Study on the protective properties of polyurethane foam for water-entry projectile

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Abstract. When the projectile enters into the water at high velocity, the impact force will be huge, therefore, it is necessary to protect the projectile. In this paper, polyurethane foam is selected to study its protective properties for water-entry projectile. The water-entry test was designed to compare the numerical simulation results, in order to verify the feasibility and the validity of the model. In particular, the numerical simulation method was used to compare the motion and response characteristics of unprotected and protected projectile. The results demonstrated that the polyurethane foam has good protective properties and comparing the protective effect of different density polyurethane foam by numerical simulation methods, it can be seen that the better protection is achieved at a density of 0.17 g/cm³ and 0.40 g/cm³.

1. Introduction
In the naval blockade, it is a common blockade method to attack the target ship by airdropping blocking ammunition. When the entry velocity is too high, the water-entry impact will have an adverse effect on the projectile, and even make the projectile invalid: therefore, it is necessary to protect the water-entry projectile [1]. Under this background, in this work, a kind of nose cap with polyurethane foam as protective material is designed. The protective properties of polyurethane foam by means of test and numerical simulation method was analyzed.

2. Numerical check
In order to study the protective properties, the impact response of the polyurethane foam, and the water-entry projectile kinematics problems, the finite element program LS-DYNA was selected to simulate the projectile water-entry process. The water-entry test was designed to prove the validity of the LS-DYNA calculation results.

2.1. Numerical model
In order to realize a numerical simulation, a 3D model, identical to the test conditions, was implemented. Since the air has negligible effect on the calculation results, the air domain was ignored [2]. The structure was symmetrical, therefore used a quarter model. The system of elements was cm-s-g. Simulating the projectile with a quarter of an aluminum cylinder, its quality was comparable to the test piece with a thickness of 2.5 cm, whereas the radius was slightly smaller than the protective material. The protective material was a quarter sphere with a radius equal to 7.5 cm, the sides of the cube water was 60 cm. The asymmetric surfaces of the waters were set to non-reflective surface to simulating the infinite waters situation. The diagram and the grid of the model are shown in figure 1.
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Figure 1. The diagram and the grid of the model.

The material model of the foam was selected as *MAT_CLOSED_CELL_FOAM, which is well suited for low density closed cell polyurethane foams; the material parameters are shown in table 1.

Table 1. The material parameters of polyurethane foam.

| P (g/cm^3) | E (MPa) | A (MPa) | B (MPa) | C | P_0 (MPa) | ∅ | γ_0 |
|------------|---------|---------|---------|---|-----------|---|-----|
| 0.25       | 9.93 × 10^-5 | 1.71 × 10^-5 | 1.45 × 10^-5 | -4.27 | 1.0 × 10^-6 | 0.208 | 0   |

The constitutive relationship is shown in equation (1).

\[ \delta y = A + B(1 + C\gamma) \]  \hspace{1cm} (1)

A, B, C are constants given by equations (2), (3), (4). γ is volumetric strain given by equation (5) [3].

\[ A = 23.7\phi^{1.676} \]  \hspace{1cm} (2)

\[ B = 19.2\phi^{1.645} \]  \hspace{1cm} (3)

\[ C = 2.21 - 31.1\phi \]  \hspace{1cm} (4)

\[ \gamma = V - 1 + \gamma_0 \]  \hspace{1cm} (5)

Where \( \rho \) is the material density, \( E \) is the Young's modulus, \( \gamma_0 \) is the initial foam pressure, \( \gamma_0 \) is the initial body strain, \( \phi \) is the ratio of the density of the foam to the polymer.

Set the initial velocity of the projectile to 100 m/s, the obtained water-entry process is shown in figure 2. The polyurethane foam was deformed, its deformation process experiences a linear elastic section, a yield section and a compact section [4].

Figure 2. Water-entry diagram (hit the water-deformation-compaction). (a) t=3.99 μs, (b) t=48.0 μs, (c) t=105 μs and (d) t=148 μs.

2.2. Water-entry test
The schematic diagram of the test system is shown in figure 3. It consists of a ballistic gun, a test piece,
a high-velocity camera and a tank.

![Diagram of test system](image)

**Figure 3.** The schematic diagram of the test system.

The distance between the tank and the gun muzzle was 2 m. The water tank was 1 m long, 0.8 m wide and 0.6 m high; the center opening diameter was 0.4 m. The test required a velocity of 50 m/s-100 m/s. The high-velocity camera was placed at a distance of 3 m, in front of it was a bullet-proof glass.

The dynamic loading device used in this test was a 40 mm diameter smoothbore. Because the test piece was super-caliber and the required velocity was not very fast, this test piece was directly loaded from the muzzle, and the power burning gas pushed the sabot.

A Phantom color high-velocity camera was used, the sampling rate was adjusted to 10000 fps, the screen exposure and resolution at this sampling rate can meet the needs of test. The test piece was mainly divided into three parts: sabot, collet, and protective head. The sabot was 0.3 m long, its tail was concave and radius was 0.04 m. The sabot and the protective head were connected by the collet. The protective head of the test piece was a hemisphere with a radius of 0.15 m. It is made of polyurethane foam with a density of 0.25 g/cm³ and loaded by the ballistic gun to reach about 100 m/s velocity. The schematic diagram and the physical picture of the test are shown in figure 4.

![Physical picture of test](image)

**Figure 4.** The schematic diagram and the physical picture of the test.

2.3. **Comparison of test and numerical results**

![Comparison images](image)

**Figure 5.** Water-entry process of polyurethane head. (a) t=0.6 ms, (b) t=6.0 ms, (c) t=13 ms and (d) t=21 ms.

Figure 5 shows the water-entry process of the test piece; figure 6 shows the recovered protective head. It can be seen that the polyurethane head was quickly compacted and, then, largely crushed, which facilitates the detachment of the nose cap in water [5].
Comparing the test results with the numerical results, figures 7 and 8 show the penetration distance-time and velocity-time curve. As it can be observed from these figures, the test lines conformed closely with the numerical lines and the test results verified the feasibility and validity of the model, indicating that the water entry process can be simulated by this model.

Figure 7. The penetration distance-time curve.

Figure 8. The velocity-time curve.

3. The protective properties of polyurethane foam

3.1. Comparison between protected and unprotected
Modeling the water-entry process of the single projectile and the projectile with polyurethane foam, the models of the two cases are shown in figure 9.
The velocity of the projectile was displayed in two cases, and the display time was 2000 μs. As shown in figure 10, the velocity of both decreased, but the velocity reduction was different. In the case of unprotected, the velocity dropped instantaneously at the beginning; this behavior was not observed in the case of polyurethane foam.

Observing the acceleration, it changed in two cases. As shown in figure 11, related to the case of unprotected, the acceleration-time curve showed a step, the acceleration rose in an instant, because there was a large impact forces when the projectile entered into the water unprotected. This stage was the key stage of protection; when protected, this stage disappeared instead.

The protective mechanism of the protective material consisted of the absorption of a large amount of energy when subjected to impact [6]. Part of the polyurethane foam was selected to observe its energy changes, as shown in figure 12.

The yield strength is the yield limit when the metal material yields. The external force greater than the yield strength will permanently invalidate the part and cannot be recovered. Setting the yield stress of the projectile material to 355 Mbar, the ls-dyna divided the projectile into a number of units, then detected the force of each projectile unit during the water-entry process, the yield units fraction was shown in two cases, as shown in figure 13, in the case of unprotected, the yield volume fraction appeared to be a peak at about 17.2%. After adding the protective head, the maximum yield volume fraction was reduced to 0.4%.
Combined with the above analysis, protective effect was evaluated by four standards, as follows:

- **Velocity**: small velocity change means the motion was stable, achieving protective effect.
- **Energy absorption**: the protective material absorbed energy to achieve protective effect.
- **Maximum acceleration**: the smaller the acceleration, the smaller the impact force, achieving protective effect.
- **Yield stress**: the smaller the stress on the projectile the smaller the damage to the projectile, protective effect is achieved.

Using the above four standards to illustrate the role of protective materials, the comparison results of unprotected and protected are shown in table 2.

| Standard | Protection situation | unprotected | protected |
|----------|----------------------|-------------|-----------|
| Standard 1 | velocity change (m/s) | 8.2         | 1.6       |
| Standard 2 | energy absorption (J) | None        | 2985.2    |
| Standard 3 | maximum acceleration (m/s²) | 310057 | 13379     |
| Standard 4 | yield volume fraction | 17.2%       | 0.4%      |

It can be seen that using protective material, it can reduce the change of the body velocity by 80% and the acceleration peak by 96%. Operating in this manner, the yield volume fraction was reduced by 98%, the protective nose cap can ensure the placidity move velocity, the projectile was effectively protected and the protective effect was obvious.

### 3.2. The protective performance of different density

The density of materials has a great influence on the protective effect, therefore the effect was studied. The chosen densities are: 0.17 g/cm³, 0.20 g/cm³, 0.34 g/cm³, 0.40 g/cm³.

Figure 14 shows the mechanism of polyurethane foam (the density was 0.20 g/cm³); in particular, the polyurethane foam was compressed, compacted, and crushed. At the beginning, the bottom of the foam was first compressed, the projectile propelled in it, and then the top of the foam was compressed. After that, the foam was compacted, and finally crushed. When the density was bigger, the sooner was compacted. However, the smaller the density, the easier crushed. The smaller the density, the larger the pores of the polyurethane foam are more likely to be destroyed.

The velocity of the projectile before it crushed was displayed in four cases, the display time is 2000 μs. As shown in figure 15, the velocity of all decreased with time, but the velocity reduction was different.

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**Figure 14.** The mechanism of polyurethane foam.

**Figure 15.** Velocity-time curve comparison.

Further the acceleration change was observed. As shown in figure 16, the acceleration had a peak moment. At this time, the projectile was subjected to a very strong impact. The paper thinks, at this time, the foam material is compacted. The four cases were obviously different, the higher the density, the less time it took to be compacted. The time it took to be compacted were 1.66 s, 1.45 s, 1.47 s, 930 s respectively. As the density increases, the pores of the polyurethane foam became smaller and it was compacted faster.

**Figure 16.** Acceleration-time curve comparison.

**Figure 17.** Yield volume fraction.

As above, setting the yield stress of the projectile material to 355 Mbar, the yield fraction in four cases was shown in figure 17.

Combined with the above analysis, protective effect was evaluated by four standards: (1) velocity change; (2) maximum acceleration; (3) yield volume fraction; (4) compaction time, some are the same as above. The fourth standard was compaction time. The longer the time used for compaction, the longer the action time, and the better effect of protection. Using the four standards to illustrate the role of density of polyurethane foam, the comparison results are shown in table 3.

In the table, the density of the two groups with better effect is marked under each standard. It can be seen that the better protection was achieved at a density of 0.17 g/cm³ and 0.40 g/cm³.

When the density was small, the action time was longer, the energy absorption was more, and the...
velocity change was more gently, which will better protect the projectile. However, when the density was very low, it may appear that it was crushed before compacted which will affect its protective effect, so the protective material should choose a moderate density.

Table 3. Comparison of different density.

| Standard          | Density (g/cm³) |
|-------------------|-----------------|
|                   | 0.17 | 0.20 | 0.34 | 0.40 |
| Standard 1 velocity change (m/s) | 1.5   | 1.6   | 4.1   | 4.7   |
| Standard 2 maximum acceleration (m/s²) | 3618.7| 13379| 7398.9| 7265.5|
| Standard 3 yield volume fraction       | 0.00046 | 0.0042 | 0.0054 | 0.0015 |
| Standard 4 compaction time (s)        | 1.7   | 1.5   | 1.5   | 0.93  |

4. Conclusion

In this work, the design of a water-entry impact test, useful to compare with the numerical results was performed, to verify the feasibility and validity of the model.

Using four standards to evaluate the protective properties of polyurethane foam, it can be seen that polyurethane foam had good protection properties.

The effect of the density of the polyurethane foam was studied. Using four standards to compare the protective properties of polyurethane foams with different densities, it can be seen that the better protection was achieved at a density of 0.17 g/cm³ and 0.40 g/cm³.

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