Numerical analysis on deformation and energy absorption characteristics of stiffened plate under explosive impact loads

Chen Pengyu¹, Duan Hong², Hou Hailiang*¹, Jiao Liqi¹,³

¹ College of Naval Architecture and Ocean Engineering, Naval University of Engineering, Wuhan 430033, China
² China Ship Development and Design Center, Wuhan 430064, China
³ Naval Research Academy, Beijing 100161, China

Abstract: [Objectives] In order to analyze the deformation and energy absorption characteristics of the stiffened plate under explosive impact loads, [Methods] the finite element analysis software LS-DYNA is used to simulate and calculate the deformation and energy absorption of the clamped stiffened plate under the explosive impact loads. The one-way stiffened plate is taken as the study object, the deformation and energy absorption characteristics are analyzed, the overall deflection and the local deflection of the stiffened plate are obtained, the ratio of these two deflections is used to indicate the proportional relationship between the local energy absorption and the overall energy absorption of the stiffened plate. [Results] The results show that the overall deformation of the stiffened plate decreases as the relative stiffness increases under certain explosive impact loads. The ratio of the local deflection to the overall deflection increases as the relative stiffness increases. The ratio of the local energy absorption to the overall deformation and energy absorption increases as the relative stiffness increases. [Conclusions] The dimensionless relative stiffness and deflection ratio proposed in this paper can provide study references and ideas for the ship anti-explosion and venting structure design.

Key words: explosive impact; stiffened plate; local energy absorption; numerical simulation

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0 Introduction

With the development of anti-ship missile technology, the semi-armor-piercing anti-ship missile has become a major threat to the broadside above the waterline of surface ship. The anti-ship missile warhead mostly uses high-energy charge, which significantly enhances the damage ability, and the damage caused by the explosive impact loads on the structure of the ship is greatly enhanced. How to effectively absorb the energy of the explosive impact loads is of great significance for the protection of the ships. The explosive impact loads mainly affect the large plastic deformation of the ship structure, and the main structure of the cabin is one-way stiffened plate. Therefore, research on the energy absorption characteristics of stiffened plates under explosive impact loads has always been the focus of the fields of explosion and shock resistance of ships.

The deformation and energy absorption problems of stiffened plate under the explosive impact loads are complicated. For the dynamic response of stiff-
ened plates, scholars in China mainly study the failure modes of stiffened plates (such as shear failure, tensile tear, large plastic deformation) and elastoplastic deformation theory through experiments and numerical simulation methods, but there are relatively few studies on the deformation and energy absorption of stiffened plates. Wu et al. \cite{1} studied the deformation and damage of naval panels under the explosive impact loads. Considering the influence of the strain relationship and the mid-film force during the large plastic deformation, the energy method was used to derive the plastic deformation and damage formulas of naval panels (stiffened plate) to calculate the deformation energy of the stiffened plate, and the maximum displacement of the center of panels was obtained according to the energy principle. However, when the strength of the stiffener is larger, the deformed shape differs greatly from the assumed shape, causing a large deviation in the calculated value. Nurick et al. \cite{2} carried out the deformation and failure experiments of single clamped stiffened square plates under uniform explosive load, and the results show that the failure mode classification of single clamped stiffened square plates is similar to that of metal plates. Yuen and Nurick\cite{3} carried out the experimental studies on the deformation and failure modes of clamped square plate with a single stiffener, two parallel stiffeners, a cross stiffener and double cross stiffeners under uniform explosive load. Based on the energy principle and the rigid plastic material model, Liu et al. \cite{4} studied the plastic dynamic response of square and rectangular stiffened plates under the explosive impact loads and derived the motion control equation of plastic dynamic response of the structures. Liu et al. \cite{5} analyzed the large-deflection plastic dynamic response of a single clamped stiffened square plate subjected to explosive loads and deeply studied the theoretical solution of deformation under deformation failure mode I (overall large plastic deformation). Zhu et al. \cite{6} studied the deformation and energy absorption characteristics of the composite target plate under the explosive impact loads, and they compared and analyzed honeycomb arrangement and the deformation and energy absorption characteristics of the composite target plate with different sandwich structures that are filled with rubber material inside the honeycomb under the same explosive impact loads using the numerical simulation method. Xia et al. \cite{7} studied the anti-contact explosive performance of steel plate clamped steel tube composite plates and proposed that steel tube deformation is the main way to dissipate energy for composite plates. According to the good deformation capacity and energy absorption characteristics of steel tube, they also proposed a sandwich type explosion-proof composite plate with a layered structure of steel plate-core layer of steel tube-steel plate. Through the numerical simulation and equivalent calculation theory, Zhao et al. \cite{8} studied the dynamic response of composite stiffened plates under explosive impact loads and established the dynamic response analysis theory of orthotropic stiffened plates under explosive impact loads. The results show that the theoretical calculation results are close to the numerical simulation results. Deng et al. \cite{9} studied the energy absorption characteristics of square-hole honeycomb sandwich plates under the explosive impact loads, and analyzed the deformation mechanism and energy absorption characteristics of square-hole honeycomb sandwich plates by numerical simulation, to obtain the optimal relative density of the sandwich layer. The results show that at this relative density, the sandwich layer has the highest energy absorption rate, and the influence of the thin-wall spacing, thickness and height of core layer, and panel thickness on the energy absorption rate of each part of the sandwich plate was also discussed. Li et al. \cite{10} simulated the explosion resistance of the graded corrugated sandwich plate under the airblast loads, studied the influence of the filling mode on the explosion resistance, and analyzed the energy absorption characteristics of the sandwich structure. Chen et al. \cite{11} studied the deformation and energy absorption characteristics of foam aluminum materials, mainly including the effects of density, pore distribution and loading strain rate on the deformation and energy absorption characteristics of foam aluminum materials. The results show that with the increase of density, the energy absorption capacity of the foam material with uniform pore distribution is obviously better than that with uneven pore distribution, and the loading speed has a certain influence on the stress and strain behavior of the foam material but has no effect on the energy absorption capacity. Ren et al. \cite{12} adopted the finite element analysis software LS-DYNA to study the dynamic response characteristics and anti-explosion protection performance of the reinforced structure of ship under the underwater explosive impact loads, and the results show that the rib structure type is an important factor affecting the deformation response speed and plastic deformation amplitude of stiffened plates. Under the
same surface density, the double-layer bottom reinforced structure can effectively improve the overall performance of the anti-explosion protection of the structure. Mei et al. [13] analyzed the dynamic energy absorption characteristics of the double-layer explosive-proof bulkhead structure and mainly studied the failure mode and energy absorption characteristics of the double-layer bulkhead structure under the near-explosive impact loads.

The above scholars mainly adopt numerical simulation when studying the dynamic response and energy absorption characteristics of stiffened plates. Although the LS-DYNA software can be used to better simulate and analyze the deformation and damage process, pressure and displacement cloud map of the stiffened plate, there are still limitations in the energy output. The local energy absorption output by the panel includes the overall deformation and energy absorption of the stiffened plate, and the local energy absorption cannot be separately output. Therefore, the energy output from the panel grouping cannot directly explain the proportional relationship between the local and overall deformation and energy absorption of the stiffened plate. Although it is difficult to directly solve the ratio of the overall deformation and energy absorption of the panel to the local energy absorption of the panel, the overall deformation deflection of the stiffened plate and the local deformation deflection of the panel are relatively easy to be obtained. Therefore, the local deflection of the panel is defined as the difference between the final deflection of the stiffened plate and the final deflection of the stiffener, and the ratio $\alpha$ of the local deflection of the panel to its overall deflection is taken as a reference for the ratio of overall energy absorption to local energy absorption, so that the variation law of the ratio of overall energy absorption to local energy absorption of stiffened plate can be well described.

Since the main factor affecting the energy absorption characteristics of the stiffened plate is the ratio of the strength of the stiffened plate to the strength of the stiffener when the explosive impact load is fixed, this paper will carry out the numerical simulation of the stiffened plates with different structural parameters under the explosive impact loads, to reveal the energy absorption characteristics of the stiffened plates, analyze the influence factors, and discuss the variation law of the ratio of the overall energy absorption of stiffened plate to the local energy absorption of panel. Then experiment verification is carried out.

1 Numerical model

In order to study the energy absorption law of the overall stiffened plate and the panel under the explosive impact loads, and the proportional relationship between the two, the numerical simulation calculation is carried out by using LS-DYNA software, and under the same impact load, multiple models (M1–M12) are established according to the different strength ratios of stiffeners and panels. In the simulation calculation, the explosive charge used is 100 kg, and the explosion distance (the explosion point is directly above the center of the stiffened plate) is 2.5 m.

Fig. 1 shows the structure of the stiffened plate model. The model has a length of $l=5\,400\,\text{mm}$ and a width of $d=2\,800\,\text{mm}$, and there are extension areas of 200 mm as boundary conditions in the length and width directions. Therefore, the area of the stiffened plate in the middle is $5\,000\,\text{mm} \times 2\,400\,\text{mm}$. The stiffener in the area has a height of $h=180\,\text{mm}$; the plate thickness is $H=3\,\text{mm}$; the rib spacing is $a=500\,\text{mm}$. Fig. 2 shows the finite element model of the stiffened plate structure.

![Configuration of the stiffened plate](image1)

![Loading area](image2)

In the established simulation model, the plate, stiffener and auxiliary structure adopt the Plastic_Kinematic bilinear elastoplastic constitutive model, and the strain rate effect is described by the Cowper–Symonds model.

$$
\sigma_d = \left( \sigma_0 + \frac{E_p}{E - E_p} \varepsilon \right) \left[ 1 + \left( \frac{\varepsilon}{D} \right) \right]^{\frac{1}{n}}
$$

where $\sigma_d$ is the dynamic yield strength; $\sigma_0$ is the static yield strength; $\varepsilon$ is the effective plastic strain.
strain; $E$ is the modulus of elasticity; $E_u$ is the hardening modulus; $\varepsilon$ is the equivalent plastic strain rate; $h$ is the thickness of the stiffener; $D$ and $n$ are constants, and for low carbon steel, generally $D = 40.4 \text{s}^{-1}$ and $n = 5$. The deck material used in this paper is Q235 low carbon steel with a material density of $\rho = 7800 \text{kg/m}^3$ and a static yield strength of $\sigma_0 = 235 \text{MPa}$. The failure model of the material adopts the maximum equivalent plastic strain failure criterion, and the ultimate failure strain of the material is taken as 0.3.

The area enclosed by the yellow border in Fig. 2 is the area where the load is loaded on the stiffened plate, i.e., the range of 5000 mm $\times$ 2400 mm in Fig. 1. In the calculation, the explosive load is simulated by the CONWEP (Conventional Weapons Effects Program) algorithm, and the Load_Blast model is applied to the panel on the side with the stiffener, and the loaded explosive charge and the explosion distance are as described above. The simulation time is 30 ms.

The relative stiffness $K$ (dimensionless parameter) of the stiffener is defined as follows:

$$K = \frac{M}{M_0 a}$$

where $M = b \sigma_0 h^2 / 4$ is the plastic ultimate bending moment of the stiffener; $M_0 = \sigma_0 d^2 / 4$ is the plastic ultimate bending moment of the stiffened plate.

Table 1 presents the thickness of the stiffener and relative stiffness parameters for each model.

<table>
<thead>
<tr>
<th>Model</th>
<th>$b$ /mm</th>
<th>$K$</th>
<th>Model</th>
<th>$b$ /mm</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>2</td>
<td>14.4</td>
<td>M7</td>
<td>14</td>
<td>100</td>
</tr>
<tr>
<td>M2</td>
<td>4</td>
<td>28.8</td>
<td>M8</td>
<td>16</td>
<td>115</td>
</tr>
<tr>
<td>M3</td>
<td>6</td>
<td>43.2</td>
<td>M9</td>
<td>18</td>
<td>129</td>
</tr>
<tr>
<td>M4</td>
<td>8</td>
<td>57.6</td>
<td>M10</td>
<td>20</td>
<td>144</td>
</tr>
<tr>
<td>M5</td>
<td>10</td>
<td>72.0</td>
<td>M11</td>
<td>22</td>
<td>158</td>
</tr>
<tr>
<td>M6</td>
<td>12</td>
<td>86.4</td>
<td>M12</td>
<td>24</td>
<td>172</td>
</tr>
</tbody>
</table>

2 Experimental verification of numerical simulation method

According to the above calculation method and material parameters, the damage of the explosive impact load on the clamped square plate is numerically simulated. The grid size is set to 5 mm $\times$ 5 mm, and the boundary conditions are four clamped sides. Fig. 3 shows the comparison between the numerical simulation results and the experimental results obtained in Reference [14] (In Fig. 4, $\delta$ is the deformation deflection; $L$ is the half width of the plate; $2L = 500 \text{mm}$; and $x$ is the coordinates of the point on the center line of the plate). In the experimental conditions of Reference [14], the square plate size is 500 mm $\times$ 500 mm; the explosive charge is 400 g; the charge form is columnar; the charge size is 131.2 mm $\times$ 50.2 mm; and the explosion distance is 148 mm.

As can be seen from Fig. 3(a), the square plate undergoes overall plastic deformation. The deformation of the plate is mainly concentrated in the middle of the square plate, and substantially no obvious deformation occurs at the boundary of the plate and its vicinity. The tensile bending deformation mainly occurs in the middle region, and the maximum deformation deflection value is 42.3 mm, which is much larger than the plate thickness. It can be seen from Fig. 3(b) that the simulated deformation agrees well with the experimental results, and the deformation is mainly concentrated in the middle of the square plate. The surrounding boundary and its vicinity are substantially free of deformation. The maximum deformation deflection value of the plate calculated by the simulation is 39.9 mm, and the error between the simulation and experimental results is 5.67%.

It can be seen from Fig. 4 that the deformation profile at the centerline obtained by the experiment is basically consistent with the simulation results, and the error between the experimental results and the numerical simulation results is within 10%. The
above results meet the requirements of engineering calculations, and it is considered that the numerical simulation methods and material parameters used in this paper are reasonable.

3 Numerical calculation results and analysis

3.1 Analysis of the overall energy absorption and deformation of stiffened plate

In the numerical simulation of the overall energy absorption and deformation of the stiffened plate, the load of the stiffened plate is applied by the Load_Blast model in the LS-DYNA software, and the loading method mainly considers the two factors of the explosive charge and the explosion distance. In the case that the intensity of explosive impact load is fixed (namely that the explosive charge is 100 kg, and the explosion distance is 2.5 m), based on the order of deformation and energy absorption of the overall stiffened plate and the local panel, the simulation results of the M1, M6 and M12 models are selected and analyzed, and the results are shown in Fig. 5–Fig. 7.

As can be seen from Fig. 5, when the relative rigidity of the stiffener is smaller \( K = 14.4 \), since the load applied is not uniform, the explosive impact load first acts on the middle portion of the stiffened plate. The stiffened plate firstly undergoes local plastic deformation and energy absorption, and at the moment \( t = 1.5 \) ms of load action, only local plastic de-
formation of the panel occurs. Under the continuous action of the load, the overall deformation of the stiffened plate does not occur, but the local deformation of the panel gradually increases. When $t=2.0$ ms, the stiffened plate begins to undergo overall plastic deformation. When $t=2.5$–3.0 ms, the overall plastic deformation of the stiffened plate increases gradually, and the local plastic deformation of the panel gradually decreases. When $t=3.0$–4.5 ms, the overall plastic deformation of the stiffened plate increases; the local plastic deformation of the panel further decreases to 0; and finally the deformation of the stiffened plate is the overall plastic deformation.

It can be seen from Fig. 6 that when $K=86.4$, the initial deformation of the stiffened plate is basically the same as that of the M1 model, namely that the local plastic deformation and energy absorption of the panel occur first, and only the local plastic deformation of the panel occurs before $t=2.00$ ms. With the continuous action of the load, the overall deformation of the stiffened plate does not occur, but the local deformation of the panel gradually increases. When $t=2.5$ ms, the stiffened plate begins to undergo overall plastic deformation. When $t=3.0$–8.0 ms, the overall plastic deformation of the stiffened plate increases gradually, and the increment of the local plastic deformation of the panel gradually decreases. Since the relative stiffness of the stiffener is larger, the final overall plastic deformation of the stiffened plate is small and the local deformation of the panel is large compared to the models of M1 and M6.

It can be seen from Fig. 7 that when $K=172$, the initial deformation of the stiffened plate is similar to the simulation results shown by the models of M1 and M6, namely that the local plastic deformation and energy absorption of the panel occur first, and only local plastic deformation of the panel occurs before $t=2.5$ ms. With the continuous action of the load, the overall deformation of the stiffened plate does not occur, but the local deformation of the panel gradually increases. When $t=3.5$ ms, the stiffened plate begins to undergo overall plastic deformation. When $t=5.5$–7.0 ms, the overall plastic deformation of the stiffened plate increases gradually, and the final overall plastic deformation of the stiffened plate is small and the local deformation of the panel is large compared to the models of M1 and M6.
It can be seen from the above analysis that under the explosive impact loads, the panel first undergoes local deformation, and the size of K has no effect on the order of local deformation of the panel and the overall deformation of the stiffened plate. The moments of the overall plastic deformation of the models of M1, M6, and M12 are respectively 2.0, 2.5 and 3.5 ms. It can be seen that with the increase of the K value, if the action time of the load required for the overall plastic deformation of the stiffened plate is longer, the overall plastic deformation of the stiffened plate is smaller, and the the local deformation of the panel is larger.

### 3.2 Characteristics analysis of energy absorption of stiffened plate panels

In order to study the energy absorption characteristics of stiffened plate panels under the explosive impact loads, the numerical simulation results of M6 model (K = 86.4) are taken as an example for analysis in this paper. Since the numerical simulation of the LS-DYNA software can only output the energy of each group as a whole, the local deformation and energy absorption of the stiffened plate panels also include the overall deformation and energy absorption of the stiffened plate. According to the 10 panel groups of the stiffened plates shown in Fig. 8, Fig. 9 shows the energy absorption characteristics of the corresponding panels, where the ordinate values of each point from left to right on the curve correspond to the corresponding panel energy absorption, respectively.

It can be seen from Fig. 9 that since the explosive is located above the center of the stiffened plate, the middle two panels are closest to the explosion center, and the intensity of explosive impact load is the largest. Therefore, the middle two panels have the largest deformation and energy absorption. Because the intensity of explosive impact load tends to decay exponentially with the increase of the distance, the plastic deformation and energy absorption of other panels also decrease rapidly with the increase of the...
3.3 Effect of relative stiffness on energy absorption characteristics of stiffened plate panels

In order to study the influence of the relative stiffness $K$ of the stiffener on the energy absorption characteristics of the stiffened plate panels, the models of M1–M11 are taken as examples. In the case that the intensity of explosive impact load is fixed (namely that the explosive charge is 100 kg and the explosion distance is 2.5 m), numerical simulation analysis is performed by changing the thickness of the stiffener ($b = 2 - 22$ mm) to change the $K$ value ($K = 14.4 - 158$).

Fig. 10 shows numerical simulation results when $K < 100$ and $K \geq 100$, respectively. It can be seen from Fig. 10 that when $K < 100$, the relative stiffness has a great influence on the deformation and energy absorption of the stiffened plate panels, and as the relative stiffness increases, the energy absorbed by the deformation of the panel gradually decreases. Therefore, the deformation and energy absorption of the two panels in the middle of the stiffened plate are greatly reduced, and the energy absorption of the panel at the edge is reduced less. When $K \geq 100$, as the relative stiffness increases, the increase of deformation and energy absorption of the stiffened plate panels is slow compared with that when $K < 100$, which can be considered as that the relative stiffness of $K \geq 100$ has little effect on the deformation and energy absorption of the stiffened plate panels.

3.4 Analysis of local energy absorption of stiffened plate panels

Due to the limitation of the LS–DYNA software in energy output, the local energy absorption of the panel output includes the overall deformation and energy absorption of the stiffened plate, and the local energy absorption cannot be output separately. Therefore, the energy output from the panel grouping cannot indicate the local deformation and energy absorption of the stiffened plate panels. Therefore, in order to more clearly analyze the proportional relationship between the local energy absorption of stiffened plate panels and the overall energy absorption of the stiffened plate, the following definitions are given: The maximum deflection of the stiffener is defined as the overall deflection $\delta_1$ of the stiffened plate, and the difference between the maximum deflection of the stiffened plate and the maximum deflection of the stiffener is defined as the local deflection $\delta_2$ of the stiffened plate panels. Finally, the ratio of the local deflection of the stiffened plate panels $\delta_2$ to the overall deflection of the stiffened plate $\delta_1$, namely, $\alpha = \delta_2/\delta_1$, is used to measure the proportional relationship of energy absorption between the overall and local deformation of the stiffened plate structure.

In the numerical simulation of M1–M5 models, the final deformation mode of the stiffened plate is the tensile tear of the edge, which has a great influence on the deflection, and the local deflection is diff-
difficult to be calculated. In the numerical simulation of the models of M6–M12, the final deformation mode of the stiffened plate is that the deformation of the stiffener is relatively small, and the plate undergoes large plastic deformation. However, there is no tensile tear failure of edge. Therefore, this section mainly analyzes the simulation results of the models of M6–M12. Fig. 11 shows the simulation results of the displacement of the model M7 in the z direction.

As can be seen from Fig. 11, since the explosive position is directly above the center of the stiffened plate, the maximum deflection of the stiffener occurs in the mid-span of the stiffener at the middle, and in each panel of stiffened plate, the two panels in the middle have the largest deformation deflection. Therefore, the maximum deflection value of the stiffened plate takes the average value of the maximum deformation deflection of the two panels in the middle of the stiffened plate, which can explain the overall and maximum deformation of the stiffened plate.

The final deformation of the stiffened plate simulated by the model M7 is as follows: The maximum deflection of the stiffener is 239 mm; the maximum deflection of stiffened plate panels is 297 mm; and the local deflection of stiffened plate panels is 58 mm. The ratio of the local deflection of the panel to the overall deflection of the stiffened plate is $\alpha = 0.243$. Therefore, it can be seen from the value of $\alpha$ that for the energy absorption distribution of the stiffened plate, the deformation and energy absorption of the intermediate panels of stiffened plate are smaller, and the overall deformation and energy absorption of the stiffened plate are larger.

### 3.5 Influence of relative stiffness on local energy absorption law of stiffened plate panels

In order to study the effect of the relative stiffness $K$ of the stiffener on the local energy absorption of stiffened plate panels, the models of M6–M12 ($K = 86.4–172$) are taken as examples. Under the same intensity of explosive impact load, the numerical simulation analysis is carried out by changing the thickness of the stiffener ($b = 12–24$ mm) to change the relative stiffness. Fig. 12 and Fig. 13 show the relationship curve between the relative stiffness and the overall deformation deflection of the panel, and relationship curve between the relative stiffness and its relative deflection ratio, respectively.

It can be seen from Fig. 12 that the relative stiffness of the stiffener has a significant linear relationship with the overall deformation deflection of the stiffened plate, namely that as the relative stiffness increases, the overall deflection of the stiffened plate...
decreases. When the thickness of the stiffened plate is constant, under the explosive impact load with the same intensity, the greater relative stiffness of the stiffener results in the smaller overall deformation of the stiffened plate.

Combining Fig. 13 and Fig. 12, we can see that when the explosive impact load is constant, the value of $\alpha$ increases as the value of $K$ increases. It can be seen from the change of the value of $\alpha$ that the ratio of the local deformation and energy absorption of stiffened plate panels to the overall deformation and energy absorption of the stiffened plate gradually increases.

4 Conclusions

In this paper, the finite element analysis software LS-DYNA is used to simulate the deformation and energy absorption law of the stiffened plate under the explosive impact loads, and the accuracy of the model established is verified. By analyzing the deformation and energy absorption characteristics of the stiffened plate under the explosive impact loads and the factors affecting the deformation and energy absorption, we can obtain the following conclusions:

1) Under the action of explosive impact loads, when the stiffened plate only undergoes plastic deformation, the local deformation of panel first occurs, and then the overall deformation of the stiffened plate occurs. The relative stiffness $K$ of the stiffener has no effect on the order of the deformation of the panel and the overall deformation of the stiffened plate.

2) Under the explosive impact load with the same intensity, with the increase of $K$, the local deformation deflection of stiffened plate panels and the time required for the stiffened plate to change from the local deformation of the panel to the overall plastic deformation will increase, but the overall plastic deformation of the stiffened plates gradually reduces.

3) Under the condition of the constant explosive impact load and the spacing $a$ and height $h$ of the stiffeners studied in this paper, when $K < 100$, it has a great influence on the deformation and energy absorption of stiffened plate panels. When $K \geq 100$, the effect on deformation and energy absorption of stiffened plate panels is slight.

4) When the explosive impact load is constant, the value of $\alpha$ becomes larger as $K$ increases. It can be seen from the change of the value of $\alpha$ that the ratio of the local deformation and energy absorption of stiffened plate panels to the overall deformation and energy absorption of the stiffened plate gradually increases.

References


爆炸冲击载荷作用下加筋板的
变形吸能特性数值分析

陈鹏宇1, 段宏2, 侯海量*, 焦立启1,3
1 海军工程大学 舰船与海洋学院, 湖北 武汉 430033
2 中国舰船研究设计中心, 湖北 武汉 430064
3 海军研究院, 北京 100161

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