Numerical simulation on truncated oval-nosed projectile penetrating into stiffened plate

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Abstract: [Objectives] In this paper, the numerical simulation method is used to study the anti-penetration performance and energy absorption mode of a stiffened plate, as well as the influence of different stiffened bars on the flight attitude of the projectile body. [Methods] Finite element software LS-DYNA is used to simulate the process of a truncated oval-nosed projectile penetrating a stiffened plate, and the results of the numerical simulation are compared with an experiment to verify the reliability of the numerical simulation method. The momentum method and mass equivalence method are used to predict the residual velocity of the projectile, and the applicability of different theoretical methods within different velocity ranges is compared. The deformation energy of different regions of the stiffened plate is then extracted to analyze the influence of the initial velocity of the projectile body on the energy absorption mode of the target plate. Finally, the structure of the stiffeners is changed and the influence of the relative position of the stiffeners on the penetration attitude of the projectile body is analyzed. [Results] The results show that the mass equivalence method is more accurate than the momentum method in predicting the residual velocity of the stiffened plate when the initial velocity of the projectile body is in the range of 300–900 m/s. The ratio of the deformation energy of the stiffened plate to the energy loss of the projectile body decreases with the increase of the initial velocity of the projectile body. The effect of a T-stiffened plate on trajectory is greater than that of a rectangular-stiffened plate. [Conclusions] The related calculation method and research results have certain reference value for research and engineering application surrounding the anti-penetration of stiffened plates.

Key words: oval-nosed projectile; penetration; stiffened plate; numerical simulation

0 Introduction

Stiffened plates are a basic structure of a surface warship [1], and the process of a semi-armor-piercing warhead penetrating the warship with its initial kinetic energy is the action process of a large-mass projectile penetrating stiffened plates. Therefore, investigating the mechanical process of a large-mass projectile penetrating stiffened plates is of great significance for the protection and damage assessment of warships.

The penetration of stiffened plates by a large-mass projectile has rarely been reported so far. Duan et al. [2-3] carried out a series of experiments on a truncated oval-nosed projectile penetrating stiffened plates under different initial conditions and calculated the residual velocity of the projectile by the equivalent mass method. Zhan et al. [4] predicted the residual velocity of a simplified truncated oval-nosed projectile penetrating a stiffened plate model by the momentum method. Wang et al. [5] predicted the residual velocity of a truncated conical projectile penetrating stiffened plates by the energy method. Liu et al. [6] examined the influence of the material parameters and plate thickness of stiffened plates on the residual velocity...
of the projectile by numerical simulation. Kong et al. [7] further studied the influence of the relevant geometric parameters of the stiffeners on the energy absorption mode of the target plates by numerical calculation. In the above research, the initial velocity of the large-mass projectile was mostly around 600 m/s. Given that the current velocity of anti-ship missiles generally falls into 300–900 m/s [8], the conclusions drawn from the above research may not be readily applicable to the full velocity range. Moreover, the above studies mostly focused on a single type of stiffened plates, failing to explore the influence of stiffened structures in different shapes at different impact points on the trajectory.

In this study, the nonlinear finite-element software LS-DYNA will be used to numerically simulate the penetration of a stiffened plate by a large-mass truncated oval-nosed projectile in the range of the projectile velocity. Then, the applicability of different theoretical prediction equations for the residual velocity of the projectile after penetration will be compared, and the relationship between the energy absorption mode of the target plate and the initial velocity of the projectile will be examined. Finally, the influences of two types of stiffening on the penetration trajectory of the projectile will be compared by changing the relative position relationship between the impact point and the stiffeners.

1 Numerical simulation of projectile penetrating stiffened plates

1.1 Geometric model of projectile and target

In this study, numerical simulation is carried out with the projectile and target in Refs. [2-3] as the research objects. The structures, sizes, and materials of the projectile and the target are consistent with those in the experiment. The target plate material is 921A steel, and the projectile material is 35CrMnSiNi2A. The targets in the experiment and simulation have a stiffened plate structure, and their geometric parameters are as follows: The thickness of the homogeneous plates is 16 mm; the vertical rectangular stiffeners are 68 mm in height and 15.2 mm in thickness; the horizontal rectangular stiffeners are 26 mm in height and 7 mm in thickness; the truncated oval-nosed projectile has a length of 370 mm, a diameter of 105 mm, and a weight of 16.185 kg. The relevant geometric parameters of the projectile and the target are shown in Fig. 1.

![Geometric diagram of projectile and target](image)

Fig. 1 Geometric diagram of projectile and target

1.2 Material parameters

Since the projectile basically does not deform during penetration [2], the projectile is assumed to be a rigid body. The Johnson-Cook equation is adopted to serve as the dynamic constitutive equation of the target plate material, and its mathematical expression is

\[ \sigma = (A + B\varepsilon^p)(1 + \ln\dot{\varepsilon}^*)(1 - T^m) \]

where \( \sigma \) is the flow stress; \( A \) is the initial yield stress under the reference strain rate and reference temperature; \( B \) and \( n \) are the strain-hardening modulus and coefficient of the material, respectively; \( m \) is the thermal softening coefficient of the material; \( \varepsilon_{eq} \) is the equivalent plastic strain; \( \dot{\varepsilon}^* = \varepsilon_{eq}/\varepsilon_0 \) is the dimensionless strain rate, with \( \varepsilon_0 \) being the reference strain rate; \( T^* = (T - T_r)/(T_m - T_r) \) is the dimensionless temperature, with \( T_r \) being the reference temperature and \( T_m \) being the melting temperature; \( c \) is the strengthening parameter of the strain rate of the material.

The parameters of the materials 921A steel and
35CrMnSiNi2A \cite{9} are listed in Table 1. In the numerical simulation, the failure strain of the material is closely related to the mesh size \cite{10}. For the mesh division in this study, the failure strain $\varepsilon_{\text{eff}}$ of 921A is set to 0.8.

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Material 921A</th>
<th>Material 35CrMnSiNi2A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho/($kg$\cdot$m$^{-3})$</td>
<td>7800</td>
<td>7850</td>
</tr>
<tr>
<td>Young’s modulus $E/$(GPa)</td>
<td>206</td>
<td>210</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>$T_i$/K</td>
<td>298</td>
<td>–</td>
</tr>
<tr>
<td>$T_m$/K</td>
<td>1763.5</td>
<td>–</td>
</tr>
<tr>
<td>$\alpha$/MPa</td>
<td>685</td>
<td>–</td>
</tr>
<tr>
<td>$B$/MPa</td>
<td>810.32</td>
<td>–</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.782</td>
<td>–</td>
</tr>
<tr>
<td>$c$</td>
<td>0.0483</td>
<td>–</td>
</tr>
<tr>
<td>$m_0$</td>
<td>1.05</td>
<td>–</td>
</tr>
</tbody>
</table>

1.3 Finite element model

In the preprocessing software LS-DYNA, the projectile and the target are modeled by employing the Solid 164 unit and the Lagrange algorithm. The meshes in the area in contact with the projectile are densified, and the side length of the squares in the densified area is twice the diameter of the projectile. The meshes are structured meshes, and the mesh size in the densified area is 3 mm. The contact mode between the projectile and the target plate is single-surface erosion contact. The four sides of the target plate are fixed for restriction, and the initial position of the projectile is 34 mm away from the target plate. The finite-element model of the projectile penetrating the target plate is shown in Figs. 2–3.

![Fig. 2 Sectional view of projectile and target model](image)

1.4 Comparative analysis of numerical simulation and experimental results

The LS-DYNA solver is used to numerically simulate the two working conditions of the truncated oval-nosed projectile vertically penetrating the homogeneous plate (experiment 2 in Ref. [3]) and the stiffened plate (experiment 1 in Ref. [2]). The curves of the projectile velocity vs. time are shown in Fig. 4.

![Fig. 4 Time-history curves of projectile velocity](image)

The residual velocity and perforation size of the projectile obtained by numerical simulation are compared with the experimental data, as shown in Table 2. According to Table 2, the maximum deviation of the residual velocity of the projectile obtained by numerical simulation from the experimental value under different working conditions is within 2%. The diameter of the perforated hole measured by the experiment under both working conditions is about 115 mm, and the difference between the diameter in the simulation and that in the experiment is small.

The perforation and damage conditions of the target plate in the simulation and experiment [2-3]

<table>
<thead>
<tr>
<th>Working condition</th>
<th>Form of target plate</th>
<th>Impact point (attitude)/mm</th>
<th>Initial velocity $(m\cdot s^{-1})$</th>
<th>Residual velocity (simulated value) $(m\cdot s^{-1})$</th>
<th>Residual velocity (experimental value) $(m\cdot s^{-1})$</th>
<th>Deviation $%$</th>
<th>Crater diameter/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Homogeneous plate</td>
<td>(Vertical)</td>
<td>607.0</td>
<td>580.5</td>
<td>584.9</td>
<td>0.75</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>2 Stiffened plate</td>
<td>0 from the vertical stiffener, and 31 from the horizontal stiffener (vertical)</td>
<td>617.7</td>
<td>563.9</td>
<td>574.9</td>
<td>1.90</td>
<td>112</td>
<td></td>
</tr>
</tbody>
</table>
under Working Conditions 1 and 2 are presented in Fig. 5.

According to Fig. 5, the perforation and damage conditions of the target plates in the experiment and simulation are basically the same. The main difference is that in Working Condition 2, the vertical stiffener near the crater on the target plate undergoes marked bending deformation but is not completely detached from the target plate in the simulation while the vertical stiffener near the crater on the target plate is detached from the target plate in the experiment.

The residual velocity of the projectile and the diameter of the perforated hole on the target plate obtained by simulation differ from the experimental values in Working Condition 2. This difference may be attributed to the following reason: The stiffened plate is regarded as an ideal entity in the numerical simulation. In contrast, the stiffeners are welded on the plate in the actual processing, and the processing of the target plate in the experiment thus may have welding defects. The comprehensive comparison of the residual velocity of the projectile and the perforation and damage mode of the target plate in the simulation and the experiment reveals that the simulation results are reliable to a certain extent.

1.5 Process analysis of projectile penetrating stiffened plate

On the basis of the above numerical simulation results, the changes in the energy of the plate and the penetrated vertical and horizontal stiffeners in each stage of the process of the projectile penetrating the stiffened plate are extracted (Fig. 6).

According to the Von Mises stress contours of the simulation results and the energy change curve of the stiffened plate, the process of the truncated oval-nosed projectile penetrating the stiffened plate can be divided into four stages, as shown in Fig. 7.

Stage 1 involves the contact between the projectile and the target, and the part of the plate in the contact area undergoes plastic deformation. As the projectile moves forward, the part where the truncated oval-nosed warhead comes into contact with the target witnesses initial perforation, and the stress wave mainly propagates along the radial direction of the plate and the height direction of the stiffener. This stage corresponds to sections Ⅵ to Ⅵ in Fig. 6. In this stage, the energy absorption of the plate and the deformation energy of the vertical stiffener caused by the vertical compression account for the main part of the energy absorption of the stiffened plate.

In Stage 2, the projectile begins to penetrate the vertical stiffener, and reaming occurs simultaneously in the areas where the plate and the vertical stiffener come into contact with the projectile. The vertical stiffener undergoes large overall plastic deformation. This stage corresponds to sections Ⅱ to Ⅲ in Fig. 6. In this stage, the kinetic energy of the vertical stiffener increases significantly due to its direct contact with the
Stage 3 involves the contact between the projectile and the horizontal stiffener. In addition to plastic deformation in the height direction, the horizontal stiffener also bends significantly along the thickness direction in this stage. As the penetration continues, stress concentration and shear and tear failure of the horizontal stiffener and the vertical stiffener in the contact area can be observed. This stage corresponds to sections III to VI in Fig. 6. In this stage, the energy absorption of the horizontal stiffener increases significantly, but its proportion in the total energy absorption of the stiffened plate is small. In addition, the reaming of the stiffened plate is salient in this stage, and each structure in the stiffened plate obtains high kinetic energy during the blooming of the petals.

In Stage 4, the projectile penetrates the vertical stiffener until the end of the reaming, and the diameter of the plate gradually expands to the crater diameter. This stage corresponds to sections IV to V in Fig. 6. In this stage, the kinetic energy of each structure in the stiffened plate gradually decreases as the reaming effect weakens. The remaining part of the projectile further comes out of the crater in sections V–VI. Because the crater diameter is slightly larger than the diameter of the projectile, the projectile is less affected by the target in this process. The deformation energy of the plate increases slightly due to the conversion of the residual kinetic energy of the plate.

2 Analysis of theoretical prediction method for residual velocity of projectile penetrating stiffened plate

The momentum method and the equivalent mass method are the main methods currently available for theoretically predicting the residual velocity of the projectile penetrating the stiffened plate.

2.1 Momentum method

The momentum method⁴ assumes that the projectile is rigid and ignores the strength effect of the target plate. The mass in the case of the truncated oval-nosed projectile penetrating the target plate is divided into the plug mass produced at the blunt head and the equivalent mass of the petal produced by reaming.

Following the above assumptions, the momentum conservation relationship in the case of the truncated oval-nosed projectile penetrating the stiffened plate can be expressed as

$$mv_0 = mv + km_v v_0 + p(x)$$  \(2\)

where \(m\) is the mass of the projectile, \(v_0\) is the initial
velocity of the projectile; \( v \) is the projectile velocity when the warhead penetrates the point \( x \) in the target plate; \( k \) is the experimental coefficient of the plug, whose size is related to the initial velocity of the projectile and the thickness of the target plate, and it is set to 1.8 in this paper; \( m_0 \) is the plug mass; \( p(x) \) is the momentum of the petal generated when the warhead penetrates the point \( x \) in the target plate; \( x \) is the distance in the target plate the warhead penetrates.

If the difference between the initial velocity and the residual velocity of the projectile is small, Eq. (2) can be simplified as\
\[
\Delta v = v_0 - v = \frac{km_0 + m_1(x)}{m}v_0
\]
where \( m_1(x) = p(x)/v \) is the equivalent mass of the petal formed when the warhead penetrates point \( x \) in the target plate.

According to Fig. 6, the kinetic energy of the stiffened plate increases first and then decreases over time. When the overall momentum of the petal is maximum \(^4\), the projectile is detached from the petal, and the velocity change of the projectile at this time is the largest. On this basis, the residual velocity of the projectile can be obtained as\
\[
v_r = v_0 - \Delta v = v_0 - \frac{km_0 + m_1(x_{\text{max}})}{m}v_0
\]
where \( v_r \) is the residual velocity of the projectile; \( x_{\text{max}} \) is the distance that the warhead penetrates the target plate when the petal momentum is maximum.

### 2.2 Equivalent mass method

The equivalent mass method assumes that when the projectile penetrates the stiffened plate, the mass of the plug in the case of projectile plugging is the intersected mass between the perforated hole and the stiffened plate. The stiffened plate can be equated with a homogeneous plate with a certain thickness according to the principle of equal plug mass. The residual velocity of the projectile can then be calculated.

For the prediction of the limit velocity \( v_c \) of the projectile penetrating the stiffened plate, the K.A. Belkin equation \(^3\) is selected, and its mathematical expression is\
\[
v_c = 6 \times 600 \sqrt{k_e \sigma_s (1 + 6 \times 160 C_e/C_m) D^{0.75} H_e^{0.7} / (m^{0.1} \cos \alpha)}
\]
where \( k_e \) is the effectiveness coefficient that depends on the masses and thicknesses of the projectile and target and the shape of the projectile head; \( \sigma_s \) is the yield strength of the target plate; \( C_e \) is the relative thickness; \( C_m \) is the relative mass; \( D \) is the diameter of the projectile; \( H_e \) is the equivalent thickness of the target plate; \( \alpha \) is the impact angle of the projectile.

The values of the parameters in Eq. (5) are as follows: \( k_e = 0.034, \sigma_s = 685 \text{ MPa}, C_e = H_e/D = 0.25, C_m = m/D^3 = 1455.41 \text{ kg/m}^3, H_e = 0.026 \text{ m} \). The energy theorem and the definition of the limit trajectory velocity are then applied to obtain the residual velocity of the projectile\
\[
v_r = \sqrt{\frac{m(v_0^2 - v_c^2)}{m + m_1}}
\]
where \( m_1 \) is the equivalent plug mass in the case of the homogeneous plate.

### 2.3 Analysis of theoretical prediction results

Under the condition of the projectile penetrating the stiffened plate in Working Condition 2, the initial velocity of the projectile falls within 300–900 m/s. Two theoretical methods are used to predict the residual velocity of the projectile, and the results are compared with those obtained by numerical simulation (Fig. 8).

According to Fig. 8, the momentum method yields a theoretical value of the residual velocity that deviates greatly from the simulated value as it ignores the energy absorption effect of the target plate as a whole. As the initial velocity of the projectile rises, the gap between the theoretical value and the simulated value gradually narrows. When combined with the corresponding empirical equations, the equivalent mass method produces a predicted residual velocity larger than the simulated value at a low velocity and a predicted value smaller than the simulated counterpart at a high velocity. Nevertheless, the deviation is small on the whole. The experimental coefficient of the plug must be fitted by experiment in the momentum method. In contrast, it can be directly calculated
using the existing empirical equation in the equivalent mass method. Therefore, the equivalent mass method outperforms the momentum method slightly in predicting the residual velocity of the projectile in the range of the projectile velocity investigated in this study.

3 Influence of initial velocity of projectile on energy absorption mode of stiffened plate

The deformation energy of the plate, vertical stiffener, and horizontal stiffener in the stiffened plate when the projectile penetrates the target plate is extracted from the above simulation results in the case of the projectile penetrating the target plate at different initial velocities. The results are listed in Table 3.

Table 3 reveals that when the initial velocity of the projectile is within the range of 300–900 m/s, the energy loss of the projectile gradually increases as the initial velocity of the projectile rises, which is mainly due to the more energy absorbed by the target plate undergoing plugging damage. On the whole, the proportion of the energy absorbed by the deformed plate and stiffeners in the energy loss of the projectile gradually decreases as the initial velocity of the projectile rises. This is mainly because the interaction time between the projectile and the target shortens with the increase in the initial velocity of the projectile, and the local effect in the process of penetration intensifies.

4 Influence of stiffened structure on penetration trajectory of projectile at different impact points

When a certain distance exists between the impact point and the stiffener, the influences of different stiffened structures on the flight attitude of the projectile are also different. The penetration of a rectangular stiffened plate and a T-stiffened plate by a projectile is numerically simulated, respectively, and the deflection angles of the projectile during and after penetrating the target are compared. The case where the projectile penetrates the rectangular stiffened plate, with the impact point being 20 mm away from the vertical stiffener and 62.5 mm away from the horizontal stiffener, is discussed as an example. The curve of the deflection angular velocity of the projectile in simulation vs. time is shown in Fig. 9.

As can be seen from the simulation results, the existence of the stiffener will change the flight attitude of the vertically incident projectile when a certain distance exists between the impact point and the stiffener, consequently changing the impact angle when the projectile penetrates the rear layers of the target plate. In the penetration process of the projectile, the force state of the projectile is asymmetric to a certain extent. Since this asymmetry is mainly caused by the penetrated stiffener, the projectile mainly deflects around the penetrated stiffener. The projectile first deflects away from the penetrated stiffener and then gradually deflects in the opposite direction. Depending on the change in the deflection angle of the projectile, the motion of the projectile can also
be divided into three stages.

In Stage 1, the projectile head comes into contact with the stiffener, and the compression effect of the stiffener part on the projectile is greater than the reverse compression effect of the part without stiffeners, ultimately resulting in the deflection of the truncated oval-nosed projectile head.

In Stage 2, the centroid of the projectile penetrates the equivalent force point at the penetrated stiffener, and the stiffener area produces an opposite torque for the force exerted by the projectile, ultimately providing the projectile with a reverse angular acceleration within the time of contact between the projectile tail and the target plate.

In Stage 3, the projectile penetrates through the target plate. The angular velocity of the projectile does not change significantly, and the projectile obtains a constant rotational angular velocity thereafter. The position relationship between the projectile and the target and the change in the deflection angular velocity in the above three stages are shown in Fig. 9.

When the initial velocity of the projectile is 600 m/s and the distance between the impact point and the vertical stiffener is 2, 5, 7, 10, 20, 30, 40, and 50 mm, respectively, the penetration of the rectangular stiffened plate by the projectile is numerically simulated to obtain the maximum deflection angle of the projectile, the corresponding flight distance under the maximum deflection angle, and the angular velocity of the projectile after it penetrates through the target plate. Furthermore, this angular velocity of the projectile after it penetrates through the target plate is used to predict the deflection angle of the projectile after it comes into contact with the target plate and then flies for 3 m. The results obtained are listed in Table 4.

According to Table 4, the influence of the relative position relationship between the impact point and the stiffener on the trajectory can be divided into two stages depending on the influence of the stiffened plate on the maximum deflection angle of the projectile when the impact point and the stiffener are far away from each other. In a certain range, the maximum deflection angle increases with the rise of the distance between the impact point and the stiffener. This is due to the large deformation of the area where the stiffener comes into contact with the projectile head in this range. As the projectile goes away, the time of the shear and tear failure of the stiffener is postponed, and the vertical deformation near the stiffener lessens. In this case, the stiffener can exert a larger angular momentum on the projectile before the shear failure. The stress is released after the tear failure of the stiffener happens, and the force of the stiffener on the projectile significantly weakens. When the impact point is far enough away from the stiffener, the stiffener mainly undergoes overall plastic deformation. As the projectile moves away, the bending degree of the stiffener decreases. The force on the projectile head gradually decreases, and the maximum deflection angle decreases accordingly.

<table>
<thead>
<tr>
<th>Deviated distance of impact point /mm</th>
<th>Maximum deflection angle/(°)</th>
<th>Flight distance at maximum deflection angle/mm</th>
<th>Angular velocity after penetration $\dot{\theta}$ (/°·s$^{-1}$)</th>
<th>Deflection angle after 3 m (predicted value)/(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.18</td>
<td>367.21</td>
<td>$-2.994.84$</td>
<td>$-13.08$</td>
</tr>
<tr>
<td>5</td>
<td>2.99</td>
<td>389.71</td>
<td>$-3.931.76$</td>
<td>$-15.65$</td>
</tr>
<tr>
<td>7</td>
<td>3.84</td>
<td>390.42</td>
<td>$-3.791.18$</td>
<td>$-14.12$</td>
</tr>
<tr>
<td>10</td>
<td>4.96</td>
<td>391.40</td>
<td>$-2.730.89$</td>
<td>$-7.94$</td>
</tr>
<tr>
<td>20</td>
<td>6.14</td>
<td>373.33</td>
<td>$-5.610.17$</td>
<td>$-24.57$</td>
</tr>
<tr>
<td>30</td>
<td>4.93</td>
<td>376.04</td>
<td>$-5.808.89$</td>
<td>$-22.25$</td>
</tr>
<tr>
<td>40</td>
<td>3.34</td>
<td>355.79</td>
<td>$-4.658.91$</td>
<td>$-18.32$</td>
</tr>
<tr>
<td>50</td>
<td>2.06</td>
<td>357.70</td>
<td>$-1.945.1$</td>
<td>$-6.76$</td>
</tr>
</tbody>
</table>

The angular velocity of the projectile after penetration depends on the contact between the projectile tail and the stiffener, and it reaches the maximum value when the stiffener has a large bending degree without obvious shear failure. In both the experiment and the above simulation, the stiffeners in the target plate are rectangular stiffeners. However, those in a real ship are generally flat-bulb steel or T-shaped profiles. The rectangular stiffeners in the above penetrated target plate in the simulation are changed into T-stiffeners to study their influence on the trajectory. The thickness and height of the web plates with T-stiffeners are consistent with those in the case of the rectangular stiffeners, and the size of the T-stiffener is $15.2 \times 68 / 18 \times 50$. The trajectory parameters in the case of the projectile penetrating the T-stiffened plate are processed in the same way as those in Table 4 to obtain the maximum deflection angle of the projectile, the corresponding flight distance under the maximum deflection angle, and the angular velocity of the projectile after it penetrates through...
the target plate. The results are listed in Table 5.

<table>
<thead>
<tr>
<th>Deviated distance of impact point /mm</th>
<th>Maximum deflection angle(°)</th>
<th>Flight distance at maximum deflection angle/mm</th>
<th>Angular velocity after penetration l/(°)·s^-1</th>
<th>Deflection angle after 3 m (predicted value) °</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.03</td>
<td>379.71</td>
<td>-3 583.53</td>
<td>-14.73</td>
</tr>
<tr>
<td>5</td>
<td>4.90</td>
<td>402.15</td>
<td>-2 859.96</td>
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<td>7</td>
<td>6.40</td>
<td>403.03</td>
<td>-1 812.54</td>
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<td>10</td>
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<td>8.86</td>
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<td>20</td>
<td>9.51</td>
<td>389.18</td>
<td>-7 850.11</td>
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</tr>
<tr>
<td>30</td>
<td>8.10</td>
<td>372.31</td>
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</tr>
<tr>
<td>40</td>
<td>5.84</td>
<td>375.63</td>
<td>-5 660.71</td>
<td>-20.84</td>
</tr>
<tr>
<td>50</td>
<td>3.69</td>
<td>355.83</td>
<td>-4 206.98</td>
<td>-15.91</td>
</tr>
</tbody>
</table>

The case where the deviated distance of the impact point is 20 mm is discussed as an example to draw the curve of the deflection angle of the projectile vs. time when the projectile penetrates two types of stiffened plates (Fig. 10).

Regarding the case of the projectile penetrating the T-stiffened plate, the change trends of the relevant trajectory data and the distance of the impact point are similar to those in the case of the rectangular stiffened plate. A comprehensive observation of the data in Tables 4 and 5 and the figure of the deflection angle of the projectile reveals that the influence of the T-stiffener on the trajectory is larger than that of the rectangular stiffener during the penetration process. The reason is that the T-stiffener is more rigid and the T-stiffened surface plate is in contact with the projectile, resulting in a force exerted on the projectile larger than that exerted by the rectangular stiffener. In some parts where the impact point is close to the stiffener, the absolute value of the angular velocity of the projectile after it penetrates the T-stiffened plate is smaller than that in the case of the rectangular stiffener. This is mainly because the projectile obtains a larger angular velocity in the first stage of the penetration of the target by the projectile. As the distance between the impact point and the stiffener rises, the absolute value of the angular velocity of the projectile after it penetrates the T-stiffened plate is significantly larger than that in the case of the rectangular stiffened plate.

5 Conclusions

In this paper, numerical simulation and theoretical methods are applied to study the case of the truncated oval-nosed projectile penetrating the stiffened plate. The main conclusions are as follows:

1) Regarding the contrast conditions in the stiffened plate penetration experiment, the penetration of the stiffened plate by the large-mass truncated oval-nosed projectile can be divided into four stages according to the order of the projectile penetrating the structure and the energy change trend of the stiffened plate. The four stages are the hole opening in the outer plate, the penetration of the vertical stiffener, the joint penetration of the vertical and horizontal stiffeners, and the reaming and penetration of the target plate. The energy absorption of the plate is dominant in the penetration process of the projectile, while that of the horizontal stiffener is less. Moreover, the ratio of energy absorption of the deformed stiffened plate decreases as the initial velocity of the projectile rises.

2) Both the momentum method and the equivalent mass method can well predict the residual velocity of the projectile. The error of the momentum method is relatively large in the low-velocity range. Nevertheless, this error decreases gradually as the projectile velocity increases. The residual velocity predicted by the equivalent mass method is more accurate when the initial velocity of the projectile is in the range from 300 to 900 m/s.

3) When the projectile penetrates the target plate vertically, the relative position relationship between the impact point and the stiffener has a significant impact on the penetration attitude of the projectile. During the penetration, the deflection angle of the projectile first increases and then decreases to the opposite of the previous deflection angle. The maximum positive deflection angle of the projectile first rises and then decreases with the increasing distance between the impact point and the stiffener. In addition, the positive deflection angle of the projectile penetrating the T-stiffened plate is relatively large on the whole.
References


