Deformation and energy distribution of metal tubes under internal explosive loading

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Abstract. Deformation and energy distribution of two kinds of metal tubes under internal explosive loading have been studied by means of experiments and simulations in this paper. The velocity and displacement-time history of characteristic points on the flat metal tubes were measured by Photonic Doppler Velocimetry (PDV). Ls-dyna fluid-solid coupling algorithm was used to simulate the experiment. Simulation results agree well with the experimental results. On this basis, the expansive properties of the round tube in the same condition were obtained, the round tube directly expands to the maximum diameter, does not like the expansion and contraction fluctuant process of the flat tube. The simulation result shows that the flat tube will output more energy in the form of kinetic energy, while the round tube tends to store energy in the form of plastic strain energy.

1. Introduction
Explosives can output high energy in a short period of time, and work quickly, which has an important application in areas that require rapid response [1,2]. In practical applications, explosives are often coated with metal tubes or containers outside, previous studies on metal shells under internal explosive loading include two types, one is the damage problem of the metal tube, most of which are directed to the metal tube in the weapon warhead. The metal tube is expected to damage so that high-speed fragments can produce to damage the goal. Therefore, factors such as damage and scattering velocity [3-7] are often considered. The Gurney Formula [8] and related corrections [9] can predict the fragment velocity. Another type of the research is about explosion protection, the research object is mainly explosive containers [10-13]. The deformation of thin-walled shells under explosive loading has a certain research basis, most of which focused on the response of thin-walled shells under the internal explosive loading of concentrated charges. In the aspect of theoretical research, there were researchers simplified the pressure time curve generated by the explosion into an ideal triangular pressure pulse which can simplify the problem [10,11]. In addition, Fouad and Lowell used the single-degree-of-freedom analysis and energy method to predict the response of the shell wall, the theoretical analysis agrees well with the finite element analysis results [13]. Under the action of explosion loading, the structure will undergo large deformation, which causes the traditional finite element analysis no longer applicable, there will be problems such as element distortion. ALE technology can deal with the locking phenomenon caused by the distortion during the large deformation [14]. Corresponding finite element analysis software Ls-dyna [15] and Autodyne [16] can simulate such experiments. In terms of experimental research, Test equipment requires high frequency response due to the rapid explosion response. Related experimental equipment includes X-ray
photography, high-speed photography, electric probes, dynamic pressure gauges, strain wires, fiber displacement interferometer etc. [10,14,17-21].

In the above studies, the energy generated by the explosion of the explosive is transmitted to the metal directly or through the air, and the research objects are mainly weapons or explosive containers. The research object of this paper is the flat tube components (flat tube, filler, and lead detonation cord), the strong impact generated by the explosive does not directly affect the external structure, but a certain attenuation is generated by the filler, and evenly acts on the metal tube. The metal tube produces a large expansion, causing the external structure to produce the expected damage. At the same time, the explosive product is enclosed inside the metal tube without cracking and therefore no pollution [19]. In this paper, the expansion process of the metal tubes under the internal explosive load was obtained by means of experiment and simulation analysis. The velocity and displacement-time history curve and energy distribution were analysis, which has certain guiding significance for engineering practice.

2. Experiment design
The test specimens are the flat tube components. We used the Photonic Doppler Velocimetry (PDV) [20,21] developed by Yang Jun et al to monitor the change of velocity and displacement at characteristic points on the flat tube. The basic principle of PDV is to use a fiber laser to output laser light, the laser is divided into two beams. One laser is irradiated on the test point which is the test laser and another laser is used as reference laser. When the test laser is reflected back and processed with the reference laser, the displacement and velocity of the test point can be obtained. To prevent the overall displacement of the tube from affecting the test results, the ends of the test specimens were clamped. The test device and cross-sectional view of the test specimens are shown in figure 1. Through the test method, the expansion velocity and displacement history of the four points in the middle section of the flat tube were obtained. In fact, due to the symmetry of the structure, two points can already represent the motion and deformation characteristics of the tube. But the explosion experiment is not repeatable and the experimental results often have certain discreteness. In order to obtain as much effective data as possible in one experiment, four measured points were set, among which, points 1 and 3 are symmetrical points, the test results are basically the same, similar to points 2 and 4.

![Figure 1. The test device and cross-sectional view of the test specimens.](image)

3. Simulation analysis
We used Hypermesh to create and mesh the geometric model according to the actual size of the
specimen and Ls-dyna fluid-solid coupling algorithm to simulate the experiment. The flat tube was in
the form of Lagrange elements, detonation cord, lead, the filler and air were Euler elements. Its
element models are shown in figure 2.

![Finite element model](image)

Figure 2. Finite element model.

The material parameters of the flat tube components refer to relevant references and research
reports [22-24], the detonation velocity of the detonation cord is the average value used for this
experiment provided by the manufacturer of the cords. The specific parameters are shown in table 1.

| part                  | parameters                                      |
|-----------------------|-------------------------------------------------|
| Detonation Cord(RDX)  | ρ=1.5g/cm³, D=7240m/s, P_CJ=23.11Gpa, A=611.3Gpa, B=10.65Gpa, R₁=4.4, R₂=1.2, A, B, R₁, R₂, ω are the coefficients of the JWL equation of state, which are depended on the kind of the explosive. |
| Lead                  | ρ=11.34g/cm³, C=2006m/s, S₁=1.429, γ₁=2.77 |
| Filler(polymer)       | ρ=0.95g/cm³, E=3Gpa, ν=0.47, σ_y=0.015Gpa     |
| Air                   | ρ=1.29×10⁻³g/cm³, γ=1.4, E₀=2.5×10⁻⁴Gpa, V₀=1 |
| Flat tube             | ρ=7.83g/cm³, E=205Gpa, ν=0.29;                 |
| (1Cr18Ni9Ti)          | σ_y=0.34Gpa, k=1.34Gpa, n=0.34                 |

The detonation cord, lead, and air were subject to the corresponding equation of state. The equation
of state for the explosive was the JWL equation of state as equation (1).

\[
P = A \left(1 - \frac{\omega}{R_V} \right) e^{-\frac{\gamma V}{R_V}} + B \left(1 - \frac{\omega}{R_S} \right) e^{-\frac{\gamma V}{R_S}} + \frac{\omega E}{V}
\]  

(1)

Where \( P \) and \( V \) represent the pressure and relative specific volume of the explosive respectively, \( E \) is
the internal energy of the explosive per unit volume, and \( A, B, R_V, R_S, \omega \) are the coefficients of the JWL
equation of state, which are depended on the kind of the explosive. \( E₀ \) is the initial internal energy per unit volume of explosive and \( V₀ \) is the initial relative specific volume, which are the initial
values of \( E \) and \( V \) before the detonation reaction.

The Gruneisen equation of state was used for lead. This equation defines the pressure of the
material in the form of equations (2) and (3) when \( \mu \) has different values.

\[
P = \frac{\rho_0 C^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2}\right) \frac{\mu - a \mu^2}{2 \mu^2} \right]}{1 - (S_1-1) \mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2}} + (\gamma_0 + a \mu) E \quad (\mu \geq 0)
\]  

(2)
\[ P = \rho_0 C^2 \mu + (\gamma_0 + a \mu) E \quad (\mu \leq 0) \quad (3) \]

Where \( C \) is the intercept of the \( v_s-v_p \) curve (shock wave velocity - post wave particle velocity curve). \( S_1, S_2, \) and \( S_3 \) are slope parameters of the \( v_s-v_p \) curve; \( \gamma_0 \) is the Gruneisen coefficient, \( a \) is the first-order volume correction to \( \gamma_0 \). \( \mu \) is a parameter indicating the change of the material volume, \( \mu = \rho/\rho_0 - 1 \), \( \rho \) is the current density of the material, and \( \rho_0 \) is the initial density of the material.

The air was modelled with the gamma law equation of state as equation (4).

\[ P = (\gamma - 1) \frac{\rho}{\rho_0} E \quad (4) \]

Where \( P \) is the pressure in the air, \( \gamma \) is the ratio of specific heats, \( \rho/\rho_0 \) is the ratio of current density to initial density, and \( E \) is the internal energy of air per unit volume. In the finite element analysis of the explosion, this equation of state is often used for the ideal gas [16,24].

4. Result and discussion

4.1. Comparison of simulation and experimental result

The velocity and displacement-time history of the feature points obtained by simulation analysis are compared with the experimental results. We did four experiments, of which points 1, 3 are structural symmetry points, so the results are the same, similar for points 2 and 4. Velocity and displacement time curves of points 1 and 3 are shown in figure 3. Curves of points 2 and 4 are shown in figure 4.

![Figure 3. Experimental and simulation results of points 1 and 3.](image)

From the experimental and simulation results, it can be seen that the points 1 and 3 of the flat tube experience the process of expanding firstly and then contracting and gradually becoming stable. The points 2 and 4 are slightly expanded, greatly contracted, expands outward and finally stabilizes gradually. The motion process is complicated. The experimental results of the maximum expansion velocity of points 1 and 3 are between 212.38-256.58 m/s, average value is 236.95 m/s, for points 2 and 4, the experimental value is between 46.84-158.65 m/s, average value is 101.21 m/s, the location of points 2 and 4 is narrow which is difficult to monitor, so the experimental results are somewhat discrete. The simulation result for points 1 and 3 is 255.86 m/s, and 127.26 m/s for points 2 and 4, which are all in the range of the experimental results. As for the maximum expanding displacement, the experimental results of point 1,3 is between 8.45 mm and 9.55 mm, 9.01 mm on average, for points 2,4, the results range from 0.26 mm to 0.63 mm, average value is 0.43 mm, correspondingly, the simulation displacement results are 9.55 mm and 0.48 mm on points 1,3 and 2,4 respectively. The
data results show that the simulation and experimental results correspond well, which proves that the simulation results are reliable.

Figure 4. Experimental and simulation results of points 2 and 4.

4.2. Comparison of expansion velocity and displacement of round and flat metal tube

The same method, material parameters and detonation cord were used to simulate the expansion process of the round metal tube with the same quality as the flat tube, the wall thickness of the two kind of tubes and the perimeter of the section are the same. Therefore, geometrically, points 1 and 3 on the flat tube are closest to the detonation cord, points 2 and 4 are farthest, the distance between the points on the round tube and the detonation cord is between the above two. The geometric comparison figure and element model of round metal tube components are shown in figure 5.

Figure 5. Geometry comparison of two tubes and finite element model of round metal tube components.

The expansion velocity, displacement of feature points on two tubes were obtained as shown in figure 6.

The results of the data show that the round tube does not have the large fluctuation process of expansion and contraction like the flat tube, but gradually expands to the maximum value to reach the stable stage. The maximum expansion velocity is 168.20 m/s, which is between the 1, 3 and 2, 4 points of the flat tube, and the displacement tends to be stable at 2.10 mm after expanding to the maximum value 2.14 mm. In order to understand the energy distribution of explosive energy on two kinds of metal tubes during the internal explosive load, more in-depth study was then carried out.
4.3. Analysis of explosion energy distribution

To reduce the influence of boundary on the calculation of explosion energy distribution, the middle parts of the test specimens were extracted as independent parts shown in figure 7.

The total energy of the detonation cord, the kinetic energy and plastic strain energy of the metal tubes in the middle portion were output. The data was subjected to dimensionless treatment with reference to the initial total energy of the detonation cord in this middle potion. The energy change process is shown in figure 8. Since the energy of the detonation cord is released at the moment of explosion, its change with time is basically the same in both cases, so it is represented by the same curve in the figure.

As shown in figure 8, the maximum kinetic energy of the flat tube accounts for 27.65% of the initial energy of the detonation cord, and the final stable plastic strain energy ratio is 40.43%. For the round tube, the extreme value of the kinetic energy is 24.10% and the final stable plastic deformation energy ratio is 50.03%. The initial energy of the detonation is consistent. The flat tube is more inclined to output the explosive energy in the form of kinetic energy. The extreme value of kinetic energy and the duration time that the kinetic energy is greater than zero are longer than that of the round tube. Round tube tends to store energy in the form of plastic strain energy, and the final stable energy value is larger than that of the flat tube. This is due to the fact that the flat tube will have more energy loss during expansion and contraction.
5. Conclusion

In this paper, the motion and deformation process of the flat metal tube under internal explosive loading have been tested and simulated. The experimental and simulation results correspond well. The deformation characteristics of round tube and energy change history of both tubes were also analysed by the simulation results. The main conclusions are as follows.

- Under the internal explosive loading, the flat tube expands and then contracts in the direction of the short axis (points 1 and 3), in the direction of the long axis (points 2 and 4), it expands slightly, contracts, expands outward and then finally gradually stabilizes.
- Under the internal explosive loading, the round tube directly expands to the maximum deformation and stabilizes gradually.
- The maximum kinetic energy value of the flat tube accounts for 27.65% of the initial energy of the detonation cord, and the final stable plastic deformation energy ratio is 40.43%. The maximum kinetic energy value of the round tube is 24.10%, and the final stable plastic deformation energy ratio is 50.03%. For the flat tube, its duration time that the kinetic energy greater than zero are longer than that of the round tube.
- The flat tube tends to output energy outward in the form of kinetic energy, while the round tube stores energy in the form of plastic deformation energy. Therefore, it is preferable to use a flat tube for destroying the external structure, and round tube is better to protect the external structure, energy is stored in the form of its own plastic deformation energy.

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