Damage Mode of Long Tube Structure at Different Water Depths under Strong Impact

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Abstract. In order to study the damage mode of the structure under strong impact, the finite element analysis software ABAQUS acoustic-coupling method is used to calculate and analyze the strong impact of the long tube structure under different water depths and different impact factors. The study obtained damage patterns influenced by impact factors and water depth conditions. It provides a reference for the calculation and impact design of underwater structures under strong impact.

1. Introduction
The non-contact underwater explosions of ships and submarine structures usually have severe structural vibrations and large plastic deformation, resulting in extensive impact damage and damage to the overall structure of various important hull equipment [1]. In recent years, the structure of non-contact underwater explosions has attracted more and more attention. Underwater explosion and explosion load on the structure of the impact damage process mechanism is more complex, so the experiment is the most direct and effective research approach [2]. It is difficult to carry out the explosion test of large structures and requires huge funds. Therefore, numerical methods to study the failure mechanism of underwater explosions and structural impact resistance have become effective alternatives. Fox [3] combined the DYNA3D and USA programs to analyze the nonlinear dynamic response under the lateral impact of underwater explosion. Miller [4] used DYNA3D/DAA to analyze the dynamic response of spherical and cylindrical shells under the action of underwater explosion shock waves. Yu Xiaofei [5] used MSC. DYTRAN to study the antiknock performance of reinforced cylindrical shell under underwater explosion. Geers [6] proposed a semi-empirical calculation formula for underwater explosion load that can be used underwater, and can simulate shock waves and bubble pulsation loads better. ABAQUS uses sound field and structural coupling technology, suitable for underwater explosion analysis in the far field. In this paper, ABAQUS is used to analyze the far-field explosion of the long tube structure, and the damage mode of the structure under strong impact is summarized.

2. Calculation Model
The calculation model uses a single-layer shell long tube structure. The main dimension of the calculation model is 7.0m in diameter, the total length of the model is 50m, and the thickness of the shell is 30mm.

Figure 1. Long Tube model. Figure 2. Model assembly drawing.
The use of finite element analysis of the transmission of underwater explosion shock waves requires careful selection of the cell size, and the thickness of the cell grid is closely related to the wavelength of the analysis. Over-grid causes low computational accuracy and even leads to non-convergence of simulation results. The denser the meshing, the higher the calculation accuracy, and the closer the solution is to the real situation, but the more computing resources are used, the more time is consumed, which is not conducive to improving the calculation efficiency.

The ABAQUS calculation of the stability limit $\Delta t_{\text{stable}}$ needs to be calculated based on the cell length $L^e$ and the material wave velocity $C_d$:

$$\Delta t_{\text{stable}} = L^e / C_d$$  \hspace{1cm} (1)

The size of the mesh is related to the load frequency component of the structure. Since it is difficult to analyze the frequency of the load in the time domain, it is necessary to determine the frequency component of the load by spectral analysis of the impact load. It is necessary to divide a certain number of meshes within a stress wave wavelength to ensure that the waves propagate in the flow field and structure without distortion. The mesh size estimation formula is:

$$l_{\text{max}} = \lambda_e / n$$  \hspace{1cm} (2)

$$\lambda_e = \theta \cdot c$$  \hspace{1cm} (3)

$$\theta = 8.4 \times 10^{-3} W^{1/3} \left( W^{1/3} / R \right)^{-0.23}$$  \hspace{1cm} (4)

where $\lambda_e$: the wavelength of the stress wave in the structure, $n$: represents the number of grids required in the wavelength of a stress wave, $c$: the wave velocity of the stress wave, 5000 m/s in the steel; $W$: dose; $R$: burst distance; $\theta$: decay constant.

According to the above formula, the grid size should be 300mm, so that dividing the grid is beneficial to improve the accuracy of the calculation as much as possible without occupying too much computing resources.

Using the Cowper-Symonds model to describe the strain rate effect of a material

$$\sigma_y = \left[ 1 + \left( \frac{\varepsilon}{C} \right)^P \right] \sigma_0$$  \hspace{1cm} (5)

where, $\sigma_y$ for the dynamic yield stress, $\sigma_0$ is the static yield stress, $\varepsilon$ is the strain rate, and $C$ and $P$ are the strain rate parameters.

The material related parameters are shown in table 1:

| $\rho$ (kg m$^{-3}$) | $E$ (Pa) | $\mu$ | $\sigma_0$ (MPa) | $C$ (s$^{-1}$) | $P$ |
|---------------------|---------|-------|-----------------|---------------|------|
| 7800                | 2.1E+11 | 0.3   | 590             | 40.4          | 5    |

where $\rho$ is density, $E$ is Young's modulus, $\mu$ is Poisson's ratio.

3. Numerical Calculation and Analysis

3.1. impact factor

Using an impact factor based on the plane wave assumption to describe the underwater explosion impact environment, the form of the impact factor is:

$$C = \sqrt[3]{W / R}$$  \hspace{1cm} (6)
where \( W \) is the drug pack equivalent, \( R \) is the shortest between the drug pack and the structural shell distance.

The effect of impact factor on the damage mode at 300m water depth is studied. The explosion contact point is set at 1/2 of the length of the structure. The working conditions are set as shown in table 2.

| Working condition number | water depth/m | impact factor/kg\(^{1/2}\)-m\(^{-1}\) |
|-------------------------|--------------|--------------------------------------|
| 1                       | 300          | 3                                    |
| 2                       | 300          | 2.5                                  |
| 3                       |              | 2                                    |

The damage effect of the structure under the condition of 300m water depth, impact factor is 3kg\(^{1/2}\)-m\(^{-1}\) is shown in figure 3 and figure 4. According to the displacement cloud map and PEEQ cloud map, the structure is resistant. The overall instability of the shell is presented. The surface of the pressure-resistant shell presents a plurality of in-situ concave half-wave failure modes, completely losing the bearing capacity, and the equivalent plastic strain on the surface of the pressure-resistant shell reaches or exceeds 0.3. The pressure-resistant shell will break, and it can be considered that the structure has suffered an irreversible overall instability/break under this condition.

Figure 3. Local structure displacement cloud.
Figure 4. Local structure PEEQ and fracture.

The structural instability failure process under this condition is analyzed in detail, as shown in the following figure. Figure 5(b) is the displacement cloud diagram of the pressure-resistant shell of the explosion-proof surface at the time of 0.01s. The shock wave is applied to the pressure-resistant shell for a short time, and the impact surface of the pressure-resistant shell begins to produce obvious displacement. At 0.03s, the structure meets the explosion surface. Larger concave deformation has begun to appear. At 0.04s, the concave deformation of the structure continues to be continued. At 0.05s, the pressure-resistant shell reaches the maximum unstable shape.

Figure 5. Damage process.
The damage effect of the structure under the condition of 300m water depth, impact factor is $2.5kg^{1/2}m^{-1}$ is shown in figure 6 and figure 7. The surface of the pressure-resistant shell of the section presents a single-inward concave half-wave type of instability failure.

Figure 6. Local structure displacement cloud. 
Figure 7. Local structure PEEQ.

The damage effect of the structure under the condition of 300m water depth, impact factor is $2kg^{1/2}m^{-1}$ is shown in figure 8 and figure 9. There is no instability da-mage in the structural pressure-resistant shell, and a slight plastic strain zone appears on the impact surface of the pressure-resistant shell. Non-strength parts with a small internal thickness of the structure produce a certain plastic strain.

Figure 8. Local structure displacement cloud. 
Figure 9. Local structure PEEQ.

3.2. Water depth effect

Exploring the influence of water depth on the damage mode when the impact factor is fixed, the working conditions are set as shown in table 3:

| Working condition number | water depth/m | impact factor/kg$^{1/2}m^{-1}$ |
|--------------------------|---------------|--------------------------------|
| 1                        | 600           | 0                              |
| 2                        | 400           | 2.5                            |
| 3                        | 200           |                                 |

Table 3. Changing water depth working condition setting.

The damage effect of the structure under the condition of 600m water depth is shown in figure 10. Due to the large water depth, the hydrostatic pressure is extremely high, resulting in structural instability of the local compartment. Even without additional impact loads, the struure fails and loses the bearing capacity for hydrostatic pressure loads.

Figure 10. Local structure displacement cloud.

The damage effect of the structure under the condition of 400m water depth, impact factor is $2.5kg^{1/2}m^{-1}$ is shown in figure 11 and figure 12. The surface of the pressure-resistant shell of the section presents a single-inward concave half-wave type of instability failure. However, the degree of
failure is greater than the 300m water depth under the same impact factor, and the damage is more serious.

![Figure 11. Local structure displacement cloud.](image1)

![Figure 12. Local structure PEEQ.](image2)

The damage effect of the structure under the condition of 400m water depth, impact factor is $2.5 \text{kg}^{1/2} \cdot \text{m}^{-1}$ is shown in figure 13 and figure 14. There is no instability damage in the structure, but a small amount of plastic strain occurs in the non-strength members inside the structure.

![Figure 13. Local structure displacement cloud.](image3)

![Figure 14. Local structure PEEQ.](image4)

### 3.3. summary

The damage effect of the structure under the impact of strong shock waves under different water depth conditions can be summarized into the following 4 categories:

**Damage Mode 1:** Exceeding the structural limit depth, the shell of structure is partially destabilized under the hydrostatic pressure load.

**Damage Mode 2:** The shock wave is transmitted from the water to the pressure-resistant shell, and the stress wave in the pressure-resistant shell is transmitted into the non-strength member with a small thickness. This stage can be regarded as the stress wave propagating in the variable-section material structure, according to the stress wave. Propagation characteristics, transmission waves larger than the incident wave stress value act on non-strength members with small load carrying capacity, resulting in stress wave plastic damage of non-strength members, resulting in internal profile damage. Moreover, as the depth continues to increase or the burst distance continues to decrease, the degree of damage will increase, and after reaching the critical condition, damage mode 3 will be entered.

**Damage Mode 3:** After the shock wave acts on the impact surface of the pressure-resistant shell, high-stress areas and even certain plastic damage appear on the impact surface of the pressure-resistant shell. Then, local pits appear, and the depression develops along the lateral and longitudinal directions, forming an axial failure mode of the pressure-resistant shell. As the depth continues to increase or the explosion distance continues to decrease, the damage degree will increase, and after reaching the critical condition, damage mode 4 will be entered.

**Damage Mode 4:** Under the action of shock wave, the whole structure is unstable, the internal support of the structure is greatly deformed, and the structure produces huge plastic strain until the shell is broken, forming a failure mode of overall buckling.

### 4. Conclusion

In conclusion, the simulation results show that:

1. There are four kinds of damage modes under the strong impact of the long tube structure under water, including a) structural failure under hydrostatic pressure, b) damage to the profile, c) large plastic deformation to form a depression d) the overall structure is unstable, resulting in breakage or breakage. (2) When the water depth is constant, as the impact factor increases, the degree of damage becomes larger. After reaching the critical condition, it enters a more serious damage mode. (3) When the impact factor is constant, as the water depth increases, the hydrostatic pressure becomes larger, resulting in a greater degree of structural damage. In the case
of large water depth, no additional strong impact is required, and structural failure occurs under hydrostatic pressure.

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