Numerical study of fragments from cylindrical casing with one of end caps fully constrained

Yue-guang Gao\textsuperscript{a}, Shun-shan Feng\textsuperscript{a}, Yun Chen\textsuperscript{b}, Xiang Xiao\textsuperscript{a}, Bo Zhang\textsuperscript{a}, Qi Huang\textsuperscript{*}

\textsuperscript{a}State Key laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, PR China
\textsuperscript{b}China Ordnance Industry Equipment Research Institute, Beijing 10081, PR China

huangqi@bit.edu.cn

Abstract. In order to study the process and characteristic of the fragments in the warhead with one end cap under full constraint condition, we established a cylindrical casing with two end caps which one of them was fully constrained using the simulation analysis. The result showed that the fragmentation of cylindrical casing with one end full constrained has its own characteristic. The Mach stem was generated when the detonation wave propagated to the fully constrained end cap under the condition of one end detonation, working on unreactive explosives and causing the nearby fragment subjected to nearly 2.5 times the normal pressure to obtain a higher speed. The cylindrical casing first ruptured at the contact surface with the fully constrained end, and then at the end cover of the initiating end, and then the rupture extends to the whole cylindrical casing. The detonation products started to leak out from the rupture, driving fragments to fly, and forming two dense flying areas. The analysis of this paper can provide a reference for the optimal design of this kind of warhead.

1. Introduction
When evaluating the damage effect of fragments on the target, the damage effect of a single fragment with a certain speed and mass is usually considered, but it is more reasonable to consider the overall response of the target structure under the action of multiple fragments and shock wave. In this case, it is very important to study the spatial distribution of fragments.

Huang [1] used X-ray to capture the spatial distribution of fragments of cylindrical casing without end caps. Arnold [2] used the witness plate to record the fragment distribution of cylindrical casing with openings at both ends. Through his experiment, it could be found that the fragment distribution was uneven, with a large mass in the middle part and smaller fragments on both sides. Kong [3] studied the space mass distribution of fragments generated by a cylindrical casing with end caps at both ends by numerical simulation. Krapp [4] carried out experiments, and recovered fragment masses within given ranges of angles, which was plotted as a function of the spatial angle. Gullis et al. [5] reported an experiment and a corresponding simulation. According to the witness plates at a given distance from the charge, one can found that the number of fragments was not uniform over the height of each plate. Grisaro [6] found that the spatial mass distribution of fragments that struck a protective wall was not uniform. It had been found that there is a ‘intense strip’, which is impacted by the...
heaviest fragments. They establish a simplified model for the non-uniform spatial distribution of fragment.

At present, there are few studies on the spatial distribution of fragments from cylindrical casing with one end fully constrained. In this paper, a cylindrical casing with one end fully constrained was built in our numerical simulation model, and static explosion test of corresponding warhead was further carried out to explore the formation law and spatial distribution of fragments.

2. Numerical simulation

The finite element software AUTODYN was used for numerical simulation, which was widely used to analyze nonlinear dynamic problems such as explosions and dynamic impacts. There are many previous studies have carried out simulation using the SPH algorithm, and the results have shown that SPH method is able to precisely simulate dynamic cracking and fragmentation, obtain the fragment velocity and even calculate the distribution of fragment size[6-9].

In this paper, the SPH method was used to simulate the fragmentation process of the cylindrical casing with one of end caps fully constrained, which was detonated at the center of one end unconstrained. Due to the symmetry of the cylindrical casing, only 1/4 of the model needs to be simulated.

Reasonable material selection of state equation and the constitutive relation played a key role to the accurate result of numerical simulation. The material of casing and explosive charge were made of 30CrMnNi2A and COMP-B. Combined with the late test, the dynamic response of COMP-B was described by the JWL equation of state JWL model, and Johnson-Cook (JC) model was used to described the mechanical properties of 30CrMnSiNi2A steel. One end of the cylindrical casing was set to be constrained, and the simulation model was shown in Figure 1. 12 gauss points were set on the surface of the casing to obtain the fragment velocities.

![Figure 1. Simulation model of cylindrical casing with one of end caps fully constrained.](image)

3. Results and discussion

3.1. Propagation of shock waves

After the detonation of the explosive charge, the explosive charge began a rapid reaction and generated shock waves in the explosive, which was shown in Figure 2a. The initial shock wave was a spherical wave in the explosive. When the shock wave propagated to the internal surface of the cylindrical casing, it was reflected. The reflected shock wave overlapped with the previous spherical shock wave and continued to propagate along the charge, which was shown in Figure 2b–d. As shown in Figure 2e–g, when shock waves spread to the fully constrained end cap, because the shell wave impedance is greater than that of the explosive, the reflected wave was shock wave, which was continually overlap with the shock wave in the original direction. The reflected shock wave was also a spherical wave, and two shock waves were overlapped. As a result, the Mach stem was generated near the end cap, which was recorded by gauss point 1 in Figure 3. It can clearly see that the pressure peak in 0.0085 ms, and the peak pressure was much higher than other gauss points, which was about 2.5 times that of other gauss points. Figure 4 shows the Mach stem phenomenon observed near the fully constrained end cap. The strong shock wave reflected from the fully constrained end cap continued to
propagate in the explosive, but its intensity gradually decreased with time, and its acceleration strength
to the unconstrained end cap and cylindrical casing also gradually weakened.

Figure 2. The propagation of detonation waves.

Figure 3. The pressure of measuring points.

Figure 4. Mach stem effect near fully constrained end caps.

3.2. Expansion and breakage of the casing
As shown in Figure 5a, the shock waves produced strong compression wave in the casing and
propagated along the casing. The casing began to expand and accelerated under the effect of shock
waves, and then the detonation products with high temperature and pressure generated from the
explosive charge further accelerated the casing. When the casing expanded out of the strength limit of
the material, the casing would break into a lot of fragments.

Due to the acceleration effect of Mach stem, higher velocity was obtained for the casing which
was close to the full constrained end cap, and the cylindrical casing broke first near the full
constrained end cap. With the acceleration of detonation products, the casing continued to expand, and
the cylindrical casing near the unconstrained end cap was followed by obvious rupture at about 0.025ms (Figure 5c). Then the unconstrained end cap was separated from the cylinder and continued to accelerate and break under the acceleration of detonation products, which was shown in Figure 5d–e. The unconstrained end cap can be divided into two parts, one of them generated fragments with larger quality in the middle of the end cap, the other part close to the edge of the end cap became a circle of fragments. The fragment velocity was basically stable at about 0.1 ms.

| (a) 0.006ms | (b) 0.02ms | (c) 0.025ms |
| (d) 0.04ms | (e) 0.075ms | (f) 0.12ms |

**Figure 5.** Shell expansion and fracture.

### 3.3. Leakage of detonation products

The leakage of detonation products was a complicated dynamic process. The detonation products of high temperature and high pressure flew out from the crack of the failed casing. In this section, the leakage process of detonation products of the cylindrical casing with one of end caps fully constrained was discussed in detail.

When the explosive charge was detonated, the shock waves spread rapidly in the explosive and detonated the rest explosive charge, which was shown in Figure 2a-h. When shock waves passed through the whole charge, the Mach stem was generated near the end cap fully constrained. The detonation products began to expand. Failure occurred first in the connection part of the cylindrical casing and the end cap fully constrained due to the effect of Mach stem, and the detonation products began to fly out from the gap in the failure part (Figure 6a). With the further expansion of the detonation products, the connection between the cylindrical casing and the unconstrained end cap also began to crack, and the detonation products flew out from the gap (Figure 6b). With the further expansion of the casing, the cylindrical casing also began to crack, and the detonation products also started to fly out from the cracks in the cylindrical casing (Figure 6c).

As shown in Figure 5d, after the separation of the end cap and cylindrical casing, the casing was accelerated due to the effect of the detonation products. But the rarefaction waves broke into the detonation products from the gap, which caused the pressure of detonation products dropped rapidly and the acceleration effect of that was also reduced. The acceleration difference and stress difference between the center part and the edge part of the unconstrained end cap began to occur, and the end cap began to broke in a ring when the strength limit of the casing material was exceeded, and the detonation products flew out from the crack (Figure 6d). The ring of the unconstrained end cap
continued to break (Figure 5c–d). The acceleration of fragment gradually decreased, and the velocity basically tended to be stable around 0.075ms (Figure 3).

| (a) 0.015ms | (b) 0.022ms | (c) 0.038ms | (d) 0.045ms |
|-------------|-------------|-------------|-------------|

**Figure 6.** The leakage of detonation products.

3.4. **Spatial distribution of fragments**
In the end, the fragment velocity tended to be stable, and the number of fragments was also stable. The fragment data was imported into MATLAB, the equatorial surface of the casing was regarded as 0°, the angle close to the end cap fully constrained was negative, and the angle close to the end cap unconstrained was positive. The relationship between the number of fragments and scatter angle was obtained in Figure 7. As can be seen from Figure 7, the fragment distribution included two concentrated areas, among which more fragment parts were concentrated between -20° and 20°, and the other part was distributed between -8° and -16°. Since the effect of Mach stem, there were more and smaller fragments near the end cap fully constrained. Another part of the fragment distributed in 30°~70°. As shown in Figure 5c–d, this part of fragment mainly came from the unconstrained end cap, and there were more fragments near the edge of the end cap. According to the theory of dynamic pressure damage theory, due to the influence of the rarefaction waves, the compressive stress area near the edge of the unconstrained end cap would be reduced faster, and the radial crack would propagate within the tensile stress area, the crack would propagate faster from the outer casing surface to the inner surface, more fragments were generated, and fragments with larger quality were in the center of the unconstrained end cap, which was consistent with the results in the simulation (Figure 8).

**Figure 7.** Number distribution of fragments.

**Figure 8.** Top view and side view of fragment spatial distribution.
4. Conclusions
In this paper, SPH method in AUTODUN was used to simulate the warhead with one of the ends fully constrained. The propagation of shock wave, expansion and fragmentation of cylindrical casing, leakage of detonation products and spatial distribution of fragments were simulated and analysed. There are some conclusions:

(1) After the detonation of the warhead, the Mach stem will occur at the fully constrained end cap, which caused the pressure of the nearby casing was almost 2.5 times that of the other part of the cylindrical casing.

(2) After the explosive charge was detonated, the cylindrical casing first failed in the connection part of the cylindrical casing and the end cap fully constrained, then in the connection part of the cylindrical casing and the unconstrained end cap, and finally extended to the whole cylindrical casing, and detonation products leaked out from the rupture.

(3) The distribution of the fragment was divided into two concentration areas, one of them was generated by the cylindrical casing, which distributed between -20° and 20°, and the other was generated by the unconstrained end cap, which distributed between 30° and 70°, and the fragments included a circular ring of small fragments and several large fragments in the middle.

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