Simulation Study on the Deflection Response of the 921A Steel thin plate under Explosive Impact Load

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Abstract. The Ship cabin would be subject to high-intensity shock wave load when it is attacked by anti-ship weapons, causing its side board damaged. The time course of the deflection of the thin plate made of 921A steel in different initial conditions under the impact load is researched by theoretical analysis and numerical simulation. According to the theory of elastic-plastic deformation of the thin plate, the dynamic response equation of the thin plate under the explosion impact load is established with the method of energy, and the theoretical calculation value is compared with the result from the simulation method. It proved that the theoretical calculation method has better reliability and accuracy in different boundary size.

1. Introduction

In the modern defence system of combat platform in marine, the surface ships have become vital roles [1]. With the improvement of anti-ship missile guidance technology, the threat of large surface ships is increasing. The passive protection structure which is the last line of defence of a large surface ship is the key to the design of the ship's anti-explosive structure. Most of the ship's side panels mainly use 921A steel materials. Also, 921A steel is China's own research and development of ship materials, which is high-strength as well as weldable structural steel and suitable for the manufacture of shells, containers, pipes and military machinery.

The dynamic response of the sheet under the impact of the explosive load begins with the thin circular plate. Wierzbiki and Florence[2] have carried on the experimental research and the theoretical research to the solid plate with shock wave effect including the strain rate effect. To quantitatively predict the plastic deformation of the plate under the impact of the impact load, Rajendran [3] proposed an empirical method for the prediction of plastic centre deflection in air under single DOF (SDOF). Hu Jiang-Yi [4] and so on using the RAVS method to approximate the fluid-structure interaction and to predict the transient motion of the double-layer cylindrical shell under the impact of detonation waves. Kong Xiang-Shao [5] et al. studied the effect of bulkhead opening on the cabin and the failure of the cabin under the impact of shock wave pressure by using the general fast coupling algorithm in the multi-Euler field. Zheng Cheng [6] et al. studied the elastic-plastic response of rectangular plates under explosive loading by the elastic-plastic method, and carried out the explosion response test of thin plates of different thickness.

WANG Fang [7] et al. had conducted theoretical analysis and experimental study on the large deformation response of the four-side constrained square target plate under the impact of blast shock. The relationship between the deformation deflection of the thin plate and the impact load is given

according to the similarity of Hopkinson explosion in consideration of the influence of the boundary of the plate.

Richard Villavicencio [8] et al. studied that the boundary slip has obviously affected the deformation of the laterally supported beam subjected to the impact load. The plastic deformation of the thin plate with both ends under the impact load is studied by numerical deformation method.

In this paper, AUTODYN software is used to simulate the deformation and damage of the thin plate made of 921A steel under the impact load with the action of three-dimensional multi-Euler domain fluid-solid coupling algorithm.

2. 921A steel material tests

As a sort of ship material in the naval vessels, 921A steel has a wide range of applications. The use of the ship in the process will certainly be affected by the impact of various effects, so the study of the dynamic load of the ship has important significance for its improving ship reliability, and these studies require dynamic performance data of the material, such as material stress-strain relationship [9].

Fig 1. MTS material static mechanical performance testing machine

The mechanical properties of 921A steel were tested by MTS material testing machine (Fig. 1) and SHPB experimental device. Then The Johnson-Cook model parameters were obtained. The material parameters of the specimen are based on the experimental J-C model parameters. The specific parameters of the J-C model are as follows:

$$\sigma = (537 + 2981\varepsilon^{1.255})(1 + 0.0063\ln \dot{\varepsilon}^{*})\left[1 - (T_f)^{1.52}\right] \qquad (1)$$

Which provides a basis for the next study of the response of the ship under dynamic loads. Part of the data by material tests are shown in Table 1.

Tab 1. Part of the parameters of 921A steel

Density	Elastic Modulus	Poisson's ratio	Shear Modulus	Elastic wave velocity	Shear wave velocity	Volume Modulus
4.5g/cm3	113Gpa	0.33	43Gpa	5000m/s	3100m/s	110Gpa

3. Theoretical analysis

For a thin plate with a geometric dimension $2a \times 2b \times \delta$, the displacement equation of the thin plate can be given according to the actual deformation shape of the thin plate under the action of the shock wave:

$$
\left.\begin{array}{l}
w_x = w_{x0} \sin \dfrac{\pi x}{2a} \cos \dfrac{\pi y}{2b} \\[3mm]
w_y = w_{y0} \cos \dfrac{\pi x}{2a} \sin \dfrac{\pi y}{2b} \\[3mm]
w_z = w_{z0} \cos \dfrac{\pi x}{2a} \cos \dfrac{\pi y}{2b}
\end{array}\right\}
\tag{2}
$$

Where w_x、 w_y and w_z are the deflections in the x、 y and z directions, respectively; w_{x0} and w_{y0} are the maximum deflection in the x and y directions, respectively; w_{z0} is the deflection of the centre point of the plate in the z direction.

Under the action of an explosive shock load, the thin plates that are constrained around will form a large deflection plastic deformation (far greater than the thickness) in extreme times, and a distinct plastic hinge will form at the boundary. When the thin plate deforms after a large deflection, the total potential energy of the thin plate includes: the elastic and plastic bending deformation energy of the plate U_b, the middle of the strain energy U_m (caused by the mask force) and the four sides of the fixed boundary of the plastic hinge bending deformation energy U_l.

The bending deformation energy U_b can be calculated as follows:

$$
U_b = \frac{E\delta^3}{24\left(1-\upsilon^2\right)} \int_0^a \int_0^b \left[\left(\frac{\partial^2 w_z}{\partial x^2}\right)^2 + \left(\frac{\partial^2 w_z}{\partial y^2}\right)^2 + 2\upsilon \frac{\partial^2 w_z}{\partial x^2}\frac{\partial^2 w_z}{\partial y^2} + 2\left(1-\upsilon\right)\left(\frac{\partial^2 w_z}{\partial x \partial y}\right)^2 \right] dxdy
\tag{3}
$$

On the of elastic deformation case, the middle strain energy U_{me} can be calculated as follows:

$$
U_{me} = \frac{E\delta}{2\left(1-\upsilon^2\right)} \int_0^a \int_0^b \left[\varepsilon_x^2 + 2\upsilon\varepsilon_x\varepsilon_y + \varepsilon_y^2 + \frac{1}{2}\left(1-\upsilon\right)\gamma_{xy}^2 \right] dxdy
\tag{4}
$$

The above equation is only applicable to the calculation of the midline strain energy of the plate during the line elastic response stage.

When the thin plate enters the plastic response stage from the elastic stage, the corresponding strain value $\varepsilon > \varepsilon_p$. During the plastic deformation process, the middle strain energy U_{mp} can be calculated as follows:

$$
U_{mp} = \int_0^a \int_0^b \int_0^\delta \left[\sigma_0\left(\varepsilon_x + \varepsilon_y\right) + \tau_p\gamma_{xy} - \sigma_0\varepsilon_p - \frac{1}{2}\tau_p\gamma_p \right] dxdy
\tag{5}
$$

The bending deformation energy of the plastic strands at the fixed edges of the four sides can be calculated by:

$$
U_1 = \int_0^b M_p\theta_1 dy + \int_0^a M_p\theta_2 dx
\tag{6}
$$

In the above equation, U_l is the rotational plasticity of the boundary plastic hinge; θ_l, θ_2 are the rotational angles of the two boundary regions respectively; M_p is the plastic bending moment of the unit length plate, and

$$
M_p = 2\int_0^{\frac{\pi}{2}} \sigma_0 z dz = \frac{1}{4}\sigma_0\delta^2
\tag{7}
$$

Where σ_0 is the yield stress of the material, and

$$
\left\{
\begin{array}{l}
\theta_1 = \left.\dfrac{\partial w_z}{\partial x}\right|_{x=a} = w_{z0}\dfrac{\pi}{2a}\cos\dfrac{\pi y}{2b} \\[4mm]
\theta_2 = \left.\dfrac{\partial w_z}{\partial y}\right|_{y=b} = w_{z0}\dfrac{\pi}{2b}\cos\dfrac{\pi x}{2a}
\end{array}
\right.
\tag{8}
$$

The effect of the blast wave on the thin plate is closely related to the time t_m. For the thin plate, if t_m is much smaller than the vibration period T, the damage of the thin plate caused by shock wave depends mainly on its impulse I. Therefore, the initial kinetic energy of the thin plate can be solved by the momentum theorem.

Thus the initial kinetic energy of the thin plate can be described as:

$$W = \int_0^a \int_0^b d\left(\frac{1}{2} m_i V_0^2 \right)$$

(9)

Where m_i is the mass per unit area of the thin plate, $m_i = \rho h$; ρ is the mass density of the thin plate.

It can be seen from the reference [10] that the action time of the shock wave is much smaller than the characteristic period of the structural response, and its action can be regard as an impulse. Therefore, the initial kinetic energy of the plate can be obtained by the momentum theorem, which is [10].

$$W = \frac{8 X Y A_i^2}{\rho \delta H^2} \cdot m_{ef}^{4/3}$$

(10)

According to the energy conservation theorem, when the initial kinetic energy is all converted into the potential energy of the thin plate, the thin plate reaches its maximum deformation. At that time there are

$$W = U_b + U_m + U_1$$

(11)

Bringing the above variables into the energy equation, it can be

$$\frac{\pi^4 (1-2\upsilon) E \delta^3}{384 (1-\upsilon^2)} \cdot \frac{w_{z0}^2}{a^2} + \frac{\pi^4 E \delta}{4096 (1-\upsilon^2)} \cdot \frac{w_{z0}^4}{a^2} + \frac{\left(4\sqrt{3} + 3\pi^2\right) \delta \sigma_0}{48} \cdot w_{z0}^2 - \frac{(4+\upsilon)\delta\sigma_0^2}{3E} \cdot a^2$$

$$+ \frac{4\sigma_0\delta^2}{\sqrt{3}} w_{z0} - \frac{8 A_i^2 m_e^{4/3}}{\rho \delta H^2} \cdot a^2 = 0$$

(12)

To obtain the centre of the thin plate deflection w_{z0} when the specific boundary size of the thin plate is a, the numerical solution of the above nonlinear equations is calculated by using the Newton method on the MATLAB software.

4. Numerical Simulation

In order to verify the characteristics of 921A steel material under the impact wave, five simulation models are established, where the boundary size of the plate is 500 mm × 500 mm and the thickness of the plate as well as other parameters are shown in Table 2. As the thin plate is a thin-walled structure, its thickness direction size is much smaller than the other two directions, therefore using the standard Lagrange algorithm or Euler algorithm would result in a small time step. Assuming that there is no wave propagation and zero strain in the thickness direction, and no shear and rotational moments are transmitted, so the thin plate structure is modeled with Shell unit. To optimize the calculation process and shorten the calculation time, establish the 1/4 finite element calculation model to calculate.
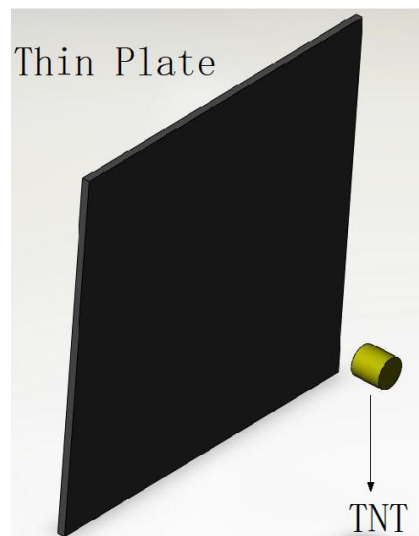
Fig 2. Simulation calculation model

Tab 2. Parameters of simulation study

Numbering	Charge Quantity (TNT/g)	Thickness of thin plate (mm)	Detonation Distance (m)
1	700	1	0.98
2	708	1	0.80
3	700	2	0.47
4	1108	1	1.33
5	1078	2	0.95

921A steel thin plates are used in these calculations. Taking into account the material as a strain rate sensitive material, the Johnson-Cook strength model is adopted, which is a viscoplastic constitutive relationship constitutive model. Using the equivalent stress of Von Mises, which is related to equivalent plastic strain, the equivalent plastic strain rate and the temperature of the material, thus determine its dynamic yield stress, namely:

$$\sigma_d = \left(M + N \times \varepsilon^\beta \right) \cdot \left(1 + c \times \ln \dot{\varepsilon}^* \right) \cdot \left(1 - T_f^\alpha \right) \tag{13}$$

Among them, σ_d is the dynamic yield stress, M is the static yield stress, N and β are both material hardening coefficients. c is the strain rate enhancement parameter, α is the material thermal softening parameters, ε^* is the plastic strain rate, T_f is the dimensionless temperature, furthermore:

$$T_f = \left(T - T_r \right) \big/ \left(T_m - T \right) \tag{14}$$

Among them, T is the ambient temperature, T_r is the room temperature, T_m is the melting point for the material.

Figure 3 shows the deflection process of the thin plate under the impact of the shock wave, and the numerical results are shown in Table 3.
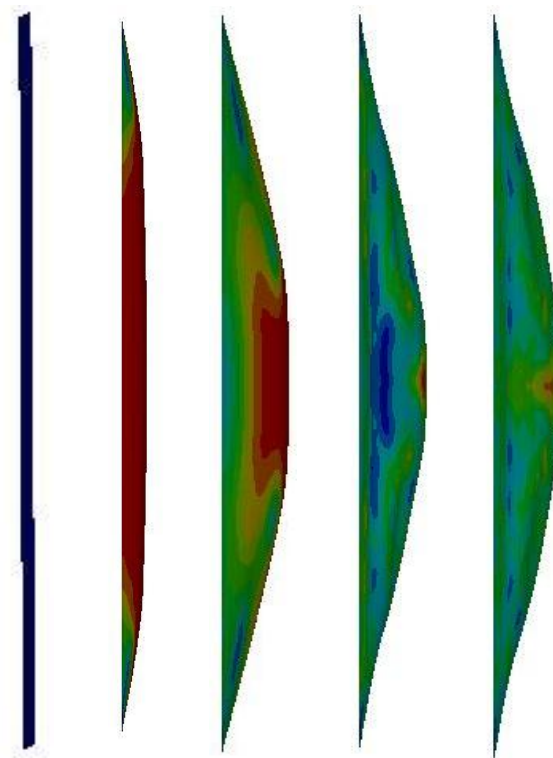
(a)t=0ms (b)t=1ms (c)t=1.5ms (d)t=2ms (e)t=5ms
Fig 3. Process of deflection of the thin plate under the impact

Tab 3. Comparison of simulation values and theoretical values

Number	Simulation Values/mm	Theoretical Values/mm	Relative Deviation
1	48.0	40.8	4.8%
2	53.0	52.0	1.8%
3	49.2	55.8	11.8%
4	50.5	44.6	11.6%
5	42.7	36.8	13.8%

Considering that the actual load on the thin plate is the reflected shock wave load, it is assumed that the reflection coefficient of the reflectance impulse is similar to the reflection coefficient of the overpressure over a certain range. Taking into account the effect of the weight of the charge on the deflection of the thin plate, that is, under the same specific impulse effect, the more weight of the charge, the more deformation of the thin plate under the impact of the shock wave. So according to the Hopkinson explosion similarity rate, the relationship between the deformation deflection of the thin plate and the impact load should be corrected by considering the influence of the weight of the charge.

Comparing the theoretical calculation values with the simulation results, it can be seen that the relative deviation of the five groups is less than 15%. It can be seen that the fluid-solid coupling algorithm used in this paper has good reliability and accuracy. The main reason for the error is that the strain rate effect of the material is not considered in the theoretical calculation. The 921A steel is a kind of strain rate sensitive material, so the numerical deformation values are less than the theoretical calculation values.

5. Conclusion
According to the above numerical simulation results compared with the theoretical calculation, it is verified that the simulation method has good accuracy and reliability. Through the numerical simulation analysis of the response of the thin plate under the impact of the shock wave load under different initial conditions, the following conclusions are obtained:

921 steel thin plate will produce elastic deformation under the impact of explosive shock wave load. The 921A steel material parameters measured by the material test are used to simulate the numerical simulation of the thin plate under the impact shock wave load, and it can coincide with the deflection deformation value calculated by the energy method, which proved that the fluid-solid coupling algorithm could effectively simulate the response of 921A steel thin plate under the impact shock wave load.

Acknowledgments

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