Equivalent design of stiffened panel based on load characteristics

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Abstract. In order to use a cheaper and homogeneous steel plate to replace the real stiffened panel in warhead tests, we numerically simulated and analyzed the deformation and failure characteristics of the stiffened panel as well as the force characteristics of the projectile in the warhead-target interaction. Based on the energy equivalence method, we first used the acceleration curve of the warhead in actual target penetration process as the reference for equivalent design and replaced it using a three-layered homogeneous steel plate. To visually assess their equivalence, we introduced Pearson correlation coefficient in statistical analysis to reflect their correlation. The results showed that the equivalent design method based on load characteristics make both consistent not only in the kinetic energy loss but also in the warhead’s target-piercing acceleration process, thus realizing the equivalence from process to final state.

1. Introduction
Stiffened panel, consisting of an equal-thickness steel plate (panel), as well as longitudinal and rib stiffeners, is the typical structure of multiple decks and cabins of large surface ships and vessels. It in a given mass can mostly reduce the residual velocity of a missile so as to protect its own internal structure. A semi-armor-piercing warhead aimed at a large ship usually strikes its deck above or at the shipboards from its two sides, penetrating into the interior of the hull and exploding there. It is well known that modern large ships are characteristic of multiple layers, multiple cabins, thick protective armor, complex internal structure, and so on [1]. Thus, to effectively damage such a target, the warhead of a missile needs to penetrate its multi-decks/protective compartments to reach its vulnerable parts (such as fuel/oil tank, engine room, ammunition cabin, etc.) so as to carry out explosion. Many studies [2-4] have shown that the differences among the ship's structural members as its ribs and beams will lead to significantly different vulnerabilities of stiffened plates at different positions. When the warhead attacks different positions, i.e., different impact points, the penetrating ability of the warhead and anti-penetration strength of the hull are proven significantly different.

It is known that different positions on the stiffened panel respond differently to the impact of the
warhead. When testing the warhead’s ability to pierce the target or structural strengths during warhead development stage, using the real stiffened panel as the test target for every test will incur a series of disadvantages such as more trial conditions, massive costs, and inability to fully evaluate risks [5]. Taking structural strength test as an example, it is necessary to consider the most severe working conditions in the experimental design, that is, the impact point should be chosen at the intersection of stiffeners on each layer of the target plate. In actual tests, especially in the obliquely target-penetrating case, both the posture of the projectile body and the penetrating angle of attack obviously change with the increase of the number of target-pierced layers. Thus, it is very difficult to control the initial impact position of each layer. To reduce the effect of these procedural random factors on the test results and simultaneously lower the experiment amount and costs, it is necessary to explore the equivalence of stiffened panels and the method using homogeneous steel plate to replace the stiffened panel.

At present, the equivalent design for the stiffened panel structure [5-8] mostly employs the energy equivalent method, that is, “when a certain thickness of the homogeneous target plate and an actual shipboard structure are impacted by the same warhead at the same incident angle, if their ballistic limit velocities are the same, or their residual ones of the initial velocities of the same warhead are the same, they are considered equivalent” [6]. This design follows the principle that “both the homogeneous target plate and the actual shipboard structure have the same ability to absorb the kinetic energy of the warhead” [7], and pays attention to the consistency of the initial and final states of their velocities, but rarely considers the specific changes in the warhead-target interaction, thus resulting in significantly different mechanical environment experienced by the warhead in certain operating conditions. Based on the equivalent of the energy method, this study considers the load characteristics of the warhead in its actual target-piercing process, referring to the actual size of the stiffened panel, conducting the equivalent design based on the load characteristics, and finally making the stiffened panel equivalent to a multiple layers, small interval, homogeneous steel plate. The design results showed that our design method can not only make both consistent in the residual velocity of the warhead, but also keep them better consistent in the acceleration history, thus realizing the equivalence from the process to the final state.

2. Stiffened panel structure model

2.1. Geometric model

Taking the deck of a ship as the research object, based on the data in the literature [5], the stiffened panel of the deck consists of equal-thickness steel plate (panel) with thickness of 30 mm, inter-rib spacing of 2000 mm, and inter-longitudinal spacing of 600 mm (figure 1c), T-shaped ribs with flange plate width of 160 mm, thickness of 16.7 mm; web depth of 240 mm (figure 1a), and \( \Gamma \)-shaped longitudinal made of a 40 mm wide and 6.7 mm thick flange plate and a 133 mm deep and 6.7 mm thick web (figure 1b).

![Figure 1. Schematic of the stiffened panel structure.](image-url)
2.2. Analytical model

Modelling for the stiffened panel frame in the finite element program takes the most severe working conditions into consideration, using the intersections of ribs and longitudinals as the target points of the warhead, a 2 m × 2 m square near the target point as the modeled area, and the hexahedral voxel for meshing. All the contact areas among the panel, ribs, and longitudinals are treated as the common nodes. The meshes near the warhead-target contact areas are locally re-meshed with the denser unit size of 4 mm. The clamped, constraint boundary conditions are applied around the target panel.

![Figure 2. Schematic of finite element modelling for the stiffened panel.](image)

The stiffened panel is made of 921A hull steel. In the numerical simulation, the Johnson-Cook (J-C) constitutive model is used to describe the flow stress and failure strain of the target material. The model takes the material softening caused by strain rate enhancement and adiabatic temperature rise into consideration and is suitable for calculating changes in metal materials from quasi-static to large deformation, high strain rate, and high temperature. The specific form is as follows:

$$\sigma_y = \left( A + B\dot{\varepsilon}_p^n \right) \left[ 1 + C \ln \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0} \right] \left[ 1 - \left( \frac{T^*}{T_m - T_r} \right) \right]$$  \hspace{1cm} (1)

where $\dot{\varepsilon}_p$ is the equivalent plastic strain; $T^* = (T - T_r) / (T_m - T_r)$, $T_m$ and $T_r$ are the melting temperature and room temperature, respectively; $A$, $B$, $n$, $C$, and $m$ are material parameters, respectively. Table 1 shows the material parameters used in calculation in the J-C model [9].

| $\rho$ (kg/m$^3$) | E/GPa | $v$ | $A$/MPa | $B$/MPa | $C$ | $n$ | $m$ |
|------------------|-------|-----|---------|---------|-----|-----|-----|
| 7800             | 205   | 0.28| 760     | 500     | 0.014| 0.53| 1.13|
| $C_p$ (J/(kg·K)) | $T_c$ | $T_m$ | $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ |
| 400.9            | 294   | 1765| 1.13   | 0       | 0    | 0    | 0 |

3. Warhead model

3.1. Geometric model

An anti-ship missile warhead generally has a diameter of 300 ~ 500mm and a pointed oval or tapered to facilitate its target penetration and increase its strength. In this study, we further polished (CRH=2) the warhead and processed it into an oval one figure 3b on the basis of a truncated conical warhead (figure3a) reported previously [10]. The modified warhead is 1150 mm long and about 400kg with a cylindrical section with outer diameter of 350mm.
3.2. Material model
The shell of the warhead is made of 30CrMnSiNi2A with high strength and high toughness. Only is the counterweight effect of its internally filled explosive is considered in the calculation. The explosive is replaced by the inertial, linear elastic material with density of 1850 kg/m³, elastic modulus of 3.05 GPa, and Poisson’s ratio of 0.28 [7]. The shell material of the warhead adopts the elastoplastic hardening constitutive model, and its strain rate effect is described using the Cowper-Symonds model with the dynamic yield strength \( \sigma_d \) given as:

\[
\sigma_d = \left[ 1 + \left( \frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{n}} \right] \sigma_y + \gamma E_p \varepsilon_{\text{eff}}^p
\]  

(2)

where \( \varepsilon \) is its strain rate; \( \varepsilon_{\text{eff}}^p \) is its failure strain; \( \sigma_y \) is its static yield stress; \( C \) and \( p \) are its strain rate parameters used to characterize its sensitiveness; \( E_p \) is its plastic hardening modulus; and \( \gamma \) is the hardening constant. Table 2 lists the material parameters used in the calculation model [11].

| \( \rho \) (kg/m³) | \( E \) (GPa) | \( v \) | \( \sigma_y \) (Mpa) | \( E_p \) (Mpa) | \( P \) | \( \varepsilon_{\text{eff}}^p \) |
|---|---|---|---|---|---|---|
| 7800 | 210 | 0.3 | 1400 | 1215 | 4.47 | 0.6 |

4. Numeric simulation of warhead-target interaction process
In this numeric simulation, the ANSYS/LS-DYNA dynamic finite element program is applied to simulate the warhead’s target-penetrating process. The warhead hits the target in a vertical manner, that is, at an entry angle of 0° and an attack angle of 0°, with the initial velocity of 700 m/s. The erosive contact dynamics algorithm is employed to achieve the warhead-target interaction on the warhead-target impact interface. In addition, the voxel deletion method is used to model the failure of the structure.

4.1. Deformation and failure features of stiffened panel
Figure 4 shows the deformation and failure process of the stiffened panel subject to warhead impact. From the figure, clearly, the warhead-target interaction process can be divided into four stages. In the first stage, the warhead first hits the steel plate and interacts with the steel plate to penetrate the homogeneous steel plate. The presence of the stiffeners significantly increases the rigidity of the steel plate, preventing the steel plate from undergoing overall deformation, but forming a cross-shaped plastic deformation area in the warhead-target contact area, as shown in figure 5. Due to a short action time, a high-stress area is generated in the warhead-target contact area. Under the high compressive stress, the steel plate is forced to move forward. Therefore, the warhead penetrates through the target and leaves a warhead hole with a specific cross shape. In the second stage, its head begins to contact with the stiffener and continues to extrude forward, with the front arc part of the warhead reaming the hole on the target plate and the steel plate material attaching closely to the front arc part of the warhead (figure 4) and turning outwards under the circular and radial tensile stresses. The stiffener subject to extrusion of the warhead undergoes plastic deformation and failure. In the third stage, the
warhead plastically enlarges the hole, continuing to extrude forward and through the longitudinal and the rib web-plate and impacting on the rib wing-plate, causing the wing plate to fracture due to impact and extrusion. Due to the "cutting" effect of the web plate, a cross cut has left on the head of the warhead (figure 6). From the figure, clearly, the thickness and height of the web of the rib are significantly greater than those of the longitudinal, thus the length and depth of the cut in the vertical direction are evidently larger than those in the horizontal direction, as shown in figure 6. In the fourth stage, the warhead finishes its entire hole-reaming process, the cylindrical section of the warhead passes through the stiffened panel, and the entire target-piercing process ends. After that, the stiffeners in and around the warhead-target interaction area undergo a great plastic deformation, and the rib’s web plate is torn up and turned backwards with an turning angle exceeding 90°. The perforated hole bored through the stiffened panel structure shows a circular shape with a diameter slightly larger than the projectile’s and the edge of the target hole has four petal-shaped upturns, which are slightly different from those of 6 or 8 upturns cut through and left on the homogeneous thin steel plate by the pointed oval warheads.

![Figure 4. Warhead’s target-penetrating process.](image1)

![Figure 5. Process of destruction of steel plate (plastic deformation).](image2)

![Figure 6. Deformation and failure of the nose of projectile.](image3)
4.2. Analysis of warhead’s force characteristics

Figure 7 shows warhead’s velocity and acceleration curves during the interaction with target. The data collecting frequency in the figure is 1000 KHz. The warhead’s force characteristics were analyzed according to the varying trend of these curves in combination of the images of target-piercing process. In the first stage, after warhead contacts with target, the missile’s acceleration reaches its peak of about 10500 g within a short period of time (≤0.1 ms). At this time, the interaction of the projectile with target is that first the warhead contacts with the steel panel, then the steel plate material, longitudinals and ribs’ wob plates under the extruding force move forward, and last the warhead leaves a hollow on the face of the panel and forms a bulge on its back, as shown in figure 9. In the second stage, the warhead’s acceleration, after reaching its peak, enters a oscillating and descent process (≤0.5 ms). In this stage, the warhead-target interaction state is that the warhead has been plastically reaming the steel plate and the reinforced structure, compressing and penetrating and stacking plate material and resulting in plastic bending deformation and failure, as shown in figure 8b. From the change in the warhead’s velocity point of view, shown in figure 8, the decay of its velocity within the first two stages accounts for about 72% of the total in the whole penetration process. In the third stage, when the acceleration drops to about 3000 g, the warhead impacts the 16.7 mm thick and 160 mm wide rib wing plate, as shown in figure 9 and the acceleration amplitude jumps to 8000g. After the rib wing breaks and fails at 0.8ms, as shown in figure 8d, the whole target-piercing and hole-reaming process basically finishes, the forward resistance to the warhead disappears, the acceleration drops close to zero, and the residual speed of the projectile is about 665.3 m/s.

Figure 7. Relationship of warhead’s acceleration to time.

Figure 8. Relationship of warhead’s velocity to time.

Figure 9. Process of warhead-target interaction.
5. Equivalent design of stiffened panel structure

5.1. Equivalent design based on energy method

In a previous report [5], the stiffened panel structure shown in figure 1 was essentially considered equivalent to a single-layer, 60 mm thick homogeneous ship steel plate using the energy method. In this study, we used the established corresponding numerical simulation model shown in figure 10 and found the residual velocity of the warhead after penetrating the 60-mm thick homogeneous 921A ship steel plate under the same initial conditions is about 665.4 m/s, which is very close to a very that of 665.3 m/s calculated from the stiffened panel frame, as shown in figure 11, indicating that both are equivalent in their ability to absorb the kinetic energy of the warhead.

![Figure 10. Finite element analysis mode.](image1.png)

![Figure 11. Velocity curves of projectile.](image2.png)

Figure 12 shows the acceleration curves of the warhead of these two targets to compare their peaks, lasting times, and overall varying trends. The maximum acceleration of the warhead is about 15600 g when cutting through the 60-mm thick homogeneous target plate and is about 10500 g when penetrating the stiffened panel frame, the former is about 48% higher than the latter. In terms of their duration through the target, the presence of stiffeners increases the warhead-target interaction time and the pulse width compared to those of the 60-mm thick homogeneous target. The similar results are obtained from the varying curves of their velocities as shown in figure 9b also indicate that the time is longer for the projectile to drop its velocity at penetrating the stiffened panel to the balanced state. In addition, the overall acceleration trend for the 60-mm thick homogeneous target is similar to a triangular pulse load, that is the acceleration of the warhead after reaching the peak decays quickly until reaching its balanced state while that of the stiffened panel are characteristic of low amplitude, long pulse width and multiple peaks as the acceleration of the warhead after reaching the peak falls in an oscillating and descent process with two jumps.

![Figure 12. Comparison of the acceleration curves of the projectile.](image3.png)
From above analyses, it is clear that although the final residual speed of the warhead penetrating the two kinds of targets is the same, their force characteristics and speed change processes are significantly different.

5.2. Equivalent design based on load characteristics

Based on the above-mentioned difference of the single-layer homogeneous target and the stiffened panel in response to warhead’s acceleration, we put forward an equivalent design method based on the load characteristics and the energy equivalent principle. Its core design idea is to perform the equivalent design according to the acceleration varying features of the warhead in its actual target penetration process to realize similar speed variation trend and value. The specific design process is as follows:

1) According to their positioning order, make the steel panel, longitudinal and rib of the stiffened panel equivalent to that of a single-layer, homogeneous steel plate, respectively.

2) Find the thickness of the first layer steel plate. Starting from the 30-mm thick panel, considering the contribution of the longitudinal and rib to the overall stiffness, with the inertial moment of the stiffened panel in the thickness direction as the target value, which can be directly extracted from the 3-D modeling software, use the approximation principle to make the panel equivalent to a steel plate of uniform thickness. The thickness of the first-layer steel plate is calculated to be 34 mm and 35 mm.

3) Find the thickness of the 2-nd layer steel plate, which is used to simulate the extrusion and plastic reaming of the warhead on the longitudinal and rib web plate. In brief, first calculate the masses of both longitudinal and rib web plate within the range of 1.5 to 2 times the cross section of the warhead body and then make them equivalent to the homogeneous steel plate of the same cross section based on the same total mass. After calculation, the thickness of the layer is determined to be 13 mm, 15 mm and 17 mm.

4) Find the thickness of the 3-rd layer steel plate, which is used to model the impact of the warhead on the rib wing plate. Given the thickness of the wing plate is 16.7 mm and considering that the width of the wing plate (160 mm) is smaller than the diameter of the warhead, the thickness of this layer is determined to be 14 mm, 15 mm and 16 mm.

5) Find the spacing between equivalent steel plates. Referring to the heights of actual longitudinal and rib web plates, such as the height of the rib web plate is 240 mm, the spacing between the 3rd layer target plate and the 1st layer target plate is determined to be 240 mm.

6) Numerically simulate the penetration of the warhead through 3 layers steel plates. First, compare the speed curves and acceleration curves of both stiffened panel and its equivalent steel plates after completing one working condition calculation. Second, adjust the total thickness of the 3 layers of targets according to the residual velocity, and the thickness or spacing of each layer of target according to the acceleration curve.

Using the above method, after calculating and adjusting 2 to 3 times, one can usually obtain satisfactory results. In this study, the stiffened panel shown in figure1 is considered equivalent to a 3 layered, homogeneous 921A steel plates with their corresponding thickness of 35 mm, 15 mm and 16 mm, as shown in figure14.

**Figure 13.** Stiffened panel.  
**Figure 14.** 3 layered spacing steel plate.
Figure 15. Comparison of the history curves of the warhead’s velocity.

Figure 16. Comparison of the history curves of the warhead’s acceleration.

The residual speed of the warhead after penetrating the equivalent 3 layered target is 666.1 m/s and that after penetrating the stiffened panel is 665.3 m/s (as shown in figure 15), with a difference of only 0.12%, indicating that both have same ability to absorb the kinetic energy from the warhead. Moreover, both of them have a good similarity in acceleration peak, duration, and overall changing trend, as shown in figure 16. In order to more intuitively express the correlation between the two, we introduce the Pearson correlation index \( r \) in the statistical analysis to reflect the similarity of the two curves. The Pearson correlation index is defined as follows:

\[
    r = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \overline{y})^2}}
\]  \( (3) \)

where \( x_i \) corresponds to the velocity or collected acceleration data of the stiffened panel;

\( y_i \) corresponds to the velocity or collected acceleration data of the equivalent target;

\( \overline{x} = \frac{1}{n} \sum_{i=1}^{n} x_i, \)

\( \overline{y} = \frac{1}{n} \sum_{i=1}^{n} y_i, \) \( -1 \leq r \leq 1, \) the larger the \( r \) value, the stronger the correlation between them.

Table 3 lists the results of correlative analysis. From the table, it is obvious that the stiffened panel is equivalent to the 3 layered target plate with correlation index of the speed changing curves of the warhead during penetrating these two targets being 0.9963, and the correlation index of their acceleration curves being 0.8843, and these indexes increase to 0.9648 and 0.7895, by 3% and 12%, respectively, when the stiffened panel is equivalent to the 3 layered, 60mm thick homogenous target plate, indicating that the equivalent design is more reasonable.

Table 3. Correlation analysis results.

| Target type                      | Initial speed (m/s) | Residual speed (m/s) | Acc. Peak (g) | Corr. Index \( r \) |
|----------------------------------|---------------------|----------------------|---------------|----------------------|
| Stiffened panel                  | 700                 | 665.3                | 10500         | 1                    | velocity curve |
| 60-mm steel plate                | 700                 | 665.4                | 15600         | 0.9648               | acceleration curve |
| 3 layered spacing steel plate    | 700                 | 666.1                | 11400         | 0.9963               |                 |
6. Conclusion
The stiffened panel structure utilizes its overall plastic deformation and failure as well as the large bending of its rib beam structure to consume the velocity of the projectile. Compared with the single-layer, homogeneous steel target, the warhead’s load curve is characteristic of low amplitude, long pulse width and multiple peaks.

The equivalent design based on load characteristics uses the warhead-target interaction process as the design reference and can more truly simulate the force environment of the warhead. Compared with the equivalent design based on the energy method that only considers the target-piercing speed loss, the former is more reasonable. The equivalent design method discussed in this paper can be generalized. The obtained results are applicable not only to the warhead used in this study but also to those with similar outline dimensions and mass.

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