# Failure Mechanism of Fixed Arch Steel Storage Tank Due To the Projection of Fragments Base on Finite Element Analysis

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*Abstract*— **In chemical industrial parks, container explosion accidents can easily trigger a domino effect, and the metal fragments produced can easily hit nearby target equipment or devices, causing the consequences of the accident to escalate. The ABAQUS/Explicit was used to conduct finite element simulation analysis by a fixed arch storage tank as an example in this study. By setting different fragment parameters, multiple control groups were set to control variables, and the damage law of a single fragment factor on storage tanks was explored. From the finite element simulation results of the impact of debris on the storage tank, it can be found that the impact of debris on the storage tank is divided into two stages: tank deformation and self-recovery. The mass, velocity, impact angle, shape, impact position, etc. of the debris will have different effects on the degree of damage to the tank wall after impact. Among various factors, the impact point displacement of the cube is the largest among the shapes of the fragments; The velocity of fragments follows a linear distribution with the maximum displacement of the impact point. For every 10 m/s increase in fragment velocity, the maximum displacement of the impact point increases by approximately 150 mm. The maximum displacement of the impact point gradually increases with the increase in the mass of the metal fragments, but the magnitude of the displacement increase gradually decreases; The maximum displacement of the impact point is mainly determined by the horizontal velocity of the metal fragments. The larger the impact angle, the smaller the horizontal velocity, and the smaller the maximum displacement of the tank wall in the horizontal direction; The higher the position of the debris impact tank, the greater the deformation of the impact point.**

***Index Terms***— **ABAQUS; Damage mechanism; Fragment impact; Vault storage tank**

## I. INTRODUCTION

China is a big country that realizes the growth of oil consumption, and ensuring China's energy security is a necessary condition for maintaining national economic development and security. Large steel storage tanks with large capacity, low cost, good stability and simple structure stand out and are widely used in the storage of oil and natural gas. However, the large capacity of the storage tank and the flammable and explosive nature of oil and natural gas make the storage tank extremely potentially dangerous. Common tank accidents in China include fire explosion, leakage and collapse, etc. Fire explosion has the characteristics of wide range of action, strong destructiveness and great lethality. Once a tank explosion occurs, it will often cause a large number of casualties and property losses.

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Therefore, scholars at home and abroad have done a lot of research on tank impact. However, most scholars mainly focus on the impact of explosion pressure on the tank head-on, mainly focusing on three aspects: debris ejection trajectory, hit probability and probability evaluation of destroying the target tank.

Aiming at the research of debris trajectory, Chen Gang [1] By solving the trajectory equation proposed by Mébarki, the distribution function and probability density function of debris throwing distance are calculated by Monte Carlo method, and the influence of spherical tank size on debris throwing distance is calculated. Sun [2] The effects of the volume of spherical tank, horizontal tank and vertical tank on the debris throwing distance were studied respectively. It was found that the probability of debris hitting the target tank was 10% greater within 8D (D is the diameter of the container) than when the container volume was ignored, and the container volume had little effect on the debris throwing distance when it exceeded 14D.

In view of the research on the probability of debris concentration, Nguyen [3] Considering the three-dimensional contour of the target tank, it is considered that the intersection of the trajectory equation of debris ejection and the contour equation indicates a hit. Qian xinming [4] Based on the three-dimensional trajectory of debris, it is considered that the debris hits the target when it falls in the circumscribed cubic area of the target storage tank, and the influence of multiple debris in a single simulation is considered in the hit probability model.

Research on the probability of debris destroying the target storage tank, Chen [5] argued that the critical residual wall-thickness of a storage tank cannot be readily quantified because its determination hinges on a sophisticated local-stress analysis that is sensitively dependent on material properties and wall thickness; to circumvent this difficulty, he transplanted the “loss-of-shell-area” philosophy commonly used in pressure-vessel integrity assessment and formulated a fragment-impact failure criterion based on the critical Remaining Strength Factor (RSF).Salzano[6], a criterion for judging the failure of storage tanks under the impact of explosive debris, is proposed. The damage and failure of generalized target equipment including concrete structure, brick wall structure and steel storage tank under debris impact are studied, and two impact depth formulas based on debris quality are derived respectively. It is considered that penetration failure occurs when the impact depth is greater than the thickness of target equipment.

The research on the domino effect accident caused by explosive debris involves a wide range of disciplines at present, from the throwing distance of explosive debris, the probability of hitting the target storage tank, to the failure probability of the target storage tank and so on. However, these studies lack quantitative analysis of the damage effect of impact load on the storage tank structure, such as the shape, mass, direction of debris and different positions of the tank wall. In this paper, taking the storage tank with fixed vault as an example, the finite element simulation analysis of the impact process is carried out by using ABAQUS/Explicit software. By setting different debris parameters, such as the shape, speed and mass of debris, as well as the impact angle and position of debris, the control variables are set up in groups of control groups to explore the damage law of a single debris factor to the storage tank.

## II. NUMERICAL MODEL

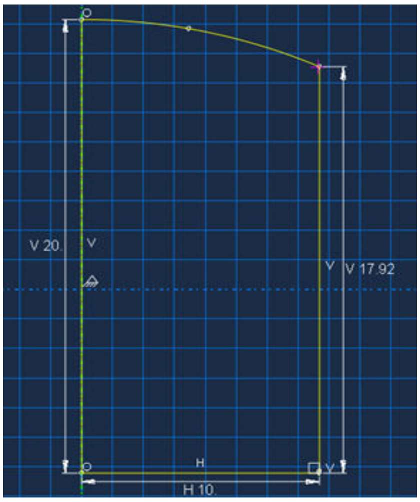
In the chemical industry park, storage tanks generally store a large amount of flammable and explosive media. If there is overpressure or fire, it is easy to cause an explosion accident. The debris generated by the explosion will impact other storage tanks in the tank farm and even penetrate the tank wall, resulting in a secondary explosion. Scholars at home and abroad mostly focus on the impact of explosion pressure on storage tanks, such as the collision probability[7] between explosion[8] debris and target storage tanks. And impact depth And so on, there is little research on the damage law of the impact on the storage tank caused by many factors such as the shape, mass and direction of the debris and the different positions of the tank wall.

In this paper, ABAQUS/Explicit software and FEM method are used to simulate the penetration behavior of small debris in the whole process of impacting a fixed dome storage tank. The influence of many factors such as the shape, mass, impact speed, impact angle and impact position of the debris on the penetration behavior is studied to find out the damage law of the storage tank.

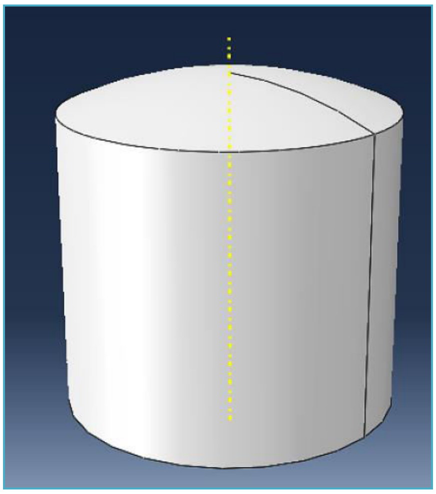
### A Tank model

#### A.1 Geometric model of storage tank

The target storage tank selected in this paper is a large-scale steel storage tank with fixed vault, which is common in China at present, and the storage tank volume is 50003. The schematic diagram of the target storage tank is shown in Figure 1. Refer to Code for Construction of Vertical Cylindrical[9] Steel Welded Storage Tanks (GB 50314-2014). The tank model is designed with a diameter (D) of 20m, a tank wall height of 17.82m and an overall height (H) of 20m.




(a) storage tank size



(b) tank as a whole

Fig 1. schematic diagram of target storage tank

In practical engineering, the tank wall of a large steel storage tank is welded by multiple steel plates, and the hoop force at the bottom of the tank wall is the largest, which gradually decreases with the height of the tank wall. Therefore, the thickness of the bottom steel plate on the tank wall is the largest, and the thickness of the steel plate decreases with the increase of the tank wall height. In this paper, in order to explore the impact damage law of a single debris parameter on the storage tank, idealization is carried out, and the target storage tank thickness is treated as uniform 10 mm.

#### A.2 Material model

Q345 steel is used as the material of the simulated debris and the material of the target storage tank, and the parameters of Q345 steel are shown in Table 1. Table 2 shows Parameters of Johnson-Cook material model; Table 3 shows the parameters of Johnson-Cook damage failure criterion.

The material of storage tank is Q345, and Johnson-Cook constitutive model and Johnson-Cook damage failure model are adopted. The constitutive[10] equation of Johnson- Cook material model is like equation (1).

Johnson-Cook damage failure criterion is widely used in metal materials, which considers stress triaxiality, strain rate and temperature effects. Damage of unit[11] Defined as equation (2).

**The failure strain is expressed as [12] equation (3).**

Table 1. Material parameters of Q345 steel

| Q345 Steel | density | modulus of elasticity | Poisson's ratio | thermal conductivity | specific heat capacity |
|---|---|---|---|---|---|
| Material parameter | 7850kg/$m^3$ | 210000MPa | 0.3 | 44W/(m·℃) | 460J/(kg·℃) |

Table 2. Johnson-Cook material model parameters of Q345 steel

| A/MPa | B/MPa | C | n | m | $T_{melt}$/°C | $T_{trans}$/°C |
|---|---|---|---|---|---|---|
| 374 | 795 | 0.01586 | 0.45451 | 0.88559 | 1500 | 20 |

Table 3. Johnson-Cook Damage Failure Criterion Parameters of Q345 Steel

| $d_1$ | $d_2$ | $d_3$ | $d_4$ | $d_5$ | $T_{melt}$/°C | $T_{trans}$/°C | $\dot{\varepsilon}$ |
|---|---|---|---|---|---|---|---|
| 0.123 | 0.236 | 2.43 | 0.058 | 0 | 1500 | 20 | 1 |

$$\bar{\sigma} = [A + B(\bar{\varepsilon}^{pl})^n]\left[1 + C\ln(\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0})\right](1 - T^m) \quad (1)$$

In the equation (1), $\bar{\sigma}$ represents the equivalent stress; $\bar{\varepsilon}^{pl}$ represents the equivalent plastic strain; $\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0}$ represents the dimensionless plastic strain rate; $\dot{\varepsilon}_0$s the strain rate from a quasi-static test; $T^m = (T_c - T_{trans})/(T_{melt} - T_{trans})$, where $T_c$ is the specimen temperature, $T_{trans}$ is room temperature, and $T_{melt}$ is the melting point; $[A + B(\bar{\varepsilon}^{pl})^n]$ represents the strain hardening effect; $\left[1 + C\ln(\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0})\right]$represents the strain rate strengthening effect; $(1 - T^m)$ represents the thermal softening effect; A、B、C、m、n are material constants.

$$R = \frac{\Delta\varepsilon_P}{\bar{\varepsilon}_f^{pl}} \quad (2)$$

In equation (2), $R$ denotes the damage parameter, which ranges from 0 to 1. Initially, $R = 0$, and material failure occurs when R reaches 1; $\Delta\varepsilon_P$ represents the incremental equivalent plastic strain per time step, $\bar{\varepsilon}_f^{pl}$ refers to the failure strain under the current stress state, strain rate, and temperature.

$$\bar{\varepsilon}_f^{pl} = \left[d_1 + d_2\exp\left(d_3\frac{p}{q}\right)\right]\left[1 + d_4\ln\left(\frac{\dot{\bar{\varepsilon}}_f^{pl}}{\dot{\varepsilon}}\right)\right](1 + d_5 T) \quad (3)$$

In equation (3), $d_1$、$d_2$、$d_3$、$d_4$ and $d_5$ are material parameters; $P$ represents the pressure; $q$ denotes the Mises equivalent stress; and $\dot{\varepsilon}$ is the reference plastic strain rate.

A.3 Grid division of storage tank

The tank wall is modeled by solid deformation, and the tank wall is divided by hexahedral grid C3D8R. The overall size of the target tank is 200mm, the nearly global size is 0.8, and the number of seeds is about 3,000.

The tank wall is in contact with the debris by penalty function, and the contact boundary can penetrate each other. The surface of the debris is set as the contact main surface, and the geometric characteristics of the impact position of the tank wall are extracted and set as the contact slave surface. When the tank wall fails due to impact, the failed grid is deleted to ensure that the debris can continue to act on the effective grid. When the storage tank is impacted, it is not only subjected to the load of debris, but also restrained by the bottom plate. Therefore, A fixed constraint is applied at the bottom of the storage tank to prevent unintended displacement during the simulation analysis.

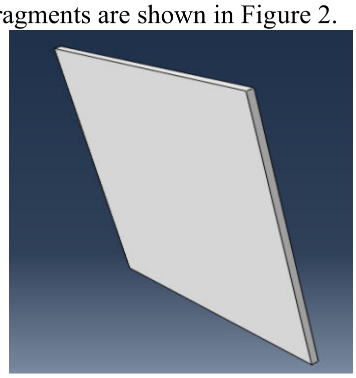
B Debris model

B.1 Geometric model

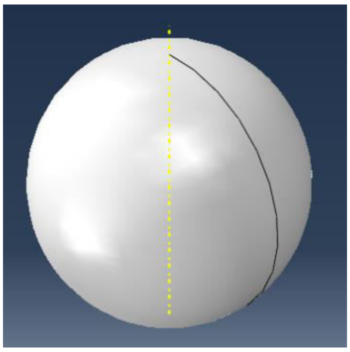
In this paper, ABAQUS is used to simulate the impact of metal fragments on the storage tank. By changing the shape, mass, speed and angle of the fragments, the dynamic response of the tank wall after being impacted by different fragments is analyzed.

(1) Fragment shape

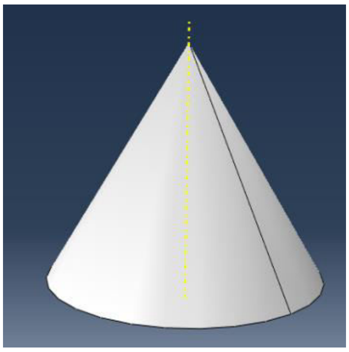
According to the different contact surfaces between metal fragments and the tank, this paper sets up three different fragments, namely cube, sphere and cone, and the contact surfaces between these three shapes and the tank wall are plane, convex and sharp corners respectively. The shapes of the three fragments are shown in Figure 2.



a) cube



b) sphere



c) cone

Fig2. Fragment Shape Diagram

(2) Other debris parameters

In addition to the control group of debris shape, this paper also compares the speed and mass of debris, as well as the impact angle and impact position of debris. The specific parameters are shown in Table 4. In addition, the top, middle and bottom of the tank in the impact position are represented by dividing the tank height into three parts, and taking the center point of each part as the impact point in this area.

Table 4. Other debris parameters

| Debris velocity | Debris mass | Impact angle | Impact position |
|---|---|---|---|
| 50m/s | 1000kg | 0° | top |
| 60m/s | 2000kg | 30° | middle |
| 70m/s | 3000kg | 60° | bottom |

B.2 Simulation of impact process

In order to analyze the damage of the storage tank after being impacted by debris, combined with the above research on the factors such as the speed, mass and angle of debris, a set of parameters about the storage tank and debris, that is, the cubic metal debris with a mass of 2000kg horizontally impacts the tank wall at a speed of 60 m/s (the impact angle is 0), is modeled in ABAQUS software. After the impact of debris, the damage of the tank wall simulated by finite element method is shown in Figure 3.

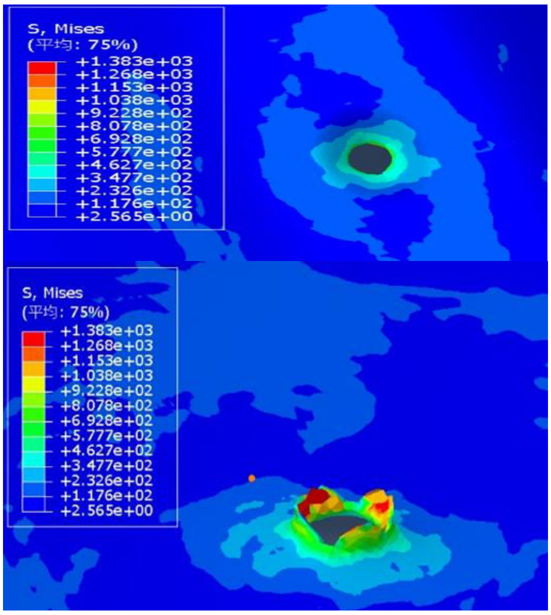



Fig.3 Simulation results of debris impact on wallboard

In the simulation results, smooth bullet holes appear on the front, and the stress around the perforation is the highest, which decreases gradually in the form of a ring. The failure shape of the back crack is irregular petal-shaped, and the stress is concentrated at the top of the "petal".

## RESULTS AND DISCUSSION

A Simulation analysis of impact process

In the simulation results summarized in 1.3, we can not only get the damage of the tank wall, but also get the dynamic response of the whole process after the tank is impacted by debris. In this paper, the change of the displacement of the impact point with the impact time is taken as the reference index of the dynamic response, and then the whole process of the response of the storage tank after impact is analyzed. The simulation results are shown in Figure 4.

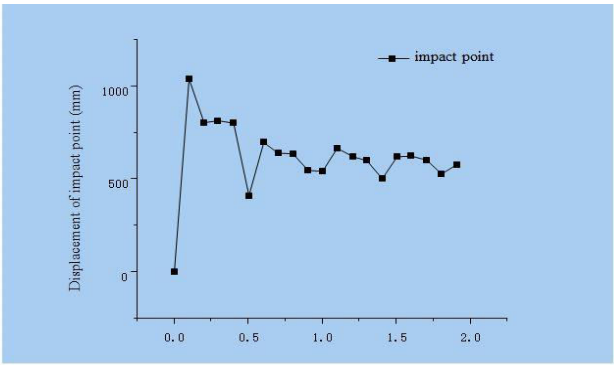



Fig.4 Time history curve of impact point displacement

According to Figure 3, the displacement change characteristics of the impact point of the storage tank are obvious when it is impacted by explosive debris, which is mainly divided into two stages: the debris deforms the storage tank and the storage tank recovers itself. During the period of 0~0.2s, the storage tank is in the main concentrated stage of deformation. During this period, the explosive fragments impact the storage tank with great kinetic energy, and the impact point of the storage tank is deformed sharply during this period, reaching the maximum displacement quickly, which is also the main stage of the storage tank being cracked by impact. Subsequently, the metal fragments did not penetrate the tank wall because the fragments were out of contact with the tank wall about 0.2s. After 0.2s, the tank wall began to recover itself, and the vibration phenomenon appeared near the impact point. With the increase of impact time, the vibration phenomenon of the tank wall gradually weakened, and finally the deformation of the tank wall stabilized at about 500mm, that is, the deformation of the tank after being impacted by fragments. When the impact point reaches the maximum displacement, it is the most dangerous stage of the tank wall. When analyzing the influencing factors of debris, this paper mainly studies the influence of debris on the tank at this stage.

B Debris shape influence

In order to analyze the influence of debris shape on the storage tank more clearly, this paper uses three shapes of cube, sphere and cone to simulate the plane, convex surface and sharp corner respectively, and analyzes and simulates the influence of explosive debris. In the process of finite element simulation, in order to eliminate the influence of other factors, the same tank was selected as the impact target, and no liquid was stored in the tank. The debris velocity was 60m/s and the mass was 2000kg, and the tank was impacted horizontally. The impact position of the fragments in the tank wall is selected and compared. The simulation results are shown in Table 5.

Table 5 Impact Analysis of Debris Shape

| Fragment shape | Maximum displacement of center point (mm) | Residual velocity (m/s) |
|---|---|---|
| cube | 1937.3 | 1.37 |
| sphere | 1726.8 | 2.21 |
| cone | 974.86 | 0.45 |

When explosive fragments are in the impact tank, the changes of impact point displacement and fragment velocity with time are shown in Figure 5 and Figure 6 respectively. When metal fragments impact the storage tank, the impact on the storage tank mainly includes penetration and deformation.

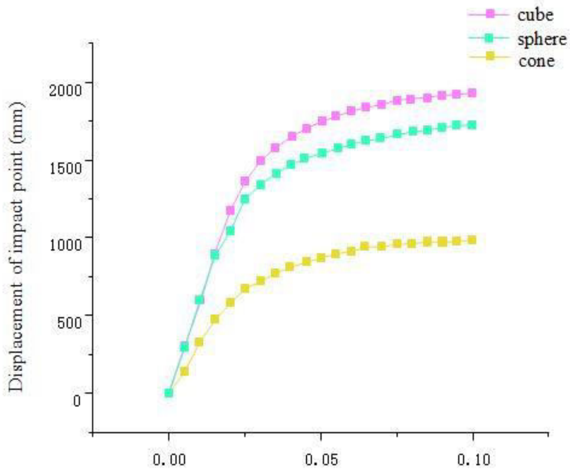



Fig. 5 Displacement change of impact point

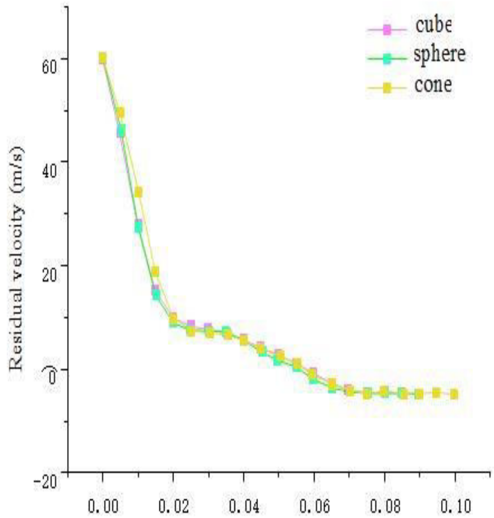



Fig. 6 Velocity change at impact point

Figure 5 shows the maximum displacement change of the impact point when the debris impacts the storage tank. When it is 0~0.02s, the velocity of the debris is larger, the displacement of the impact point is more intense, and the velocity of the debris decays faster. When the velocity decays to a certain extent, such as 0.02~0.06s, the kinetic energy of the debris is not enough to support the tank wall to produce a rapid displacement change, and the displacement change at the impact point slows down and the debris attenuation slows down; At present, because the kinetic energy of metal fragments is not enough to penetrate the tank wall, the residual velocity of fragments is shown in Figure 6. At 0.07s, the velocity of fragments becomes 0m/s, and the impact point reaches the maximum. Moving, the tank wall rebounds and gives the debris a reverse speed.

The three types of metal fragments exhibited a similar trend in velocity variation upon contact with the tank wall: in the same time interval, their velocities underwent two distinct stages—a rapid decline followed by a gradual reduction. The final residual velocity of different fragments after impact is basically the same, indicating that the energy consumed by the three fragments is basically the same in the same time, and when the cubic fragments impact the tank wall, the maximum displacement of the impact point is greater than that generated by the spherical and conical fragments, which may be due to the different ways in which the three fragments impact with the tank wall, and the cubic fragments contact with the tank wall with the maximum contact area, thus reducing the friction between them. Attenuated kinetic energy is mainly used for the deformation of the tank wall. When the ball and cone contact with the tank wall, it mainly concentrates on one point. With the increase of contact time, the contact area between the debris and the tank wall gradually increases. When the impact point moves along the horizontal direction of the debris, it produces a tangential friction force on the debris and consumes some kinetic energy. Under the same mass and speed, the cubic fragments have the greatest influence on the displacement of the tank wall, which makes the tank wall more likely to fail.

Chen Siyu[13] The finite element simulation software is used to simulate the impact of different types of explosive fragments on the spherical tank. It is found that the impact process is basically the same when different types of explosive fragments impact the storage tank, but the impact displacement caused by cubic fragments on the spherical tank is the largest, which is consistent with the results obtained by simulating the impact of metal fragments on the vertical storage tank in this paper.

C Debris velocity effect

In this paper, the debris velocity is set to 50m/s, 60m/s and 70m/s to simulate and analyze respectively. The explosion fragments in this finite element simulation analysis are cubic fragments, and the other parameters are the same as those in the fragment shape analysis, so as to better explore the influence of speed on the maximum displacement of the tank wall. Select the impact position in the tank as debris, and the simulation results are shown in Table 6.

Table 6 debris velocity impact analysis

| **Initial velocity of debris (m/s)** | **Maximum displacement (mm)** | **Residual velocity (m/s)** |
|---|---|---|
| **50** | 832.47 | 3.41 |
| **60** | 987.32 | 3.08 |
| **70** | 1148.66 | 2.52 |

It can be seen from Table 6 that the initial velocity of metal fragments directly affects the kinetic energy of the fragments under the same mass. The greater the initial velocity, the greater the kinetic energy, the more energy absorbed by the tank wall after the fragments impact the tank wall, and the greater the influence on the deformation and displacement of the tank wall, showing a positive correlation trend.

In order to better analyze the data in Table 6, draw it as Figure 7. From the figure, it can be seen that the velocity of explosive debris is linearly distributed with the maximum displacement of the impact point between 50 and 70 m/s, and the maximum displacement of the impact point increases by about 150 mm when the debris velocity increases by 10m/s.

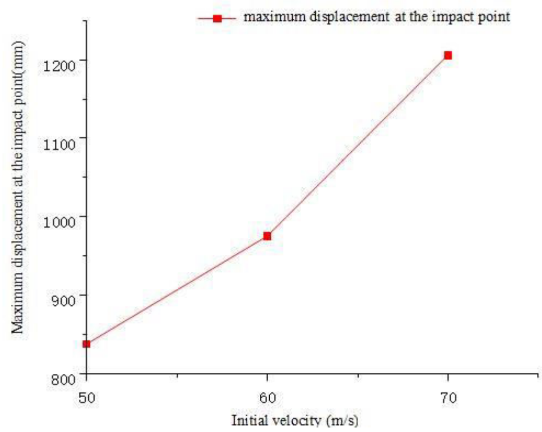



Fig. 7 Relationship between debris velocity and impact displacement

When explosive fragments impact the tank wall at different speeds, the displacement of the impact point changes with time as shown in Figure 8.

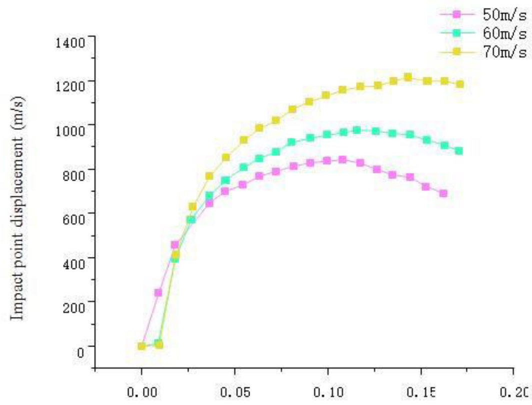



Fig. 8 Impact results at different speeds

As shown in Figure 8, when the fragments impact the tank wall at different speeds, the speed has the same attenuation trend. First, the impact point of the tank wall is severely deformed in a short time at the initial stage of contact between the metal fragments and the tank wall, which is also the main stage of tank wall deformation. During the subsequent contact time, the kinetic energy possessed by the fragments is not enough to make the storage tank continue to deform violently, and the attenuation of the velocity of the metal fragments and the displacement change of the impact point are slowed down until the velocity of the fragments drops to zero. At this time, there is no external force on the tank wall, and the displacement of the impact point reaches the maximum, and the tank wall begins to drive the metal fragments to rebound and give the metal fragments a reverse velocity.

When the speed of debris is less than 60 m/s, the tank wall is not broken by the impact of debris, but it begins to rebound after reaching the maximum displacement. The failure form is mainly that the impact position is sunken, and when the speed is greater than 70 m/s, the tank wall cracks. Because the kinetic energy possessed by debris cannot penetrate the tank wall, the maximum displacement of the impact point increases with the increase of speed, but it does not rebound after reaching the maximum displacement, and the failure form is mainly that the tank wall breaks.

It can be seen from Table 6 that when the impact velocity of fragments is low, the residual velocity given to fragments by the tank wall is large, which may be because when metal fragments impact the tank at a small initial velocity, the displacement of the impact point reaches the maximum in a short time, and the impact velocity of fragments rapidly drops to zero in a short time. The deformation of the tank wall is mainly concentrated near the impact point, and the deformation range is small, so the tank releases more energy when rebounding. In short, under the same mass, the initial velocity of metal fragments directly affects the kinetic energy of the fragments. The greater the initial velocity, the greater the kinetic energy, and the more energy absorbed by the tank wall after the fragments impact the tank wall, which has a greater impact on the deformation and displacement of the tank wall.

Through the impact of thin-walled plate fragments on the vertical fixed-roof storage tank, it is found that the damage form of explosive fragments to the storage tank is plastic deformation when the speed is 60~75m/s, and the tank will rupture when the speed is greater than 80 m/s, which is similar to the change form of the damage form of fragments to the storage tank with speed in this paper.

D Debris quality influence

Combined with the above analysis of the quality of explosive debris and the statistical results of scholars on the quality of explosive debris over the years, this paper intends to analyze and study the quality of explosive debris in three situations: 1000kg, 2000kg and 3000kg. In the process of finite element simulation, in order to eliminate the influence of other factors, the initial velocity is 60m/s, and the other debris and storage tank parameters are the same as the analysis of the influencing factors of debris velocity. The simulation results are shown in Table 7.

Table 7 Debris Quality Impact Analysis

| Fragment mass (kg) | Maximum displacement (mm) | Residual velocity (m/s) |
|---|---|---|
| 1000 | 1032.31 | 4.34 |
| 2000 | 1643.26 | 2.23 |
| 3000 | 2064.94 | 3.78 |

When explosive fragments impact the tank wall with different masses, the displacement of the impact point changes with time as shown in Figure 9.

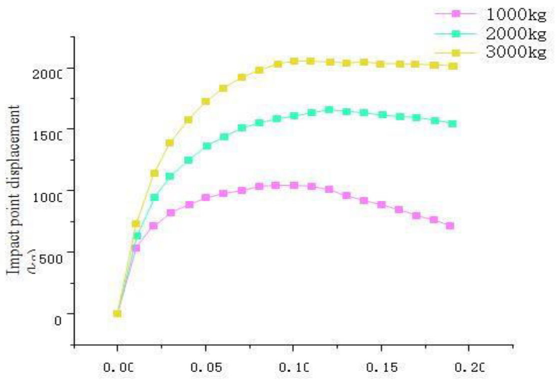



Fig. 9 Variation of debris mass and impact point displacement

As can be seen from Figure 9, the maximum displacement of the impact point gradually increases with the increase of the mass of metal fragments, but the amplitude of the displacement increase gradually decreases. This may be due to the fact that the mass of explosive fragments is directly reflected in the size of metal fragments, and the contact area between the explosive fragments with large mass and the tank wall is larger, and the area of plastic deformation of the tank wall will also increase at the same time, which makes the overall deformation of the tank wall more difficult, so the maximum displacement of the impact point of the tank wall gradually increases.

When the metal fragments have the same speed, with the increase of mass, the impact point will be given greater acceleration when the fragments contact with the tank wall, resulting in more severe deformation at the initial stage of contact. When the mass of metal fragments is less than 2000kg, the central displacement deformation of the impact point is relatively smooth; when the mass of metal fragments is more than 3000kg, the time for the deformation of the impact point to reach the maximum displacement is shorter than that of the metal fragments with small mass, which is because the tank wall is cracked at this time, and the force on the tank wall is mainly concentrated below the fragments. This may be due to the fixed constraint below the tank, when the fragments impact the tank, the lower part cannot move in a large range, and the upper part of the tank can unload the force through fluctuation.

E Debris angle effect

In this paper, the impact of debris angle on the storage tank is simulated and analyzed with the projection angles of 0, 30 and 60 respectively. In the process of finite element simulation, the mass is 2000kg, and the other parameters are the same as the analysis of the influencing factors of debris quality, so as to better explore the influence of speed on the maximum displacement of tank wall. Select the impact position in the tank as debris, and the simulation results are shown in Table 8.

Table 8 Impact Results of Tank Impact at Different Angles

| Impact angle (°) | X-axis residual velocity Degree (m/s) | Y axis residual velocity Degree（m/s ) | Residual velocity（m/s ) | X-axis maximum Displacement (mm) | Maximum in y axis Displacement (mm) | maximum displacement (mm) |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| 0 | 3.08 | 0 | 3.13 | 989.43 | 0 | 998.98 |
| 30 | 3.68 | 0.245 | 3.67 | 898.37 | 84.66 | 889.483 |
| 60 | 6.41 | 0.12 | 6.359 | 546.25 | 87.94 | 549.75 |

When explosive fragments impact the tank wall at different angles, the changes of impact points in horizontal and vertical directions with time are shown in Figure 10 and Figure 11 respectively.

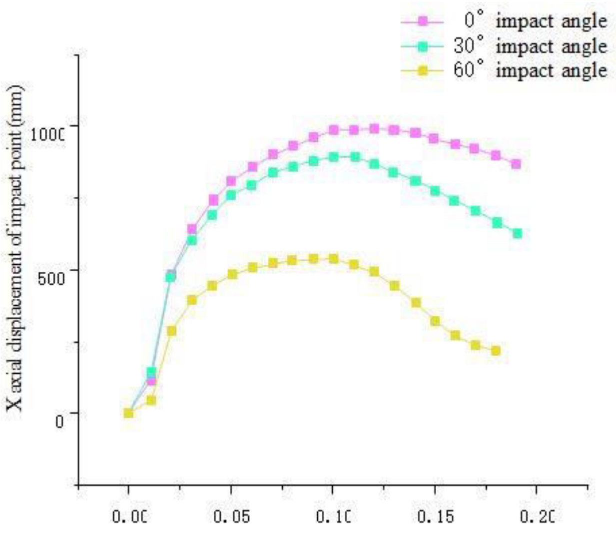



Fig. 10 Horizontal displacement change of impact point

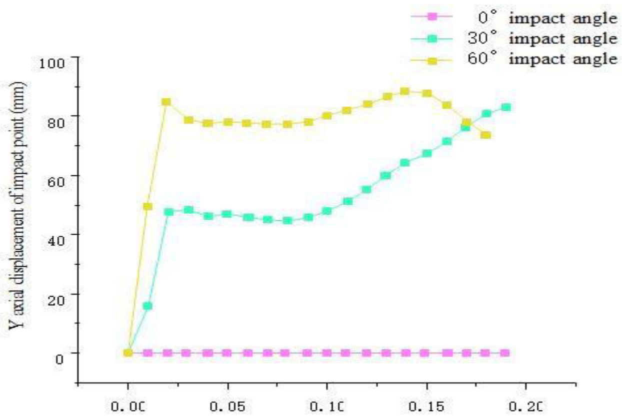



Fig. 11 Vertical displacement change of impact point

As can be seen from Figures 10 and 11, the maximum displacement of the impact point is mainly determined by the horizontal velocity of the metal fragments. When metal fragments impact the tank wall at the same speed, when the impact angle is less than 60, the larger the impact angle, the smaller the horizontal velocity and the smaller the maximum displacement of the tank wall. Compared with the velocity in the horizontal direction, the velocity in the vertical direction decays faster, and the velocity in the vertical direction basically decays to zero within 0 ~ 0.02 s.

This may be due to the vertical structure of the thin-walled cylinder of the tank wall, which makes the tank wall more prone to deformation in the horizontal direction than in the vertical direction when it is impacted by debris at a certain angle, and the impact of debris gives the tank wall a horizontal displacement, and the horizontal deformation generated at the impact point provides an inclined impact platform for the vertical movement of debris. The movement of the impact point in the horizontal direction is only the tensile stress of the adjacent materials, and because there is no liquid in the tank, the tank wall can produce a large area of horizontal displacement. However, the vertical deformation of the impact point is not only subject to the compressive stress provided by the material below the impact point, but also to the tensile stress provided by the material above, which makes the vertical deformation of the impact point more difficult.

The deformation trend of the impact point in the horizontal direction is the same as that of the horizontal velocity of the debris. At the initial stage of contact between the metal debris and the tank wall from 0 to 0.04s, the debris provides an acceleration for the tank wall, which makes the tank wall sag and deform. At about 0.04 s, the velocity of the impact point tends to be consistent with that of the metal debris, and the deformation speed of the impact point slows down. At 0.1s, the velocity of the metal debris decreases to 0m/s, and the horizontal displacement of the impact point reaches the maximum value and begins to rebound. Therefore, the greater the impact angle, the smaller the component velocity of the fragments in the horizontal direction, the smaller the maximum displacement of the impact point, the greater the degree of rebound, the greater the speed given to the metal fragments, and the less the energy absorbed by the tank wall through horizontal deformation.

The change trend of the impact point in the vertical direction is the same as that of the metal fragments in the vertical speed. At 0~0.02s, the metal fragments make initial contact with the tank wall, which is also the time period when the vertical speed of the metal fragments mainly does work. The impact point rapidly deforms in the vertical direction, and the vertical speed of the fragments decreases rapidly. Within 0.02~0.1s, the impact point is mainly deformed in the horizontal direction, and it is in a stable state in the vertical direction. At 0.1s, the impact point reaches the maximum deformation in the horizontal direction, and the impact point begins to rebound. Because the residual velocity of the debris in the vertical direction and the residual velocity in the horizontal direction synthesize an oblique downward velocity, the impact point drives it to move downward while recovering the horizontal displacement. When the impact angle is 60, the crack occurs at the impact point at 0.15s, which is due to the same speed.

In this case, with the increase of impact angle, the vertical velocity of metal fragments is also increasing. The vertical velocity of metal fragments decreases rapidly after impacting the tank wall, and the impact point does not give the vertical velocity to the metal fragments during the rebound process, which shows that the vertical velocity of metal fragments all does work for the tank. Therefore, between 0 and 60, when the impact angle is small, the horizontal displacement of the impact point is the main failure form of the storage tank, and when the impact angle is large, the rupture of the impact point is the main failure form of the storage tank.

F Impact position influence

In order to better analyze the impact of explosive fragments on the different heights of the tank wall, this paper selects three points above, in and under the tank as the impact points for comparative analysis, all of which use cubic metal fragments with a mass of 2000kg to horizontally impact the tank at a speed of 60 m/s. The displacement curves of the impact points above, in and under the tank are shown in Figure 12.

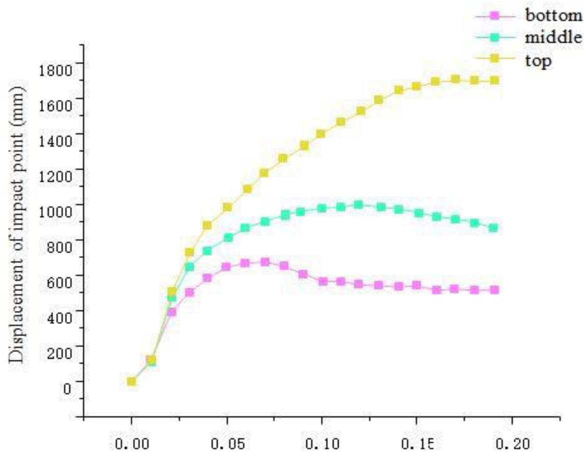



Fig. 12 Displacement of impact point at different tank wall heights

As can be seen from Figure 12, under the same impact condition, with the height of the impact point increasing gradually, the deformation of the impact point is also increasing. When metal fragments impact the tank at the speed of 60m/s, the tank wall is plastically deformed, and with the increase of the height of the impact point, the maximum displacement deformation of the impact point on the tank is higher than other tank walls, and the overall structural deformation of the tank is the most severe, and the tank wall has no rebound stage, at this time, the tank wall enters plastic deformation. This is because the constraint from above the impact point decreases with the increase of tank wall. Generally speaking, the higher the impact height of metal fragments on the tank wall, the greater the deformation of the tank and the higher the risk of tank failure.

CONCLUSION

(1) The dome storage tank is deformed after being impacted by metal fragments. Because the steel material used in the storage tank has good elasticity and plasticity, the tank wall is deformed inward at the initial stage of being impacted. When the velocity of metal fragments drops to zero, the impact point will rebound. When the impact point of storage tank is impacted by explosive debris, it mainly shows two stages: deformation and self-recovery of storage tank.

(2) The shape, speed, mass and incident angle of metal fragments will have corresponding effects on the deformation of storage tanks.

3) The impact of debris on different positions of the tank is also different. With the increase of the impact position, the impact resistance of the tank gradually decreases, and the deformation on the tank is the largest when it is impacted, and the tank wall is plastically deformed. In the analysis of the impact of metal fragments on the tank wall, under the same impact of fragments, with the increase of the height of the tank wall, the deformation of the tank is more severe.

REFERENCES

[1] Chen Gang, Zhu Jiping, Wu Jun, et al. Influence of explosion spherical tank size on the probability of projectile fragments hitting adjacent tanks [J]. Journal of Chemical Technology, 2010,61(6):1599-1604.
[2] Sun D L, Jiang J C, Zhang M G, et al. Influence of the source size on domino effect risk caused by fragments[J]. Journal of Loss Prevention in the Process Industries,2015,35(1):211-223.
[3] Nguyen Q B, Mébarki A, Saada R A, et al. Integrated probabilistic framework for domino effect and risk analysis[J]. Advances in Engineering Software,2009,40(9):892-901.
[4] Qian Xinming, Xu Yabo, Liu Zhenyi. Monte-Carlo analysis of BLEVE fragment ejection from spherical tank [J]. Acta Chemical Engineering, 2009, 60(4): 1057-1061.
[5] Chen Gang, Zhu Jiping, Wu Jun, et al. Study on the damage probability of the target container caused by the explosive fragments of the storage tank [J]. Journal of Disaster Prevention and Mitigation Engineering, 2012,32(2): 216-222.
[6] Salzano E, Basco A, Simplified model for the evaluation of the effects of explosions on industrial target[J]. Journal of Loss Prevention in the Process Industries, 2015, 37(9): 119-123.
[7] Chen Gang. Study on probability model of domino effect caused by explosive fragments of chemical storage tanks [D]. Hefei: China University of Science and Technology, 2011.
[8] Chen Siyu, Chen Wenjiang, Hu Zhaoji, et al. Numerical simulation of explosive fragments impacting spherical tanks and analysis of influencing factors [J]. Journal of Nanchang University (Engineering Edition), 2018,40.(4): 324 - 328; 369.
[9] Ministry of Housing and Urban-Rural Development of the People's Republic of China. Code for Design of Vertical Cylindrical Steel Welded Oil Tanks: GB 5034—2014[S]. Beijing: China Planning Press, 2015.
[10] Yang G D, Wang G H, Lu WB, et al. Numerical modeling of surface explosion effects on shallow-buried box culvert behavior during the water diversion[J]. Thin-Walled Structures,2018,133:153-168.
[11] Kong Xiangshao. Study on explosion load and response characteristics of composite multilayer protective

structure [D]. Wuhan: Wuhan University of Technology, 2013.

[12] Yao S J, Zhang D, Lu Z J, et al. Experimental and numerical investigation on the dynamic response of steel chamber under internal blast[J]. Engineering Structures, 2018, 168: 877-888.

[13] Chen Siyu. Numerical simulation of dynamic response characteristics of explosion debris impacting storage tanks [D]. Jiangxi: Nanchang University, 2018: 78.