Internal explosion load distribution and strain response of ellipsoidal end cover of explosion containment vessel

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Abstract. As a kind of limitation device of explosive products and shock wave, explosion containment vessel is widely used in military and civil fields. Due to its own structural characteristics, Mach wave convergence and collision will occur near the pole of the end cover of the cylindrical explosion containment vessel, resulting in a great pressure jump and seriously affecting the strain response characteristics of the end cover. In this paper, by means of experiment and numerical simulation, the distribution of flow field inside the end cover was explored, and it was found that the initial load of the end cover pole included the first incident wave of internal explosion, convergent re-incident wave of central section and the Mach wave convergence wave. By analyzing the strain spectrum, it is found that the different frequencies are excited by loads at different locations, so that the energy distribution under each frequency of strain is different, resulting in differences of strain. These results can provide reference for the design of explosion containment vessel.

1. Introduction

The explosion containment vessel can limit the action range of implosion shock wave and reduce the harm of explosion to the surroundings. Since 1945, when the first cylindrical explosive containment vessel for nuclear test was built at the Los Alamos national laboratory, many containment vessels have been manufactured in various countries [1-5]. Manufacturing explosive containment vessels requires adherence to certain design criteria. Including the design method proposed by ASME [6,7] and the design method of AWE [3,8], there are few mature and easy-to-use design methods at present. The reason for this problem is that the basic problems of explosion load distribution and dynamic response of the containment vessel have not been thoroughly studied. Among them, the research on cylindrical explosion containment vessels is much less than that on spherical explosion containment vessels. A. F. Demchuk (1968) [9] first described the equivalent single-degree-of-freedom (SDoF) design method for the explosion vessel, but did not perform targeted analysis on the flange, bolt and end cover. V. M. Kornev (1979) et al [10] experimentally studied the shell deformation response under the internal explosion load of cylindrical explosion containment vessels, and found that the maximum deformation...
occurs near the poles of the end covers. They attributed the strong pulsations to the whip effect. W. H. Zhu (1997) et al [11] provided the theoretical calculation results of strain growth and strain growth coefficient of vessel and end cover for the first time. The transverse shear and rotatory inertia is taken into the shell equations, which have good consistency compared with the experimental results. Since 2008, Q. M. Li and Q. Dong et al [12-16] summarized previous research results, systematically analyzed the strain growth mechanism of cylindrical shells, and gave the guidance of explosion containment vessel design method based on equivalent SDoF design method and three-dimensional finite element analysis method [14]. However, their research did not involve the end cover. Z. Wang (2013) et al [17], used TNT equivalent model to analyze the explosion impact load inside the steel storage tank by numerical simulation, and found that the maximum load appeared in the central area of the end cover due to the convergence effect of the shock wave, which usually is just at the second peak of the waveform.

Due to the difference in structure, the spherical vessel shell is subjected to the normal reflection pressure everywhere at an ideal state, while it not only produces normal reflection, regular oblique reflection and Mach reflection along the axis on the inside surface of the cylindrical vessel, but also has more complex pressure distribution at the end cover. Therefore, it is necessary to research and analyze the pressure distribution at the end cover, which will lay a foundation for studying its complex dynamic response and designing the targeted structure.

2. Experiment

2.1. Experimental setup
The internal explosion experiment is based on an existing explosion containment vessel, as shown in figure 1, and its dimensions are shown in table 1. The spherical TNT charges of 27g, 65g, 106g and 155g are set, and the charge density was 1.50g/cm³. Lift the TNT ball in the center of the container. The upper end cover is tightly connected to the vessel body by a flange-and-bolt structure. A hole is provided on the side of the vessel to facilitate the wearing of the firing line.

| Table 1. Size parameters of the explosion containment vessel. |
|-----------------------------|-------------------|-----------------|-----------------|
| Length of total $L$         | Thickness $2\delta$ | Semi major axis $a$ | Semi minor axis $b$ |
| 166.4cm                     | 2.2cm             | 40cm            | 20cm            |

Two pressure sensors are set, $P_{pole}$ is located at the pole at the end cover, and $P_{center}$ is located at the center section of the container. Because the charge detonates in the center of the container and the upper and lower ends of the container are symmetrical, the pressure time history curve measured at the bottom and that of the end cover should be the same. A relief valve was installed at the end cover, leaving it unable to measure its strain, so two tri-axial strain gauges were set at 7cm and 32.5cm radially from the pole to test the strain in Latitude direction, 45° and Longitude direction, respectively.
2.2. Explosive load at the pole of the end cover

Through previous numerical simulation studies [17-20], it was found that the initial stage of pressure at the pole of the end cover was divided into two parts, that is, the internal explosion shock wave was first received at the pole and reflected pressure was generated, and then the convergent collision wave of Mach reflection was formed at the pole. The pressure of the convergence wave is abnormally large. In this test, the time history curve of pressure was measured at $P_{pole}$ at the pole of the end cover, as shown in figure 3. However, different from previous research results, there are three pressure peaks at the initial stage of the end cover pressure in the figure, and the three pressure peaks increase one by one. For example, in figure 3(b), at the initial stage of pressure at the pole (700$\mu$s -1500$\mu$s), there are three pressure peaks that are 0.99MPa, 2.41MPa and 13.89MPa, respectively. Therefore, the initial pressure at the end cover of the internal explosion experiment should be not only under the pressure of the initial impulse wave and the convergence wave, but also under the pressure of the other part. In order to explore the three-part pressure at the pole in the initial stage, numerical simulation will be used to analyze it later.

In addition, as for the maximum pressure, the maximum convergence pressure at the pole of the
end cover is obviously greater than the normal reflection pressure at the center section. Therefore, the loading conditions at and near the pole of the end cover should be paid more attention by the designers of explosive containment vessels.

![Figure 3](image)

**Figure 3.** Comparison of pressure between the pole and the central section.

![Figure 4](image)

**Figure 4.** Strain time history curve of 65g charge.

![Figure 5](image)

**Figure 5.** Strain time history curve of 106g charge.
2.3. Strain of the end cover

Using the strain gauges at S1 and S2 measuring points, the vibration responses under the charge of 65g and 106g were measured, as shown in figure 4. In general, the S1 with a radial distance of 7 cm from the pole and the S2 with a radial distance of 32.5 cm from the pole show completely different strain characteristics.

The tri-axial strain at the S1 measurement point first appeared a vibration cycle with a faster frequency and a smaller amplitude, and then a number of vibration cycles with a relatively slower frequency and a larger amplitude. The first and second peaks of tensile and compressive strains, as well as the first vibration period and the second vibration period are shown in table 2. The average values of the periods of the three directions of two doses were 0.230ms and 0.217ms, respectively, and the average values of the secondary periods were 1.333ms and 1.270ms, respectively. Comparing the lengths of the first and second periods, it can be seen that the length of the second period is about 4-5 times that of the first period, which is obviously a strain response caused by different load excitations.

| Charge | Direction | $\varepsilon_{1\mu}$ (με) | $\varepsilon_{2\mu}$ (με) | $T_1$(ms) | $\varepsilon_{1\mu}$ (με) | $T_2$(ms) |
|--------|-----------|------------------|------------------|--------|------------------|--------|
| 65g    | Latitude  | 90.51            | -97.43           | 0.23   | 480.00           | -340.37| 1.31  |
|        | Longitude | 81.05            | -160.16          | 0.25   | 310.71           | -285.54| 1.32  |
| 106g   | Latitude  | 168.58           | -187.09          | 0.21   | 248.40           | -187.26| 1.37  |
|        | Longitude | 195.24           | -193.95          | 0.22   | 539.36           | -438.64| 1.26  |

* $\varepsilon_{1\mu}$ first peak of tensile strain, $\varepsilon_{2\mu}$ first peak of compressive strain, $T_1$ first period, $\varepsilon_{2\mu}$ second peak of tensile strain, $\varepsilon_{2\mu}$ second peak of compressive strain, $T_2$ second period.

The waveforms of strain time history curves of the three directions of S1 and S2 are basically identical, except for the difference in vibration amplitude. However, the strain response amplitude of S2 is smaller and the frequency is faster than that of S1. Taking the 106g experiment as an example, the spectrum diagrams of the two measurement points are analyzed, as shown in figure 6. It can be found that the peak frequency of strain vibration frequency in the three directions of S1 or S2 measurement points is basically the same, but the difference is that the amplitude of strain in different directions is different under the peak frequency. For example, the main frequency of the strain in the three directions of S1 is about 732.8Hz, while their amplitudes are 134.96με, 102.80με and 72.85με, respectively. Comparing the two figures (a) and (b), the energy of strain in the three directions of the S1 is mainly concentrated between 0.5kHz and 1.5kHz, and the latitude direction of the S2 still occupies the lower frequency between 0.5kHz and 1.5kHz a considerable part of the energy, and the energy distribution between 2kHz and 3.1kHz is almost the same as the low frequency part. The energy in the longitude direction and 45° direction of the S2 is mainly concentrated in the higher frequency 2kHz to 3.1kHz. This is due to the different positions, and the modes of different frequencies are excited after being subjected to the load. The consistency of the peak frequency of the vibrations makes the strain time history curves of the S1 and S2 basically coincide, respectively.
However the difference in energy distribution caused the characteristic differences of the strain time history curves of S2 and S1.

![Figure 6](image)

**Figure 6.** Spectrum of time history curve of end cover strain of 106g charge.

3. **Numerical simulation**

3.1. **Model and parameters**

In order to further explore the law of shock wave action at the pole of the end cover and analyze the evolution process of the shock wave action on the end cover, four groups of numerical simulation tests with dosage of 27g, 65g, 106g and 155g respectively, is designed in this section, which forms a comparison with the experiment. The purpose of this paper is to investigate the distribution of the internal load at the end cover of the container, which is only related to the structure of the charge and the inner wall. Therefore, the flange and bolt are simplified in the numerical model in order to improve the calculation efficiency.

1/4 model of 2D 5was adopted for numerical calculation, as shown in figure 7. Shell163 is used for the 2D explicit analysis, while the mesh size for solids is not exceed 0.6cm, and that for air is 0.1cm. Two symmetric boundary conditions about the two plane of xoz and yoz are set, respectively. The explosive is filled at the origin of the air elements with the *INITIAL_VOLUME_FRACTION_GEOMETRY* keyword.

![Figure 7](image)

**Figure 7.** 2D 1/4 model of the containment vessel.

3.1.1. **Steel.** The body and the end cover of the containment vessel are made of steel. The thickness of the vessel wall is 2.2cm, so the deformation of the solid under pressure load is not enough to affect the distribution and evolution law of the flow field. Therefore, the solid deformation is ignored in the
calculation, and *MAT_RIGID is used as the material model. The parameters are set as shown in table 3.

| Table 3. Material model parameters of steel. |
|---------------------------------------------|
| $\rho_0$ (g/cm$^3$) | $E$ (GPa) | $\nu$ |
| 7.85 | 209 | 0.28 |

3.1.2. TNT. High energy explosion combustion model (*MAT_HIGH_EXPLOSIVE_BURN) is used for the explosive, and JWL equation was used to represent the pressure of detonation product. The equation is as follows [21]:

$$p = A \left( 1 - \frac{\omega}{R_1 V} \right) e^{-\frac{R_1 V}{V}} + B \left( 1 - \frac{\omega}{R_2 V} \right) e^{-\frac{R_2 V}{V}} + \frac{\omega E}{V} \quad \text{MERGEFORMAT (1)}$$

The units of $A$, $B$ and $E$ are pressure, $R_1$, $R_2$, $\omega$ and $V$ are dimensionless. Where $E$ is the energy density and $V$ is the relative volume of detonation product. The initial energy density $E_0$ and relative volume $V_0$ should be determined when inputting parameters, and the specific parameters are shown in table 4 and table 5.

| Table 4. Material model parameters of TNT. |
|---------------------------------------------|
| $\rho_0$ (g/cm$^3$) | $P_{CJ}$ (GPa) | $v_D$ (m/s) |
| 1.50 | 17.92 | 6547.2 |

| Table 5. JWL parameters of TNT. |
|---------------------------------------------|
| $A$ (GPa) | $B$ (GPa) | $R_1$ | $R_2$ | $\omega$ | $E_0$ (GPa) | $V_0$ |
| 374.6 | 3.39 | 4.15 | 0.95 | 0.28 | 6.34 | 1.0 |

3.1.3. Air. The material model of the air is *MAT_NULL, and the state equation is *EOS_LINEAR_POLYNOMIAL. The equation can be written as

$$p = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + \left( C_4 + C_5 \mu + C_6 \mu^2 \right) E \quad \text{MERGEFORMAT (2)}$$

$$\mu = \frac{1}{V} - 1 = \frac{\rho}{\rho_0} - 1 \quad \text{MERGEFORMAT (3)}$$

If the air is considered as an ideal gas, then $C_0 = C_1 = C_2 = C_3 = C_6 = 0$. The polytropic exponent $\gamma$ is usually set at 1.4, then $C_4 = C_5 = \frac{1}{\gamma} - 1 = 0.4$[21]. The initial density $\rho_0$, the initial energy density $E_0$ and the initial relative volume $V_0$ of air are set to 1.29 g/cm$^3$, 2.5×10$^5$Pa and 1.0, respectively. The parameters are shown in table 6.

| Table 6. Material model and EOS parameters of air [22]. |
|---------------------------------------------|
| $\rho_0$ (g/cm$^3$) | $C_0$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $E_0$ (MPa) | $V_0$ |
| 1.29 | 0 | 0 | 0 | 0 | 0.4 | 0.4 | 0 | 0.25 | 1.0 |

3.2. Analysis of flow field distribution in the end cover

Commonly used explosive containers are divided into two types: spherical and cylindrical. Due to the
difference in structure, in the ideal state, the spherical explosion pressure vessel shell is subject to normal reflection pressure, and the cylindrical explosion pressure vessel not only generates normal reflection, regular oblique reflection and Mach reflection along the axial direction, but also has a more complex pressure distribution at the end cover. Therefore, it is necessary to investigate and analyze the pressure distribution at the end cover, and lay the foundation for studying its complex dynamic response and targeted structural design.

3.2.1. Mechanism of Mach reflection. As shown in figure 8, when the incidence angle \( \varphi_0 \) is greater than a critical angle \( \varphi_{0c} \), the reflection occurring at that time is not a regular oblique reflection, but a non-regular oblique reflection, also known as "Mach reflection" [23]. This is because when the incidence angle is too large, its velocity component in the direction parallel to the reflected wave is small, and the retardation of the airflow on the reflected wave is significantly reduced. In addition, the reflected wave propagates in the gas compressed and heated by the incident wave [24]. Therefore, the reflected wave propagates faster than the incident wave and gradually catches up with the incident wave, merging with it to form a new “Mach wave”. The Mach wave front, also known as “Mach rod”, is perpendicular to the wall. At this time, the intersection T (Triple point) of incident wave I, reflected wave R and Mach wave M is a certain distance away from the wall, and gradually moves away from the wall along the trajectory AB. In addition, Tx is the slip line in regions after reflection wave and Mach wave, on both sides which the density and velocity of particles are different, but the pressure is the same. In fact, the three wave fronts, trajectory and slip line near the triple point are all curved and the situation is rather complicated. However, they can be represented by straight lines in qualitative description.

![Figure 8. Schematic diagram of Mach reflection.](image1)

![Figure 9. Numerical simulation and test results of pole pressure.](image2)

3.2.2. Evolution of flow field at the end cover. Figure 10 shows the internal explosion pressure propagation and evolution. After the charge explosion at time 0, the explosive shock wave reached the vicinity of the vessel wall in about 210\( \mu \)s, and then the shock wave forms a reflected shock wave under the blocking effect of the wall and moved toward the end along the inner wall of the vessel. At 495\( \mu \)s, the Mach reflection and three-wave intersection phenomenon were obvious. It is worth noting that the reflected waves at the central section are gradually converging towards the center of the vessel. At 530\( \mu \)s, the shock wave from the central section converged successfully at the center of the container,
and a new incident wave was generated to propagate in all directions of the container. At the same time, the Mach wave crossed the corner of the end cover and the cylinder and continued to propagate along the end cover, as shown in figure 765μs. To about 840 μs, the first explosion shock wave has been applied to the end cover, at this time the first pressure peak appeared at the pole, as shown in figure 9 and figure 10. Shock waves propagate faster in denser air media, while the convergent re-incident waves of the central section propagate faster in the compressed air of the initial shock wave, while Mach waves propagate more slowly due to the blocking effect of the wall. Therefore, the convergent re-incident wave reaches the pole of the end cover at 1135μs before the Mach wave, forming a second pressure peak. At the subsequent moment of 1295μs, the Mach reflected waves from all directions converge and collide at the end cover pole, forming the third pressure jump here. In the following time, new shock waves were formed at the pole and spread around.

In addition, the waveform in figure 3 and figure 9 shows that there will still be subsequent pressure peaks at the pole of end cover. This is caused by the incident, reflection, convergence and re-incident process of the explosive shock wave. In many iterations of this process, a complex pressure field is formed, and it is possible to form a subsequent wave peak that is even greater than the pressure of initial stage, as shown in figure 3 as the 27g dose.

![Image 10. Internal explosion nephogram.](image-url)
3.3. Distribution of maximum pressure at the end cover

The distribution of the maximum pressure value of the end cover under four different charges is shown in figure 11. The distance between each observation point and the pole is represented by the radial distance. It can be seen from the figure that the maximum pressure value around the pole is extremely sensitive to the change of distance, and the maximum pressure value around the pole decreases sharply as the distance increases. As shown in figure 12, the maximum pressure peak at the pole of the end cover of 65g charge is 19.61 MPa, but the maximum pressure at the observation point of 0.5cm (five air grids) distance from the pole has rapidly decayed by about half to 10.65 MPa. Even the pressure at 1.0cm, 2.0cm and 3.0cm drops sharply to 7.83MPa and 4.58MPa and 2.97MPa, respectively. Combined with the test, the following phenomenon can be explained, that is, the test result of the pressure peak at the \( P_{\text{pole}} \) is not as abnormal as the numerical simulation. This is because the pressure peak near the end cover pole is sensitive to the pole distance, which means that as long as the hanging step of the charge during the preparation of the experiment is slightly careless leaving the charge position is not in the center, or the charge is shaken during the operation, the sensor at the \( P_{\text{pole}} \) cannot measure the pressure of the center of convergence and collision of Mach reflection wave, so only lower peak data can be recorded.

![Figure 11. Maximum pressure distribution of end cover with different charges.](image1)

![Figure 12. Comparison of pressure near the pole of 65g charge.](image2)

4. Conclusion

In this paper, the internal explosion pressure load at the pole of the end cover is tested experimentally, and the strain at the end cover is tested and analyzed. A two-dimensional numerical model was established, and the distribution and evolution of the flow field inside the end cover were analyzed. The main conclusions are as follows:

- The load at the pole of end cover is very complicated. The initial stage of the blast pressure is divided into three parts: the first incident wave of the internal explosion, the convergent re-incident wave of the central section and the Mach wave convergent collision wave.

- The pressure caused by the Mach wave convergence collision is extremely large, but it decays rapidly as the distance from the pole increases. Therefore, it is difficult to measure the pressure time history curve of the large peak in the experiment.

- Different frequencies are excited after pressure loading at different positions of the end cover. The
consistency of the peak frequency of vibration makes the strain time history curves basically coincide with each other, and the difference in energy distribution causes the difference in strain characteristics.

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