Research on the damage effect of semi-armor-piercing warhead on combined cabins of warships

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Abstract. Explosion test of 30kg Semi-armor-piercing warhead in the combined cabin of warship is completed. In the test, Upper and lower cabins are completely disintegrated. Cabins are broken in the weld zone. Maximum overpressure of lower cabin is 6.5 MPa and that of upper cabin is 0.6 MPa. By using numerical simulation method, influence of missile hole position and explosive charge velocity on damage effect is analyzed. Results show that difference of hole position will affect superposition of detonation products in cabin, thus changing position where the first structural fracture occurs in the cabin, leading to difference of damage. Increasing velocity of charge will make damage of positive direction bulkhead more serious, but damage degree of negative direction will be reduced. When velocity of charge exceeds 2 Ma, detonation products will not be able to affect cabin in negative direction of velocity.

1. Introduction
Semi-armor-piercing anti-ship warhead is one of the most effective ways to damage ship targets. Semi-armor-piercing warhead penetrates ship’s bulkheads with its own kinetic energy, drills into the ship [1]. By means of delayed detonation fuse, detonation time of charge in the warhead is controlled, and structure, equipment and personnel inside the ship target are damaged by this form of "first penetration and then detonation" [2]. For analysis of damage power of semi-armor-piercing warhead, cabin test combined with numerical simulation is often used. Advantage of the cabin test is that it can reflect the real impact state, obtain the data accurately and persuasively, but the cost is high. Advantage of numerical simulation is that it can simulate many working conditions, large number of simulation samples, and carry out in-depth research on local or some details, but setting of material model, calculation criteria and boundary setting needs to be verified for accuracy. Feldgun [3] analysed the overpressure of the explosion in the cabin with the relief hole, and gave a simplified calculation method of the pressure in the cabin. Zhu [4] studied the shock wave load characteristics of explosion in the cabin by means of experiment and numerical simulation, and optimized the underwater protective structure. Li [5] studied the damage effect of explosion impact load on the structure of the cabin panel and overall shape of cabin. State of the semi-armor-piercing warhead before detonation in the cabin will directly affect the damage power, and attitude before detonation is related to the penetration position of the projectile and movement speed of the projectile when initiation. Above content will be studied.

In this paper, damage effect is analysed by static explosion test combined with multi condition numerical simulation. In the test, semi-armor-piercing warhead is used for static explosion test in the
cabin to obtain the data of shock wave in the cabin and verify the accuracy of numerical simulation model. In the part of numerical simulation, ANSYS LS-DYNA finite element analysis software is used to establish the structure model of upper and lower adjacent tanks by APDL method, which mainly analyses two factors of penetration of semi-armor-piercing warhead to different parts of bulkhead and different penetration speed.

2. Description of test and numerical simulation scheme

In order to more accurately simulate damage effect of semi-armor-piercing warhead to cabin of warship. Based on investigation of the structures of various of ships, a typical combined type of aluminium cabin with length 4 m, width 3 m and height 2.5 m above and steel cabin with length 5 m, width 4 m and height 2.5 m below is designed [7]. Longitudinal central axis of these two cabins overlaps, these two cabins are welded by the way of steel-aluminium transition joint, and internal reinforcement is arranged according to the real warship cabin. According to actual detonation position and direction, warhead is placed statically. Photo of combined cabin and schematic diagram of finite element model are shown in figure 1.

Figure1. Photo of combined cabins and diagram of finite element model.

Structure size and stiffener arrangement of the combined cabins in numerical simulation are the same as those in the test. Steel cabin is provided a missile hole measures 30 cm across. Solid 164# element is used. Eight nodes hexahedron mapping grid is used. Plastic-Kinematic model is used to define material constitutive relationship of steel cabin. Mises yield criterion is used to define failure. Failure strain is 0.2. Material density is 7.83 g·cm⁻³. Yield strength is 500 MPa, Johnson-cook model is used to define constitutive relationship and failure of aluminium cabin. Material density is 2.71 g · cm⁻³, Young's modulus is 70.1 GPA, Poisson's ratio is 0.34, among the parameters in Johnson-cook model, a = 337 MPa, B = 343 MPa, n = 0.41, C = 0.01, M = 1. TSTS model is adopted at the weld joint, in which the weld failure stress of steel cabin is set as 400 MPa, weld failure stress of aluminium cabin is set as 270 MPa, and failure stress of steel aluminium composite transition joint is set as 196 MPa.

Explosive charge is placed in centre of steel cabin, 30 cm from ceiling in the vertical direction. According to the size of the warhead and mass of the shell, kinetic energy of the driving shell is calculated by the Gurney formula, so that 9.5kg shell charge of warhead can be approximately 6.5kg of naked charge, and charge is set as a cylinder type, using single point detonation form.

Air is described by ideal gas model and null model, in which p₀ = 1.29 kg / m³, specific internal energy E = 2 MJ / kg, and multi index γ = 1.4. Air area is 40 cm larger than outer dimension of bulkhead, and transmission boundary is set. ALE algorithm is used for fluid structure coupling. Overpressure monitoring points are set on the bulkhead.
3. Description of test and verification of model reliability
PCB113b27 sensor with a range of 680 KPa is selected for the upper aluminium cabin, and PCB113b26 sensor with a range of 3.4 MPa is selected for the lower steel cabin. Comparison of test and numerical simulation results of overpressure test is shown in table 1. Average error of test point is about 19.5%. Comparison between numerical simulation results and field photos is shown in figure 2 and figure 3. The calculated results are in good agreement with test results.

| Serial number | Monitoring point | peak overpressure in test (MPa) | peak overpressure in numerical simulation (MPa) | Error value |
|---------------|------------------|---------------------------------|-----------------------------------------------|-------------|
| 1             | D1-1             | 0.76                            | 0.54                                          | 28.1%       |
| 2             | D1-2             | 2.01                            | 1.82                                          | 9.4%        |
| 3             | D1-3             | 4.24                            | 3.96                                          | 6.6%        |
| 4             | D1-4             | 1.55                            | 0.98                                          | 36.7%       |
| 5             | D1-5             | 0.98                            | 1.32                                          | 34.7%       |
| 6             | D1-6             | 3.04                            | 2.46                                          | 19.1%       |
| 7             | D2-1             | 3.68                            | 3.71                                          | 0.8%        |
| 8             | D2-2             | 0.67                            | 0.81                                          | 20.9%       |

Figure 2. Comparison of steel cabin in numerical simulation and test.
4. Influence of missile hole location on damage effect

After reliability of model is verified, problems that can’t be reflected in the static detonation test of cabin are studied in depth. Considering that damage results of cabin will be different when semi-armor-piercing anti-ship missile attacks different parts of bulkhead, numerical simulation method is used to analyse this problem.

Consider the location of the following two types of penetrator holes, the following two options as the first group and the second group respectively are set. Diffusion of detonation products in 10ms is shown in figure 4.

4.1. Influence of the location of the holes on damage effect

The third group is added to cabin without missile hole, and three groups of peak overpressure are counted, as shown in table 2, the following conclusions can be obtained.
Figure 5. Schematic diagram of test point position and pressure time curve of overpressure at test point.

Table 2. Comparison of peak overpressure at each test point in three cases.

| peak overpressure (MPa) | 1-1  | 1-2  | 1-3  | 1-4  | 1-5  |
|-------------------------|------|------|------|------|------|
| Group 1                 | 0.87 | 0.46 | 0.96 | 7.47 | 7.56 |
| Group 2                 | 0.82 | 0.42 | 0.94 | 6.06 | 6.45 |
| Group 3                 | 0.88 | 0.47 | 1.02 | 7.52 | 7.58 |

In the first group and the third group, pressure-time history curves of five test points almost coincided. Peak overpressure is almost the same. Because of the repeated superposition of detonation products, a “cavity” appears in the cabin. The process of pressure relief is not obvious. Then, bulkhead breaks at the weld and cabin disintegrates. Effect of the existence of holes on the damage effect of cabin is relatively weak.

The values of overpressure at each test point in the second group are lower than those in the first group and the third group. The difference between values of overpressure in the second group and those in the first group is 5.7%, 8.7%, 2%, 18.8% and 14.6%, respectively. Test points numbered 1-1 ~ 1-3 are those not in the corner. Time to reach the extreme value for the first time is the same, and pressure value is the same, and they all reach peak value at the second extreme value. Peak value of the second group was slightly smaller than that of the first group and the third group. But the difference is very small. In the second group, leakage mass of detonation products is slightly larger than that of the first group, which leads to the decrease of quasi-static pressure in the cabin before the cabin is disassembled. Because the shock wave of each test point at the corner overlaps repeatedly, drop of quasi-static pressure has more influence on the overpressure at the corner than other positions, so the peak value of overpressure at the corner is smaller.

5. Analysis of damage effect of explosives with different velocity in the cabin

Semi-armor-piercing warhead is controlled by the delay fuse and detonates after penetrating into the cabin. Subjective control of detonation time and objective change of penetration environment will affect the speed of detonation, and the speed of detonation will be different. In order to further analyze the influence of explosive velocity on the damage effect of explosion in the cabin. The damage to the
cabin caused by explosive charges moving at 180 m/s, 272 m/s, 340 m/s and 510 m/s is calculated. Diagram of shock wave flow field of explosives at different velocities is shown in figure 6.

![Shock wave flow field diagram](image)

**Figure 6.** Cloud chart of velocity field of shock wave flow field at different speeds.

It can be seen from Fig. 5 that shock wave field is uniform and symmetrical in the case of static detonation, and velocity of its movement towards the surrounding is the same. In the case of dynamic explosion, the velocity of shock wave in the positive direction is obviously higher than that in the negative direction. Shock wave reaches the ceiling of cabin at 600 μs ~ 800 μs. After that, it makes extrusion movement around and overlaps with each other. The influence of the velocity of charge on the shock wave field is mainly reflected in the difference of overpressure and peak value of velocity in the positive and negative directions. These differences indirectly affect the damage form of the cabin. The action of dynamic detonation can be approximately considered as that the shock wave decelerates in a straight line along the moving direction of the explosive during the static explosion. It leads to the uneven distribution of the pressure field. This conclusion is consistent with Thornhill's conclusion.

The maximum velocity in the positive and negative directions of the velocity at each time is calculated respectively. As shown in table 3.
Table 3. velocity peak value of shock wave field in the positive and negative direction of the velocity of charge at different velocity.

| velocity | 200μs  | 400μs  | 600μs  | 800μs  | 1000μs |  
|----------|-------|--------|--------|--------|---------|  
|          | positive direction | negative direction | positive direction | negative direction | positive direction | negative direction |  
| 0        | 2315   | 1924   | 1531   | 1280   | 1170   |  
| 180      | 2415   | 1948   | 1986   | 1094   | 1621   | 964   | 1550   | 890   | 1422   | 860   |  
| 270      | 2596   | 1739   | 2043   | 1081   | 1777   | 895   | 1599   | 804   | 1481   | 744   |  
| 340      | 2702   | 1521   | 2098   | 1004   | 1836   | 743   | 1648   | 503   | 1527   | 463   |  
| 510      | 2904   | 1304   | 2332   | 723    | 1972   | 215   | 1777   | 192   | 1654   | 177   |  

Following rules can be found through the above table: In dynamic detonation, peak value of shock wave field velocity in the positive direction of velocity is larger than that in static detonation. In dynamic detonation, velocity of shock wave field in the positive direction increases with the increase of charge velocity. Similarly, the negative direction is the opposite. Dynamic detonation has a great influence on the velocity of shock wave field in the negative direction of velocity, which will seriously affect the damage effect on the bulkhead in the negative direction.

When velocity is small, change of shape occurs on the inner surface of the bulkhead. When the bulkhead breaks at the weld, the edge of the bulkhead deforms outwards under the action of detonation wave and detonation products. Therefore, when \( V_0 = 180 \text{ m/s} \) and \( V_0 = 270 \text{ m/s} \), there is wave type bending deformation of bulkhead in the positive direction of velocity. However, when the detonation velocity is high, the weld line of the bulkhead breaks in a short time, and the bulkhead in the positive direction of velocity is blasted away without large deformation. Therefore, when \( V_0 = 340 \text{ m/s} \) and \( V_0 = 510 \text{ m/s} \), velocity positive direction bulkhead only deforms outwards. When \( V_0 = 180 \text{ m/s} \) and \( V_0 = 270 \text{ m/s} \), bulkhead breaks at the corner. This shows that although negative direction velocity is lower than that of the static detonation, shock wave pressure can still cause negative direction bulkhead to break at the weld joint. When \( V_0 = 340 \text{ m/s} \) and \( V_0 = 510 \text{ m/s} \), negative direction bulkhead only deforms, and there is no fracture at the weld joint. Negative direction shock wave field velocity is too low, resulting in a small overpressure, which can’t make the bulkhead fracture.

6. Conclusion

(1) Considering the influence of the location of the missile hole on the damage effect of detonation, Missile hole model which is close to the weld is designed. Comparison of the central hole model results of the same size bulkhead. It is found that the effect of explosion damage is still small. The main reason is that the ship cabin is much larger than the missile hole, the bulkhead is thinner, the welding area is narrower, and the strength is weaker than the bulkhead. Under the action of explosion, when pressure relief occurs, the bulkhead with missile hole structure has been disintegrated, and then the detonation products leak out from the weld joint, and the hole has no pressure relief effect. Therefore, the above phenomenon appears.

(2) During dynamic detonation, the damage degree of bulkhead in the positive direction of velocity is more serious than that of static detonation. The greater velocity of charge is, the greater the flying speed of bulkhead in the positive direction of velocity is, the more serious the deformation degree of bulkhead is, and the greater the peak value of overpressure near bulkhead is. At this time, the damage effect of bulkhead in the negative direction of velocity will be weaker than that of static detonation.
When the velocity of the charge exceeds 2mA, the detonation products will not be able to affect the chamber in the negative direction of velocity. The above conclusion shows that although dynamic detonation can make the damage of bulkhead in the positive direction of velocity more serious, it can accelerate the speed of pressure relief, which leads to the drop of quasi-static pressure in the cabin and the decrease of damage degree in the negative direction of moving speed, which is not conducive to the disassembly of the cabin.

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