Numerical investigation of a fragment protection structure

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Abstract

In order to protect people and equipment from being damaged by fragments, using LS-DYNA software, this paper investigates numerically the processes of fragments impacting on a structure formed by interlaced double t steel, which is a common industry product. In the calculations, the steel fragment mass is from 0.3kg to 23kg and the velocities are from 30m/s to 100m/s. The material models are Johnson-Cook models in which parameters are adjusted through the comparison with the experimental result. It can be found from the simulations that two or three double t steel of the protection structure can hold up the fragments with small mass, high velocity, and different incident angle. For a large fragment with low velocity, many double t steel of the protection structure take effect and block the fragment. The conclusion is that the easy-made protection structure can effectively prevent fragments mentioned above from perforating.

Keywords: fragment protection structure, numerical simulation, LS-DYNA, double t steel, low velocity fragment, impact.

1 Introduction

There have been many investigations on the collision and penetration, and interaction between a target and a moving object, in which many researches have concentrated on the interaction effects of a projectile and a structure. The object usually joins with the explosive tightly at first. After the explosion, the object is accelerated by the expansion of the explosion products, and has a high velocity about 1.5-2.0km/s. For example, the long-rod penetrators, metal jets, and shaped charges with that velocity have been studied widely. In order to resist the impact of these high velocity objects, there have been many methods and structures
used. According to the different situation between target and projectile with different velocity, many researchers have investigated many structures and materials such as protection blankets [1], ceramic armor [2], steel enforced concrete, layered composite targets and glass fiber reinforced material [3], explosion vessel [4], sandbag and water containers [5], barricades [6], and so on.

Apart from the high-velocity impact and penetration, there are other instances where the velocity of the fragment is low. For instance, when the spacing or low impedance material between explosive and crust exists, the pressure pushing the crust outwards will be reduced, then the fragment velocity will be low. When an explosion vessel has to carry out an explosion experiment whose detonation power exceeds the vessel’s explosive capacity, the vessel may be fractured and produce fragments with low velocity. A similar example is that an object near to the explosive will be accelerated by the explosion products and have a low velocity. In these situations, we found that the velocity of the fragments was about 10-100m/s by using numerical simulations and theoretical analyses methods including momentum conservation, energy conservation, and explosion impulse and energy. Some mechanical movements also produce low velocity fragments.

For these fragments, the safety measures must be taken to protect people and equipment. Because the velocity of the fragments is low, the measures adopted can be simpler than that mentioned above for high velocity projectiles. The simplest method is taking enough safe distance determined from the fragmentation distance. If site conditions make it impossible or impractical to take that distance, a structure or barricades will be used to resist the fragments. General fragment-resisting materials can be stacked around the explosion site, including concrete, sand, wood and steel etc. Some modern material including those mentioned above can be used to mitigate the damage of the fragments, too. The effects of woven fabrics to resist the low velocity fragments were studied by Simons et al [7]. A lightweight fragment barrier for commercial aircraft was presented by Shockey et al [8].

For the protection problem against the low velocity fragments, we conceived a structure made of interlaced double t steel, a common industry product. The structure can be made easily. In order to evaluate the structure’s possibility and effect to resist the low velocity fragments, we calculated the interaction processes and effects between the structure and the fragments with different velocity and mass using LS-DYNA software. The results show that the structure can effectively prevent fragments with different velocity and mass from penetrating and perforating.

2 Physical model

2.1 Protection structure

For simplicity, the double t steel was selected from common industry products in China (Sun [9]). The type we selected in this paper is 20b, which originated from Chinese national standard GB706-88. The shape of the double t steel and the
structure are illustrated in figure 1. The spacing between each double t steel in the structure is distributed averagely, which was determined mainly from the convenience of the future practical operation like welding and producing of the structure. Another consideration is that the average space can allow every part of the double t steel to make sufficient strain to consume energy.

![Figure 1: The shape of the double t steel and the fragment protection structure (unit: cm).](image)

2.2 Fragments mass

The fragments mass distribution of explosively loaded devices has been the focus of investigations for many years. But it is difficult to estimate the fragments mass distribution for the above instances producing low velocity fragments. In this paper, we just want to evaluate the performance of the structure to resist the fragments. So the fragments were assumed as steel and their mass were determined mainly from the structure itself and from a more dangerous point.

From figure 1, we can see that the weakest route is an oblique route showed between two parallel slanting lines. Because only two steel plates can take effect to resist the fragment in that route, whereas there are at least four steel plates to resist the fragments in other directions. According to the width between the two lines and assuming the fragment is a steel sphere, we can get the fragment mass is about 540g. The lightest mass of the fragment in simulation in this paper is 300 g. The heaviest fragment mass we chosen is 23 kg, a hazardous case.

2.3 Fragments shape

From the point of penetration, the projectiles of long rod or with a large length-diameter ratio have stronger penetration ability. But the fragments produced by explosion have anomalistic shape in the practical situation. Hence, the fragment shape we adopted in this simulation is a regular cuboid, which has smaller thickness in one direction. This is convenient for our calculations.
2.4 Material model

The computational simulations use LS-DYNA software, a finite element code for analysing the large deformation dynamic response of structures. LS-DYNA uses explicit time integration as the main solution procedure.

We used the Johnson-Cook plasticity model for strain and temperature sensitive plasticity Hallquist [10]. It is particularly useful for problems where the strain rates vary over a wide range. It also models material softening caused by adiabatic temperature increases due to plastic heating. The flow stress is expressed as

\[
\sigma_y = \left[ A + B \left( \bar{\varepsilon}^p \right)^n \right] \left[ 1 + c \ln \dot{\varepsilon}^* \right] \left[ 1 - \left( T^* \right)^m \right],
\]

where \(A, B, C, n,\) and \(m\) are user-defined input parameters; \(\bar{\varepsilon}^p\) is effective plastic strain; \(\dot{\varepsilon}^*\) denotes effective plastic strain rate for \(\dot{\varepsilon}_0 = 1\) s\(^{-1}\), and

\[T^* = \frac{T - T_{room}}{T_{melt} - T_{room}}.\]

The strain at fracture is given by

\[
\varepsilon^f = \left[ D_1 + D_2 \exp D_3 \sigma^* \right] \left[ 1 + D_4 \ln \varepsilon^* \right] \left[ 1 + D_5 T^* \right],
\]

where \(D_1, D_2, D_3, D_4,\) and \(D_5\) are input parameters; \(\sigma^*\) is the ratio of pressure to effective stress:

\[\sigma^* = \frac{P}{\sigma_{eff}}.\]

Fracture occurs when a damage parameter

\[D = \sum \frac{\Delta \bar{\varepsilon}^p}{\varepsilon^f}\]

reaches the value of 1.

Several spall options are available with this material model. We have applied these spall options, and found the simulation results were wrong, for the spalled material behaved like rubble and expanded continuously. We neglected the spall option in this simulation by setting the limiting value \(P_c\) as a large value. This is a dangerous condition for the fragment protection structure.

The Johnson-Cook model also requires an equation of state definition (EOS) for each material. The Gruneisen equation of state was used in this simulation. It defines pressure for compressed materials as:
\[ p = \frac{\rho_0 C^2 \mu \left[ 1 + \left( 1 - \frac{\gamma_0}{2} \right) \mu - \frac{a}{2} \mu^2 \right]}{\left[ 1 - (S_1 - 1) \mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2} \right]^2} + (\gamma_0 + a\mu)E', \]

and for expanded materials as

\[ p = \rho_0 C^2 \mu + (\gamma_0 + a\mu)E', \]

where \( C \) is the intercept of the cubic shock velocity and particle velocity \( (v_s-v_p) \) curve; \( S_1, S_2, \) and \( S_3 \) are the coefficients of the slope of the \( v_s-v_p \) curve; \( \gamma_0 \) is the Gruneisen gamma; \( a \) is the first order volume correction to \( \gamma_0 \); \( \mu = \rho/\rho_0 - 1 \).

### 2.5 Model parameters

The parameters in the model are listed in table 1. In order to prove whether the parameters are suitable for simulation, we performed a calculation according as a field experiment. In that experiment, a copper projectile with mass 690g and velocity 2.2km/s impacted on a steel target with 9cm thickness. When the copper projectile penetrated the steel plate, its remanent velocity is about 100m/s. Figure 2 illustrates the velocity course of the copper projectile and the computational impact vision at different time. It can be seen that the simulation result is consistent with experimental result approximately. This indicates the parameters of the model can be used in computational simulation.
Table 1: The parameters of steel in the model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>7.84</td>
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<tr>
<td>Elastic Modulus (GPa)</td>
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</tr>
<tr>
<td>Shear Modulus (GPa)</td>
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<tr>
<td>Poisson’s Ratio</td>
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<tr>
<td>Melt Temp. (K)</td>
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<tr>
<td>Johnson-Cook Strength Model Parameters</td>
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<tr>
<td>$A$ (GPa)</td>
<td>0.793</td>
</tr>
<tr>
<td>$B$ (GPa)</td>
<td>0.510</td>
</tr>
<tr>
<td>$n$</td>
<td>0.26</td>
</tr>
<tr>
<td>$C$</td>
<td>0.014</td>
</tr>
<tr>
<td>$m$</td>
<td>1.03</td>
</tr>
<tr>
<td>$P_c$ (GPa)</td>
<td>900</td>
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<tr>
<td>Johnson-Cook Fracture Model Parameters</td>
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<tr>
<td>$D_1$</td>
<td>0.20</td>
</tr>
<tr>
<td>$D_2$</td>
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</tr>
<tr>
<td>$D_3$</td>
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</tr>
<tr>
<td>$D_4$</td>
<td>0.0</td>
</tr>
<tr>
<td>$D_5$</td>
<td>0.0</td>
</tr>
<tr>
<td>Gruneisen Equation of State</td>
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<tr>
<td>$C_0$ (m/s)</td>
<td>4578</td>
</tr>
<tr>
<td>$S_1$</td>
<td>1.33</td>
</tr>
<tr>
<td>$S_2$</td>
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<tr>
<td>$\gamma_0$</td>
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<tr>
<td>$a$</td>
<td>0.43</td>
</tr>
</tbody>
</table>

3 Results

We carried out five-set calculations. The first calculation is that the fragment has mass 23kg and velocity 30 m/s, which corresponds with the heaviest fragment in our calculation. The second one is that the fragment with mass 300g and velocity 100 m/s impacts on the structure along the route shown in figure 1. This corresponds with the lightest fragment. The third calculation is the same as the second one, but the fragment mass is 600g. The fourth one is a dangerous instance in which the fragment with mass 2.5kg and velocity 100m/s impacts on the structure perpendicularly. The fifth calculation is similar to the fourth one in which the only difference is that the incident angle of the fragment is 60 degrees.

![Figure 3: The calculation results at different time for perpendicular impact of a fragment with mass 23kg, velocity 30m/s.](image)

![Figure 4: The calculation results at different time for oblique impact of a fragment with mass 300g, velocity 100m/s.](image)
Figures 5 to 7 illustrate the simulation results for the above five calculations. For the oblique impact showed in figure 4, figure 5 and figure 7, the fragment overturns because of its horizontal velocity and the collision with the structure. The perpendicular impact in figure 3 and figure 6 do not have this phenomenon.

Figure 8 illustrates the resultant velocity course for three fragments. The declined segment in the curve corresponds to the impact course between the fragment and structure. The ascended segment represents the rebound of the fragment in the course of collision. The horizontal line describes the movement of the fragment after the rebound. It can be found that the velocities of these fragments have decreased to a small value at last. This shows the protection structure prevents fragments from perforating effectively.
4 Discussion

The structure is equivalent to multi-layer steel plate because every part of the structure is a steel plate. This has more effectiveness than single layer steel plate with equal thickness in resisting the fragments. Moreover, the assembled form of these plates can hold back the fragments with different incident angles easily. The new fragments produced by the impact of the initial fragment on the structure can be captured easily, too.

It can be found from the simulations that two or three double t steel of the protection structure can hold up the fragments with little mass, high velocity, and different incident angle. Many double t steel of the structure take effect and block the large fragment with low velocity. This shows the protection structure in this paper can resist the low velocity fragment effectively. But whether the structure can also resist the high velocity fragment or projectile effectively deserves farther investigation. Again, the configuration of each double t steel in this structure is not the best one. Furthermore, some other industry products like slot steel, angle iron, steel tube, and so on, may also construct a structure to play a special role in some situations.

Another primary hazardous factor produced by explosion is blast overpressure besides the fragments. Because of the big space between the double t steel in this structure, the structure can’t stop the continued propagation of the blast through itself. But as results of reflection, rarefaction, and diffraction of the blast through the structure, in which the propagating route of the blast have many corners, blast overpressure will be attenuated. The attenuation efficiency for the blast with different overpressure and positive duration time should be different. This can be investigated in the future.
5 Conclusion

According to the results of computational simulation and analyses, we can conclude the followings:

(1) the protection structure in this paper can effectively prevent fragments having relatively heavy mass and low velocity from perforating;

(2) computational simulation is a useful tool in evaluating the feasibility of a structure and predicting the effects and behaviour of impact and collision;

(3) the protection structure against a peculiar danger can be constructed using some common industrial products.

References