mm rear plate plus 2 layers of 6mm steel plate, slightly less than the experimental results, which may be due to the different material parameters from the calculated target plate. From the preformation diameter of the rear plate, the calculated results are close to the experimental results, which are about 1/3 times of the shaped charge diameter. The preformation shape can be regarded as ductile preformation. Based on the above analysis, it is
considered that the results of numerical calculation have certain reference value, which shows that the physical and computational methods used in the numerical calculation are reasonable.

(a) Numerical calculation results. (b) Experimental results.

Figure 3. Comparison of penetration damage of multi-layer aftereffect target.

3. Damage of water-containing composite structure under different types of charge

3.1. Damage of blasting charge to water-containing composite structure

Figure 4 shows the propagation of explosion shock wave and its interaction with target plate in 667mm water layer structure. The calculation process can clearly reproduce the interaction process between shock wave and structure. After the explosion, the front plate breaks and warps in radial direction, forming petal-like damage. When the front plate is subjected to contact explosion load, the failure process of the plate can be divided into three stages: first, the depressed stage of the plate, in which the plate and shell undergo large plastic deformation and secondly, the disc stage, in which the circumferential fracture occurs, the disc-shaped separator separated from the plate is formed at the depressed part of the first stage, and the initial breakage occurs on the plate; finally, in the crack growth stage, the circumferential strain of the initial crack edge reaches the maximum with the load applied, and the plate begins to appear circumferential cracks, which eventually forms a flower-vertical crack.

The shock wave passes through the front plate and enters the water. Due to the attenuation of the shock wave in the propagation process, the head pressure decreases gradually. After the front of the shock wave reaches the rear plate, it reflects. Under the action of the pressure, the rear plate produces a plastic deformation. Because the pressure is only about 100MPa, it does not cause serious damage to the rear plate.

Figure 4. Propagation of shock wave and interaction with target (667mm water layer structure).
Figure 5 shows the damage process of 250mm water layer structure under blasting charge, from the Figure, the shock wave reaches the rear plate at 150μs after initiation. At this time, the value of pressure is higher than the 667mm water layer structure experiment. Plastic deformation occurs on the rear plate, the degree of depression of the rear plate and the numbers of deformation targets are more than 667mm water layer structure.

![Figure 5](image)

**Figure 5.** Propagation of shock wave and interaction with plate (250mm water layer structure).

3.2. *Damage of water-containing composite structure by shaped charge*

The damage experiment results of curved water-containing composite structure under the action of shaped charge are shown in figure 6, the damage of the front plate is petal tear, while the water-containing composite structure damage is preformation and plastic deformation. The hole diameter of the front plate is 2~3 times than the diameter of shaped charge. The damage process by shaped charge to 667mm water layer structure is shown in figure 7, the shaped charge penetrates through the front plate, and then the front plate is further torn by shock wave and detonation products, during the impact process of shaped charge on water, the shock wave moves in front of the penetrator and interacts with the rear plate, and after the deformation of the rear plate, the penetrator begins, acting on the rear plate. Finally, under the combined action of the penetrator and shock wave, the rear plates are damaged by perforation, and then two layers of 6mm thick steel plates are transported through the penetrator.

![Figure 6](image)

**Figure 6.** Damage of 667mm water layer structure under the action of shaped charge (experiment).
Figure 7. Damage of 667mm water layer structure under the action of shaped charge (numerical calculation).

The comparison of numerical calculation results shows that: In the case of the equivalent charge, the damage caused by shaped charge is more serious than that caused by explosive charge. The shaped charge consumes part of the explosive energy in a certain angle and forms a shaped penetrator with high kinetic energy. Under the combined action of shaped penetrator and shock wave, it can cause perforation and plastic deformation to the rear plate of water tank and the rear target plate of water containing composite structure.

(1) Damage process analysis of aftereffect target

The penetration failure process of the shaped charge penetrator to the target with multiple intervals is shown in figure 8. After the explosion of shaped charge, a shaped charge with a length diameter ratio of 3:1 and a head velocity of about 3000m/s is produced; the shaped charge penetrates the front plate and enters the water layer. At t = 600μs, the penetrator penetrates the 667 mm thick water layer and begins to penetrate the multi-layer after effect steel plate. The mass of the penetrator is seriously eroded. At this time, the mass of the projectile only accounts for about 20-30% of the initial penetration, and the velocity is only about 60% of the initial velocity. The penetration effect on multi-layer aftereffect target depends on the mass and velocity of the residual projectile. The larger the residual mass and velocity is, the stronger the effect on the aftereffect target is.

At t=630 μs, the penetrator penetrates the rear plate of the water-containing composite structure, at the same time, due to the effect of pressure, the rear plate is sunken inward. At t=900 μs, the penetrator penetrates three layers of 25.5mm target, and its residual mass and velocity cannot damage the target plates, the penetration process stops. The main damage mode of the rear plate is the perforation caused by the penetrator, and the hole is about 1/3 times of the shaped charge diameter.
(2) Movement of penetrator in the water

The process of penetrator into a water-containing composite structure is shown in figure 9. At t=60 μs, the penetrator enters into the water layer and passes through it quickly. Due to the high speed of the penetrator, according to the principle of cavitation, when the water moves around the high-speed penetrator, the pressure of water will drop. When it drops to the saturated vapor pressure, the water will change from the liquid to the gas, thus forming the penetration cavity [6]. The diameter of the cavity increases with the movement of the penetrator, with an average diameter of about 95 mm ± 10 mm, throughout the whole movement path. The water outside the cavity is unloaded and decompressed rapidly on the free surface, and phase transformation and cavitation occur, which slows down the closure of the cavity. This makes the side and tail of the projectile maintain a long time of low resistance movement in the cavity. Except for the head of the penetrator, the side and tail of the penetrator move in the cavity, which is conducive to the penetration of the penetrator into the water medium.

(3) The influence of the thickness of water layer

Maintaining the thickness of the front plate and the rear plate, analyzing the penetration of the penetrator under different thick water layer. The damage of the rear plate is shown in table 1, figure 10 shows the damage of the rear plate and the aftereffect target. With the increase of the water layer thickness, the total thickness of the steel plate penetrated by the penetrator decreases gradually. When the thickness of the water layer is 1000mm, the rear plate cannot cause perforation. The central permanent displacement of the rear plate (indicating the deformation of the plate) decreases with the increase of the water layer thickness.
Table 1. Damage of the rear plate under different water layer thickness.

| Number | Water layer thickness /mm | Thickness of rear plate /mm | Thickness after penetration /mm | Total steel plate thickness /mm | Permanent displacement of rear plate center /mm |
|--------|---------------------------|----------------------------|--------------------------------|-------------------------------|-----------------------------------------------|
| 1      | 250                       | 13.5                       | 13.5+8×6                       | 61.5                          | 46.7                                          |
| 2      | 500                       | 13.5                       | 13.5+5×6                       | 43.5                          | 42.6                                          |
| 3      | 667                       | 13.5                       | 13.5+2×6                       | 25.5                          | 32.9                                          |
| 4      | 1000                      | 13.5                       | Projectile intrusion           | 0                             | 20.5                                          |

Figure 10. Comparison of rear plate damage and aftereffect target under different water layer thickness (different thickness of water layer).

With the increase of the water layer thickness, the mass and velocity of the penetrator are reduced when it penetrates the rear plate and the aftereffect target; the kinetic energy of the penetrator is reduced, so the penetrating ability to the target plate is reduced. At the same time, due to the attenuation of the shock wave by the water layer, the pressure of the shock wave reaching the rear plate also decrease, resulting in the reduction of the plate center permanent displacement.

Keep the thickness of the water layer, and increasing the thickness of the rear plate, comparing the penetration effect on the single-layer target after penetrating the water layer, as shown in figure 11, when the thickness of the rear plate is 27mm, the critical penetration of the target plate is achieved; when the thickness of the rear plate of the water tank is 28mm, the projectile cannot penetrate the target plate, and the mass of the residual projectile embedded in the target plate is 57g, which is about 22% of the mass of the liner. Under the same water layer thickness, the penetration thickness of the shaped charge penetrator through a single target (27mm) is greater than the total thickness of a multi-layer target (25.5mm). The analysis shows that the deformation of the target plate and fragment collapse consume more kinetic energy of the penetrator when the shaped energy penetrator acts on the multi-layer spacer plate, which results in the penetration thickness of the multi-layer spacer plate less than that of the single-layer target.

Figure 11. Penetration effect of penetrator on single-layer target (667mm water layer).
4. Damage of water-containing composite structure in different experimental environments

In the [7-9], ground simulation experiment is used to study the damage of underwater explosion of shaped charge to water-containing composite structure. In underwater explosion, due to the combined action of shaped charge and shock wave, the damage is quite different. According to the theory of stress wave transmission, the transmission pressure of underwater structure under the action of shock wave generated by explosion is [10]:

\[ p_j = \frac{2\rho f_j}{\rho_j c_j + \rho_0 c_0} \]  \hspace{1cm} (1)

\( p_j \) is the transmission pressure of the underwater structure, \( \rho_j c_j \) is the wave impedance of the underwater structure, \( \rho_0 c_0 \) is the wave impedance of the water.

Due to the thin thickness of the front plate, there is a large perforation (no matter on the ground or under the water) after the explosion. In the ground experiment, the shock wave penetrates into the water from the air, and then acts on the rear plate through the water, the pressure reaching the rear plate has a great attenuation. In the underwater experiment, the shock wave propagates in the water, and still exists when it reaches the rear plate.

Figure 12 shows the damage of the rear plate with the same thickness structure under three experimental environments. In the ground experiment, the rear plate is damaged by perforation under the action of the penetrator; the overall deformation of the rear plate is not serious, only a small amount of recesses around the bullet holes, mainly due to the local depression caused by the impact of the penetrator. In the underwater explosion of blasting charge, only shock wave load is applied to the water-containing composite structure, because the structure is fixed around, it has a large plastic deformation of concave. Under the action of underwater explosion of shaped charge, the damage of the rear plate reflects the superposition effect of two cases, the perforation occurs on a concave steel plate. Under the condition of ground experiment, the water in the tank is in an open state. Under the impact of explosion, due to the surface effect of water, part of the shock wave energy overflows the water surface, so it cannot cause large central displacement to rear plate.

![Figure 12. Damage of rear plate by different damage elements.](image1.png)

Place the shaped charge in the air and establish the numerical calculation model, as shown in figure 13. The model is consistent with figure 2 except that the medium of shaped charge is different.

![Figure 13. Interaction models of explosion and water-containing composite structure in air of shaped charge (numerical calculation).](image2.png)
The calculation results show that there is no obvious difference between the explosion of shaped charge in air and underwater, such as the velocity change rule of shaped charge, the perforation aperture of target plate and the thickness of target plate after penetration, while the plastic deformation of the rear plate is quite different, as shown in figure 14. In the case of air, the plate center permanent displacement is 24.6mm, while in the case of underwater; the plate center permanent displacement is 32.6mm. In the case of concentrated energy charge, the center permanent displacement of the underwater explosion is increased by about 33% compared with that in the case of air explosion. From the experimental point of view, under the conditions of air and water explosion, the plate center displacement is more obvious, and the difference between the two results of the numerical calculation is smaller. This is mainly because the energy dissipation of shock wave in shallow water is not considered in the numerical calculation process, and the effect of thermal effect on the deformation of the target plate is ignored.

![Figure 14. Comparison of target damage under different explosion conditions (numerical calculation).](image1)

Figure 15 shows the pressure change on the surface of the rear plate. The measuring points are 50mm, 100mm and 150mm away from the axis of action of the penetrator. The surface pressure of the rear plate for underwater explosion is significantly higher than that for air explosion under the same other conditions. For the position 50mm away from the penetration axis, the maximum pressure is about twice the pressure in the air, and the shock wave action time is longer. Therefore, the impulse acting on the rear plate is relatively large, which is also the reason for the increase of the plate center permanent displacement under the condition of underwater explosion. It can be seen from the results of experiment and numerical calculation that it is not comprehensive to study the damage of water-containing composite structure under the action of shaped charge by ground experiment.

![Figure 15. Surface pressure change of the rear plate under different explosion conditions of shaped charge (numerical calculation).](image2)

5. Conclusions
In the paper, the damage of water-containing composite structure under different types of charges and different experimental environments is studied; the main conclusions are as follows:
(1) Compared with the experimental results, the plastic deformation, perforation diameter and the number of layers through the target plate are basically the same in the numerical calculation results, which shows that the physical model and calculation method adopted in the calculation are reasonable, and the numerical calculation results have reference value.

(2) Under the action of blasting charge, the front plate is broken radially and warped to form petal shaped damage, and the rear plate has certain plastic deformation, the greater the thickness of water layer is, the smaller the plastic deformation of the rear plate is.

(3) The damage of the water-containing composite structure under the underwater explosion of the shaped charge is mainly the result of the combined action of the shaped charge and the shock wave. The shaped charge makes the target plate perforated, and the shock wave tears the shell. The combined action makes the rear plate produce large plastic deformation. The main damage mode of the rear plate is perforation plus plastic deformation, and the perforation aperture is about 1/3 times of charge diameter.

(4) When the shaped charge explodes in the air or underwater, there is no difference in the velocity change rule of the shaped charge penetrator, the diameter of the target plate and the total thickness of the target plate after penetrating. However, the plastic deformation of the rear plate is quite different. Therefore, it is limited to use the ground simulation experiment to carry out the research.

Reference
[1] Nurick G N and Shave G C 1996. Intl.J.of Impact engng. 18 99-116
[2] Zhang Zhenhua 2004 Doctoral Dissertation of Naval Engineering University 12 94-112
[3] Pei Mingjing and Li Chengbing 2008 Journal of explosives 3 15-9
[4] Wang Tuan Meng and Xiang Chun 2008, Torpedo technology 16 44-7
[5] Cao Bing 2007 Initiating explosive device 3 1-5
[6] Pan Sensen and Peng Xiaoxing 2013 Cavitation mechanism (Beijing: National Defence Industry Press) p 221
[7] Ye Benzhi, Feng Minxian and Huang Qiyou 1996 Detonation and shock wave 3 16-22
[8] Li Chengbing, Pei Mingjing and Shen Zhaowu 2006 Journal of explosives and explosives 29 1-5
[9] Cao Juzhen, Liao Zhenmin and Liang Longhe 1998 Shock wave physics and detonation physics 12
[10] Yu Tongxi and Qiu Xinming 2011 Impact dynamics( Beijing: Tsinghua University Press) p 100