

Ultimate Strength of Hull Perforated Plate Under Extreme Cyclic Loading

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Abstract: In this study, the influence of opening parameters on the ultimate strength of perforated plates subjected to extreme cyclic loading in the presence of material kinematic hardening and isotropic hardening was analyzed. It is found that the ultimate strength of the perforated plates decreases rapidly and stabilizes in the first four cycles. Plates with oblong openings have a greater ultimate strength compared to plates with rectangular openings, while the relative strengthening ratio decreases over the duration of the cycle. The location of the openings is also an important parameter that affects the strength of the structure, as the plates with openings close to the edges in the longitudinal direction have higher strengths, while in the transverse direction the strengths are higher when the openings are close to the center. Among the three opening-strengthening methods compared, the Carling stiffener method maintains a better strengthening effect under cyclic loads for many periods.

Key words: extreme cyclic loading; perforated plate; ultimate strength

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0 Introduction

Ultimate strength is the maximum level of strength that a structure can achieve when subjected to external loading or stress. Structural design based on ultimate strength maximizes material potential and reduces costs compared to structural design based on elasticity theory and maximum stress guidelines. Hull openings are a common form of structure where openings can be used for inspection, ventilation, light, or to reduce structural weight^[1]. DNV has a series of specifications for openings in longitudinally loaded members such as deck plates and double bottom plates^[2]. Openings reduce the buckling and ultimate strengths of structural components, and therefore the effect of openings must be considered in buckling and ultimate limit state design^[3]. Most of the ultimate strength analyses performed so far have been carried out in monotonic compression^[4], whereas actual ships sailing in wind and waves often encounter repetitive, extreme cyclic loads that near the ultimate strength. In this case, the hull structure will experience plastic deformation and cumulative damage during the cycles, thus reducing its ultimate strength after cyclic loading and weakening the ship's

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ability to face severe sea conditions. Therefore, it is of great practical significance to consider the ultimate strength of the perforated plates after such extreme cyclic loading.

Studies on open-ended plates have been mainly focused on monotonic compression. Narayanan et al^[5] conducted compression experiments on simply supported open-ended square plates and proposed an approximate method to evaluate the ultimate load carrying capacity of simply supported perforated plates under uniaxial compression using a simple elastic-plastic concept. Shanmugam et al^[6] extensively investigated the parameters of plate length and slenderness, opening dimensions, boundary conditions and load properties under different boundary conditions and load forms, and proposed an equation for predicting the ultimate strength of perforated plates under different boundary conditions and load forms assuming that the ratio of ultimate load to extrusion load is a function of the ratio of plate width to thickness and the ratio of opening dimensions. Paik conducted a series of studies on the ultimate strength characteristics of open-ended plates under short-edge axial compression^[7], edge shear^[8], and combined biaxial compression and edge shear loading^[9]. Wang et al^[10] calculated buckling strength (eigenvalues) and ultimate strength, and conducted a detailed analysis of the structural behavior of perforated plates. The introduction of a strength reduction factor, relative to a panel without an opening, served to quantify the strength decrease induced by the opening. Furthermore, their study observed stress concentration issues in the vicinity of the opening's hotspots. Saad-Eldeen et al^[11] conducted experiments on plates with a large central elongated circular opening under uniaxial compression. Force-displacement relations, dissipation energy, strength-strain relations, rebound forces, toughness and collapse modes were analyzed. In addition, the strength of perforated plates considering corrosion^[12], crack damage^[13] was also investigated by Saad-Eldeen et al. Ranji et al^[14] evaluated the square openings and partially rounded corners of the plates under uniaxial compression, it was found that the rounded corners of the openings had a strong reducing effect on the stress concentration factor, but had little effect on the ultimate strength of the perforated plates.

Most of the ultimate strength studies have focused on the ultimate strength behavior of hull plates under monotonic incremental loads. Considering the motion and deformation of hull beams in waves, the study of the ultimate load carrying capacity of hull structures under cyclic loading may be more realistic^[15]. Yao et al^[16] conducted a series of elasto-plastic large deflection analyses of plates subjected to in-plane cyclic loading using the finite element method and found that the residual deflection after unloading in the compression range increased with the increment of applied compression strain. Cui et al^[15] proposed a new approach to construct the average strain-average strain relationship based on previous studies. Comparison of the method with the experimental results of cyclic uniaxial compression of hull plates reveals that the proposed method is able to easily and accurately construct the average stress-average strain relationship of hull plates under cyclic compression. Li et al^[17] proposed an analytical method for the buckling and collapse behavior of plates and stiffened panels under cyclic loading and pointed out that the reversal and accumulation of plastic deformation and local buckling may permanently reduce the resistance of the structure to the subsequent structure. Xia et al^[4] considered three cyclic loading conditions to study crack exten-

sion due to low circumferential fatigue damage. When the cyclic load amplitude was less than the monotonic incremental load ultimate strength, the overall residual stresses and residual deformations induced by cyclic loading were too low to affect the residual ultimate strength of the plate. Paik et al^[18] conducted a full-scale collapse test on the substructure of a completed 1900 TEU container ship. Hu et al^[19] used a bilinear isotropic hardening model to consider crack extension under extreme cyclic loading. Li et al^[20] investigated the ultimate strength problem of hull plates under complex cyclic loading forms. The longitudinal and transverse cyclic loads were also considered, and the lateral pressure on the hull plate was also considered, and an equation was proposed to predict the ultimate strength by integrating various factors.

From a comprehensive view of the existing studies, the ultimate strength of open-ended plates under monotonic compression and more complex forms of combined loading without considering extreme cyclic loading has been studied comprehensively. The ultimate strength problem after undergoing multiple cycles of extreme loading has gradually received more attention. In this paper, we focus on the residual ultimate strength of open-ended plates after extreme cyclic loading, and conduct a parametric study on different cycle periods, opening shapes, opening positions and other parameters to analyze the influence of openings on the accumulation of cyclic plasticity and ultimate strength decrease. Finally, the optimal design of the structure is carried out with the help of genetic algorithm in order to find the balance between safety and economy of the hull perforated plates.

1 Finite element model

1.1 Geometric parameters

In this paper, a hull plate of length and width $a \times b = 2400 \text{ mm} \times 800 \text{ mm}$ is used. The plate thickness $t=15.60 \text{ mm}$, slenderness $\beta = b/t \cdot \sqrt{\sigma_y/E} = 2$, where σ_y and E are the yield strength and elastic modulus of the material, respectively. The long side of the plate is the longitudinal side of the ship, and the short side corresponds to the transverse side of the ship, as shown in Fig.1. The openings are mainly rectangular, circular and oblong, and the size of circular openings is usually between 100 mm and 600 mm. Inspection holes are usually oblong in shape and have dimensions of 400 mm×600 mm or 600 mm×800 mm^[10]. The parametric nomenclature of the openings is shown in Tab.1.

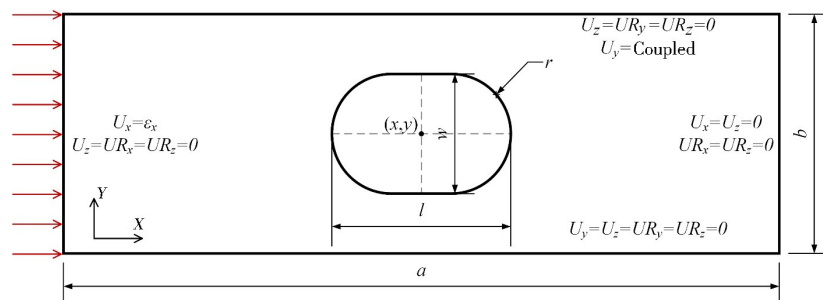


Fig.1 Geometric and boundary conditions

Tab.1 Nomenclature of opening parameters

Italic symbols	Symbolic meaning	Italic symbols	Symbolic meaning
x	Longitudinal position of the center of the opening.	y	Transverse position of the center of the opening.
$x_r=x/a$	Ratio of the longitudinal position of the opening to the length of the plate.	$y_r=y/b$	Ratio of the transverse position of the opening to the width of the board.
l	Longitudinal length of the opening.	w	Transverse length of the opening.
$l_r=l/b$	The ratio of the longitudinal length of the opening to the width of the board.	$w_r=w/b$	The ratio of the transverse length of the opening to the width of the board.
r	Radius of the corner of the opening.	$r_r=r/\min(l, w)$	The ratio of the radius of the rounded corners of the opening to the width of the opening.

1.2 Material

Conventional hull ultimate strength analysis does not consider the ratchet and Bauschinger effects of steel, and this simplification leads to an overestimation of the safety margin of the ship^[21]. Combined hardening is a hardening method that considers both kinematic and isotropic hardening, mainly for reverse and cyclic loading. Therefore, the combined Chaboche hardening model considering the ratcheting effect and the Bauschinger effect is suitable for the study.

The yield surface of this material is defined in terms of the Mises yield criterion as shown in Eq.(1):

$$f = J_2(\sigma - \alpha) - \sigma^0 = 0 \quad (1)$$

where, J_2 is the second invariant of the stress bias considering the back stress α , σ and α denote the stress tensor and back stress respectively. The back stress can reflect the plastic loading history and represents the central coordinate of the elastic range (yield surface) of the material. The initial back stress is 0. When the material enters the plastic state again, the back stress represents the difference between the subsequent yield stress and the initial yield stress. The expression of J_2 is given as

$$J_2(\sigma - \alpha) = \sqrt{\frac{3}{2} (S - \alpha^{\text{dev}}):(S - \alpha^{\text{dev}})} \quad (2)$$

where, S and α^{dev} are the bias parts of σ and α respectively, and the sign ‘:’ denotes the inner product operation.

The size of the elastic zone σ^0 in isotropic hardening is described by an exponential function of the equivalent plastic strain $\bar{\varepsilon}^{\text{pl}}$ as

$$\sigma^0 = \sigma|_0 + Q_\infty(1 - e^{-q\bar{\varepsilon}^{\text{pl}}}) \quad (3)$$

where, $\sigma|_0$ is the initial yield strength when the plastic strain is zero, which is numerically equal to the yield stress and therefore still expressed by σ_y ; Q_∞ is the maximum value that can be reached by the yield surface dimensions; q is the constant coefficient of the exponential value of the exponential function that determines the rate of change of the yield surface dimensions; $\bar{\varepsilon}^{\text{pl}}$ is the equivalent plastic strain, a parameter that does not decrease throughout the plastic deformation process and reflects the accumulation of plastic strain as shown below:

$$\bar{\varepsilon}^{\text{pl}} = \int \sqrt{d\varepsilon^{\text{pl}}d\varepsilon^{\text{pl}}} \quad (4)$$

where ε^{pl} is the plastic strain tensor.

The behavior of kinematic hardening is defined by superimposing a pure kinematic term and a relaxation term shown as

$$\dot{\alpha}_{ij} = \sum_i \left[C_i \frac{1}{\sigma_0} (\sigma_{ij} - \alpha_{ij}) \dot{\epsilon}_p - \gamma_i \alpha_{ij} \dot{\epsilon}_p \right] \tag{5}$$

where, C is the initial kinematic hardening modulus, and γ determines the rate at which the kinematic hardening modulus decreases with the increasing plastic deformation, both of which need to be obtained in cyclic tests.

The total back stress is achieved by summing the N kinematic hardening components. Chaboche^[22] suggested the use of three back stresses to model the steel.

The material parameters of S275 steel in this paper are referred to the results of Ref.[23], the validity of which has been verified in the literature with the help of ABAQUS, as shown in Tab.2.

Tab.2 Material parameters

Elastic behaviour			Hardening behaviour							
			Kinematic hardening					Isotropic hardening		
E	ν	σ_y	C_1	γ_1	C_2	γ_2	C_3	γ_3	Q_∞	q
207 000	0.3	315	13 921	765	4240	52	1573	14	25.6	4.4

1.3 Model setup

The setting of boundary conditions affects the accuracy and credibility of the finite element simulation results. The hull plate is surrounded by strong members, which usually do not fail before the plate^[7]. These components constrain the free displacement of the plate edges within the plate surface with less constraint on rotation. Therefore, it is reasonable to choose simply supported boundary conditions to restrain the edges of the plate. Compared to plates with clamped edges, perforated plates with simply supported edge constraints have lower strength^[6], and therefore the calculations are more conservative. The specific boundary conditions are shown in Fig.1, where U denotes the displacement and UR denotes the turning angle. In the simulation with the finite element software ABAQUS, the hull plate is modeled with S4R cells, assuming that it is a typical shell structure.

In this paper, the initial defect is defined as the initial deformation form shown in Eq.(6) of the model, without considering the residual stresses of the model.

$$w_0 = A_0 \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{\pi y}{b}\right) \tag{6}$$

where, m denotes the longitudinal half-wave number of the hull plate, the size of which depends on the aspect ratio of the plate. And when a/b is an integer, $m=a/b$. The half-wave number $m=3$ for this model. A_0 denotes the vertical initial deformation amplitude of the plate surface, which is usually divided into three amplitude calculation methods: slight ($0.025\beta^2t$), average ($0.1\beta^2t$) and severe ($0.3\beta^2t$)^[1]. In this paper, the initial defect amplitude is taken as the average level.

When the ship is in hogging and sagging states during the motion, the longitudinal local members are mainly subjected to tensile and compressive loads. Open deck plates and open double bottom plates belong to this category. During the service of a ship, these plates are usually subjected to multiple extreme loads, which result in cumulative plastic damage. The presence of damage reduces

the load-bearing capacity of the perforated plates, which eventually fails at strength condition less than the original ultimate strength. Therefore, it is necessary to study the ultimate strength of the hull plate containing material damage after experiencing extreme sea conditions in order to accurately assess the safety of the hull structure.

The main parameters of the extreme cyclic load are the amplitude ε_x and the number of cyclic cycles p . Here, ε_x represents the ratio of the displacement Δx under compressive load to the length a of the ship hull plate. The loading curves for four cycles of extreme cyclic loading are shown in Fig.2 with the first 16 s being the cyclic cycles of extreme loading, and the ultimate strengths studied in this paper are obtained by applying the failure load at the end of the cycle. When the number of cycles studied is reduced, the failure load is still applied after the action of the extreme cyclic load. For comparison with existing studies, the case of $p=0$ is used to represent monotonic loading. It should be noted that the time of the horizontal coordinate in the figure is a pseudo time. It is just an auxiliary parameter introduced for the purpose of solving and does not represent the real time. Although there are high-stress areas around the opening that could lead to the formation of fatigue cracks, it is essential to emphasize that this paper focuses specifically on strength-related issues and does not encompass discussions regarding fatigue and crack-related problems. A design with adequate strength and stiffness would substantially reduce the likelihood of cracking failure around an opening^[10].

The setup was implemented in the commercial finite element software ABAQUS, utilizing a static implicit solver with the incorporation of the arc-length method for nonlinear finite element analysis. The solution process involved employing the Newton-Raphson iterative method, accounting for material nonlinearity and geometric nonlinearity. The structural elements used in the analysis were reduced integration S4R shell elements. The plate with $\beta=2.0$, $l=400$ mm, $w=400$ mm, $r_r=1$ opening was taken for mesh convergence analysis. By comparing the analysis, the convergent solution can be obtained when the overall mesh size is 20 mm, and the mesh size of opening is 5 mm for refinement.

2 Results and Discussion

This chapter discusses the effects of different extreme load cycle periods, opening shapes, locations and opening strengthening types on the ultimate strength based on the equivalent plastic strain, equivalent stress and hysteresis curve, the mechanism of the accumulation of plastic damage and stress concentration phenomenon around the opening leading to the decrease of ultimate strength is analyzed.

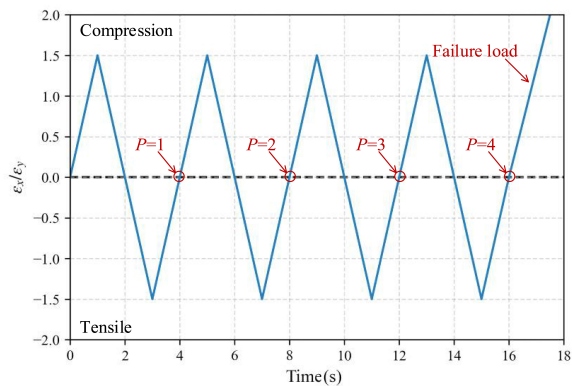


Fig.2 Loading history of longitudinal loads

2.1 Influence of cycle number and load amplitude on ultimate strength

To discuss the mechanism of the action of cyclic cycles on the ultimate strength of hull plates, an oblong perforated plate with a typical opening shape of $l=600$ mm and $w=400$ mm was taken for the study. Fig.3(a) shows the ultimate strength decrease curve for ten cyclic cycles, and it can be seen from the figure that the ultimate strength of the hull plate decreases significantly when it undergoes extreme load action for 1–4 cycles. From the fifth cycle onwards, the ultimate strength basically ceases to change when the number of cycles increases. The structure may have entered a shakedown state and no longer experiences significant plastic deformation with the loading action. The convergence of the compressive ultimate strength to a constant compressive ultimate strength value is usually observed after three loading cycles in a study of intact plates by Li et al^[17]. By comparing the ultimate strength drop curves of intact and perforated plates, it can be found that the trend of ultimate strength drops after experiencing a single extreme load ($p=1$) is slightly different, and the strength drop of perforated plates is more obvious compared to intact plates. The concentrated effect from the opening may be a key factor in the rapid decrease of ultimate strength in a single cycle. Fig.3(b) shows the hysteresis stress–strain curve expressed in dimensionless form, with the open structure reaching ultimate strength earlier. After undergoing compression to tension, the tensile load loading resulted in a highly nonlinear response with a stiffness much lower than E . This is similar to the conclusion reached in a study of intact plates by Goto et al^[24]. It is evident that the plastic damage of the hull plate is mainly generated in the first four cycles, and thus the ultimate strength decreases significantly in this phase. The subsequent study focused on the number of cycle periods that can significantly affect the ultimate strength for discussion, taking the cycle period $p=0-4$.

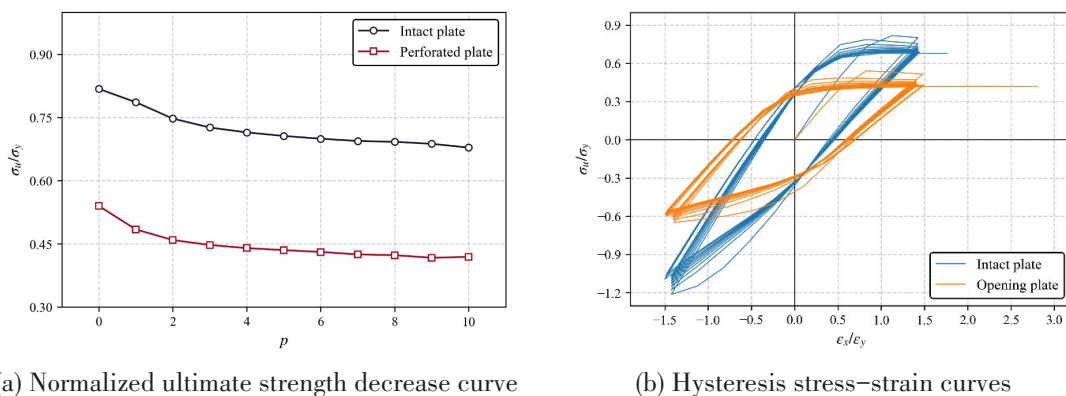
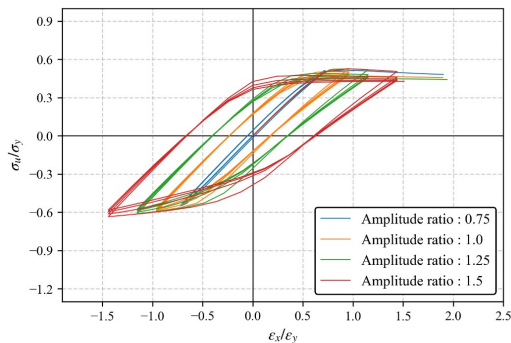


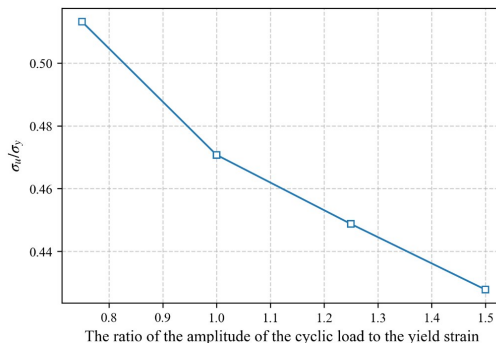
Fig.3 Normalized ultimate strength decline curves and hysteresis stress–strain curves for intact and perforated plates

Furthermore, the influence of cyclic load amplitude on the structural strength is discussed. Fig.4 illustrates the non-dimensional stress–strain curves of the structure and the normalized ultimate strength (the ratio of ultimate strength to yield strength) under different ratios of cyclic load amplitude (the maximum value of cyclic load to yield strain). From Fig.4(a), it can be observed that when the ratio is less than 0.75, there is almost no accumulation of plastic damage, which is not within the scope of this study. As the ratio increases to 1, the response during cycles changes. Fig.4(b) reveals that with the increase in cyclic load amplitude, the ultimate strength decreases after the same number of cycles. At a ratio of 1.5, the difference compared to a ratio of 1 does not exceed 0.04. The

conclusion is consistent with existing studies^[4, 18]. Subsequently, ε_x is taken as 1.5 times the yield strain ε_y (the ratio of material yield strength σ_y to elastic modulus E).



(a) Hysteresis stress-strain curves



(b) Normalized ultimate strength varying with the ratio of amplitude of cyclic load

Fig.4 Effects of different cyclic load amplitudes

2.2 Effect of opening shape on ultimate strength

When the shape of the opening changes, the response of the plate when subjected to loads also changes accordingly. Circular and oblong openings are recommended in codes, however, the use of rectangular openings is often unavoidable in structural design^[14]. In view of the full discussion of the strength changes due to rounded corners, the parameter r_r , which represents the ratio of rounded corners of rectangular openings, is designed (Tab.1 and Fig.5). With this definition, a circular opening or an oblong opening can be a rectangular opening when $r_r = 1$. It should be noted that this parameter is only used to study the variation rule of strength brought about by the rounded corner of the opening, and the focus of the study is still on oblong and rectangular openings.

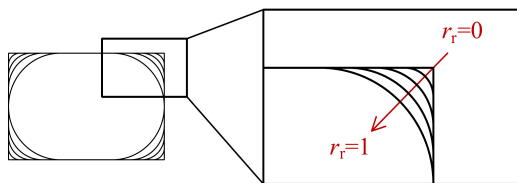


Fig.5 Schematic diagram of opening rounded corners

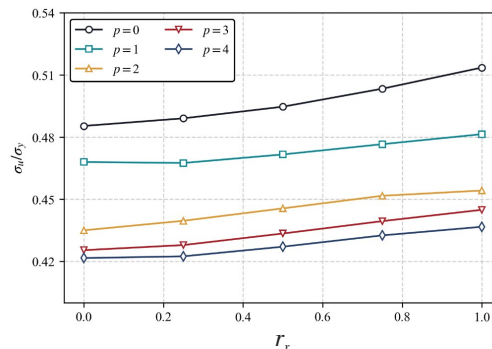


Fig.6 Variation of normalized ultimate strength with rounding ratio at different cycle periods

Fig.6 shows the ultimate strength curves for cycles $p=0-4$ with the ratio of the rounded corners as the horizontal coordinate. It is obvious that setting the filleted corner always enhances the ultimate strength of the perforated plates in four cycles, and the larger the ratio of fillet radius, the larger the ultimate strength. Fig.7 shows a comparison of two plastic accumulation damages with different opening shapes. It can be observed that the damage in the rectangular opening is highly concentrated at the corners, while the damage in the elongated circular opening is relatively uniformly distributed on both sides of the opening. However, despite the enhancement of the ultimate strength of the structure due to the rounded corners, comparison of the trends of the different curves in Fig.6

shows that the enhancement effect due to setting the rounded corners decreases with the increase of the cycle period. This indicates that the stress concentration brought by the right angle is no longer the key factor leading to the strength degradation.

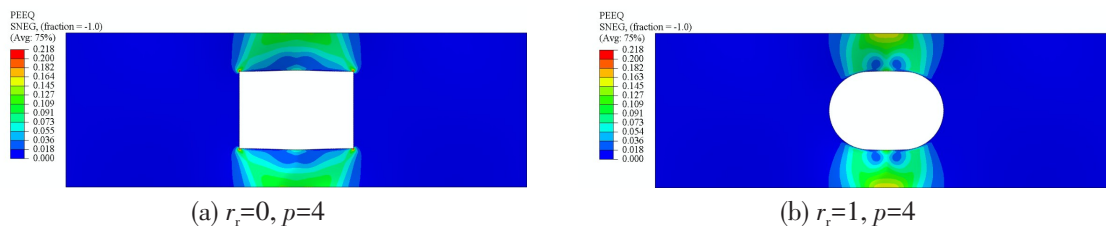


Fig.7 Equivalent plastic strain at the end of the cycle

To further examine the enhancement effect brought by rounded corners, the strength enhancement ratio η is defined as

$$\eta = \frac{\sigma_{uc} - \sigma_{ur}}{\sigma_{ur}} \times 100\% \tag{7}$$

where σ_{uc} and σ_{ur} are the ultimate strength of the perforated plate for $r_r=1$ and $r_r=0$, respectively. Different aspect ratios of the opening $\delta=l/w$ are taken to further discuss the variation law of η . The transverse length of fixed opening $w=400$ mm and the longitudinal length of opening l are 200 mm, 300 mm, 400 mm, 500 mm, 600 mm, and 800 mm, corresponding to aspect ratios of the opening $\delta=l/w$ of 0.75, 1, 1.25, 1.5 and 2, respectively.

Fig. 8 shows the results of relative enhancement ratio η with the variation of aspect ratio δ . As can be seen from the figure, the maximum relative enhancement ratio almost always occurs in the model with aspect ratio $\delta=1$, and both increasing and decreasing δ leads to a decrease in the enhancement ratio η . Ranji and Alirezaee noted that the ultimate strength of the circular perforated plate is only 4% higher than that of the square one^[14]. In cyclic loading, the strength enhancement ratio is obviously higher.

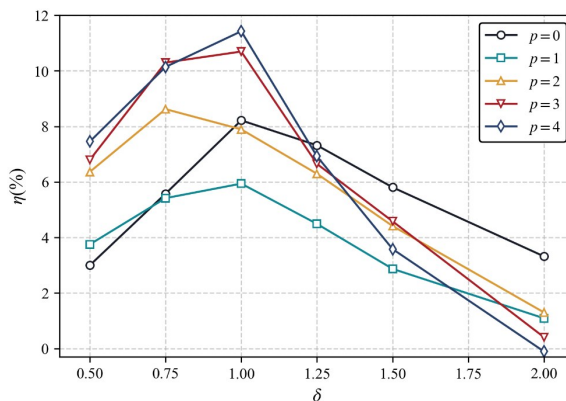


Fig.8 Percentage of enhancement of a rounded opening relative to a rectangular opening varying with period

2.3 Effect of opening position on ultimate strength

The position of the opening affects the ultimate strength. The perforated plate with $l=600$ mm and $w=400$ mm is taken as the research object. Fig.9 shows a comparison of the effects of the ratio of the longitudinal and transverse positions on the ultimate strength. From Fig.9(a), the hull plate with the opening arranged at the longitudinal center has the least ultimate strength for monotonic compression and extreme cyclic loading cycle $p=1$. And the ultimate strength of the plate is maximum when the opening is located at $x_r=0.25$ and symmetric position $x_r=0.75$. As the cycle period increases, the position of the opening corresponding to the maximum strength is closer to the longitudinal edge. The difference in ultimate strength due to the change in the longitudinal position of the opening is gradually reduced. This is consistent with the prediction of Kim et al^[3] that the ultimate

strength may be the smallest when the openings are located in the center.

The effect of the transverse position on the ultimate strength of the structure differs from that of the longitudinal position, as shown in Fig.9(b). From the transverse center to both sides, the ultimate strength decreases rapidly, and this difference is much larger than the effect brought by the longitudinal position. As the cycle period increases, the difference in ultimate strength due to the change in transverse position of the openings gradually decreases, but the fact that high strength at the center and low strength at the sides remains unchanged. Placing openings around the strong members in the main load-bearing direction helps to enhance the load-bearing capacity of the structure, while placing them in the center without reinforcement is not conducive to the load-bearing capacity of the structure.

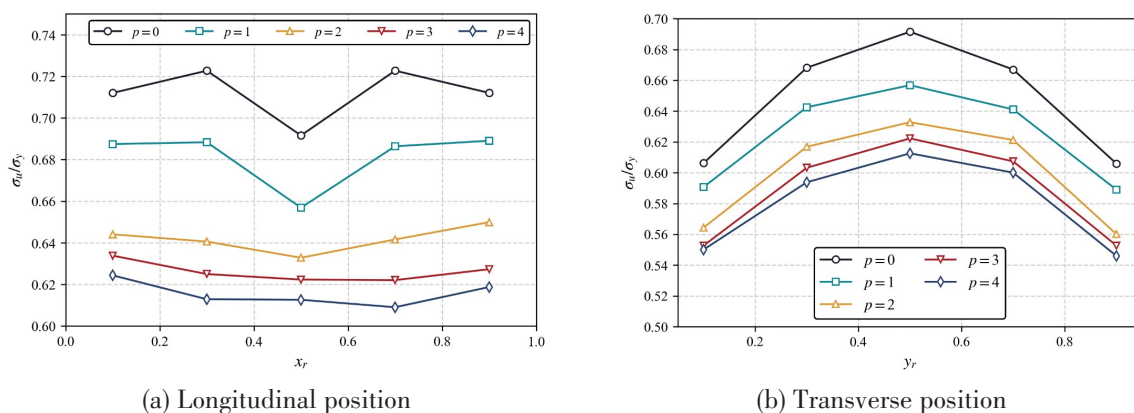


Fig.9 Effect of opening position on normalized ultimate strength

2.4 Effect of reinforcement on ultimate strength

The actual ship perforated plate is usually provided with some local reinforcement structure around the opening, and the strengthened plate has higher strength^[25]. However, the ultimate strength of the perforated plate after extreme cyclic loading has not been studied yet. To address this issue, three typical types of local reinforcement are considered: (a) Carling stiffener; (b) face-plating; (c) doubling plate stiffener, as shown in Fig.10.

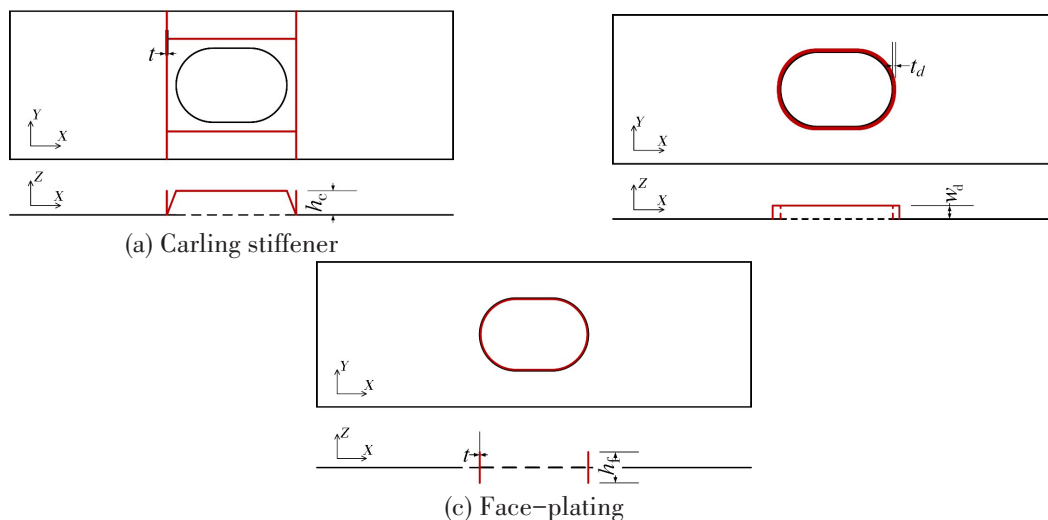


Fig.10 Schematic diagram of the opening reinforcement structure

The three methods of reinforcement are discussed using a perforated plate with $l=600$ mm and $w=400$ mm. The dimensions of the reinforcement are shown in Tab.3. One of the topics in the marine industry is to reduce the weight of the ship and save raw materials^[26]. Therefore, when using reinforcement, the strength gain from the mass or volume of the reinforcement is an important parameter to judge the effectiveness of the reinforcement. In this paper, assuming that the reinforcement material is the same as the plate, the reinforcement volume ratio v_r is defined as the ratio of the reinforced perforated plate volume V_s to the perforated plate volume V without reinforcement, as shown in Eq.(8).

$$v_r = \frac{V_s}{V} \tag{8}$$

Tab.3 Geometry of the opening reinforcement structure

Carling stiffener		Face-plating		Doubling plate stiffener		
h_c /mm	v_r	h_r /mm	v_r	w_d /mm	t_d /mm	v_r
50	1.08	80	1.08	40	30	1.07
60	1.10	100	1.10	50	30	1.09
70	1.12	120	1.12	60	30	1.11
80	1.13	140	1.14	70	30	1.13
90	1.15	160	1.15	80	30	1.15

Fig.11 illustrates the decreasing pattern of the relative ultimate strength of the three methods of reinforcement with cyclic cycles. The gain of doubling method is always lower than the other two types of reinforcement. The relative ultimate strength of the Carling method is less than that of the face-plating method at $p<2$ and is comparable in level at $p=2$. The relative ultimate strength of the Carling method is better than that of the other methods at $p>2$. From the overall trend, the ultimate strength of the three methods decreases linearly during the cyclic process, while the decline curve of the Carling method is the flattest. It can be said that under the action of longitudinal extreme cyclic loading, the Carling stiffener perforated plate can better cope with the cyclic action of multiple extreme loads.

In comparison of the strength gain effect of the three strengthening methods with increasing volume of the strengthened structure, Fig.12 is plotted with the relative volume as the horizontal co-

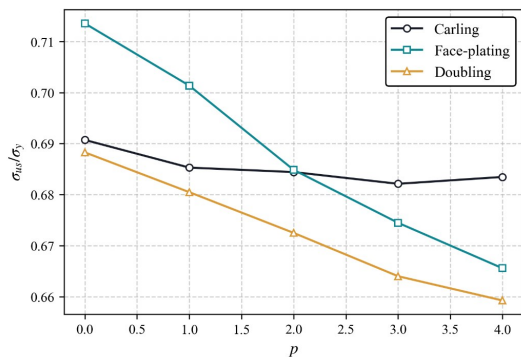


Fig.11 Variation of normalized ultimate strength of plates with different forms of reinforcement under extreme cyclic loading

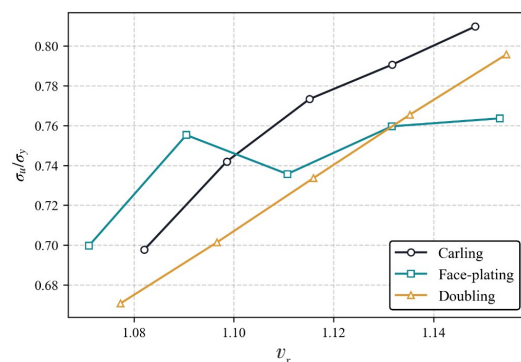


Fig.12 Variation of normalized ultimate strength with relative volume

ordinate and the dimensionless ultimate strength as the vertical coordinate. It can be found that in terms of pure ultimate strength, both the doubling method and the Carling method bring an approximately linear increase in strength gain with increasing volume of the strengthened part. In contrast, the strength gain of the face-plating method does not increase accordingly.

Fig.13(a), (c), and (e) show the equivalent plastic strains of the plate for the three reinforcement methods after four cycles. Comparing the three strengthening methods, the Carling method localizes the plastic zone inside the transverse reinforcement, while the plastic damage in the other cases gradually expands from the opening to the sides. Fig.13(b), (d), and (f) show the stress in the ultimate limit state of the plate with the three strengthening methods after four cycles. The Carling method causes the stresses to be concentrated in the regions on both sides of the opening. The Doubling plate method results in the appearance of the lowest stress zone on both sides of the opening, where the strengthening component bears a relatively higher load.

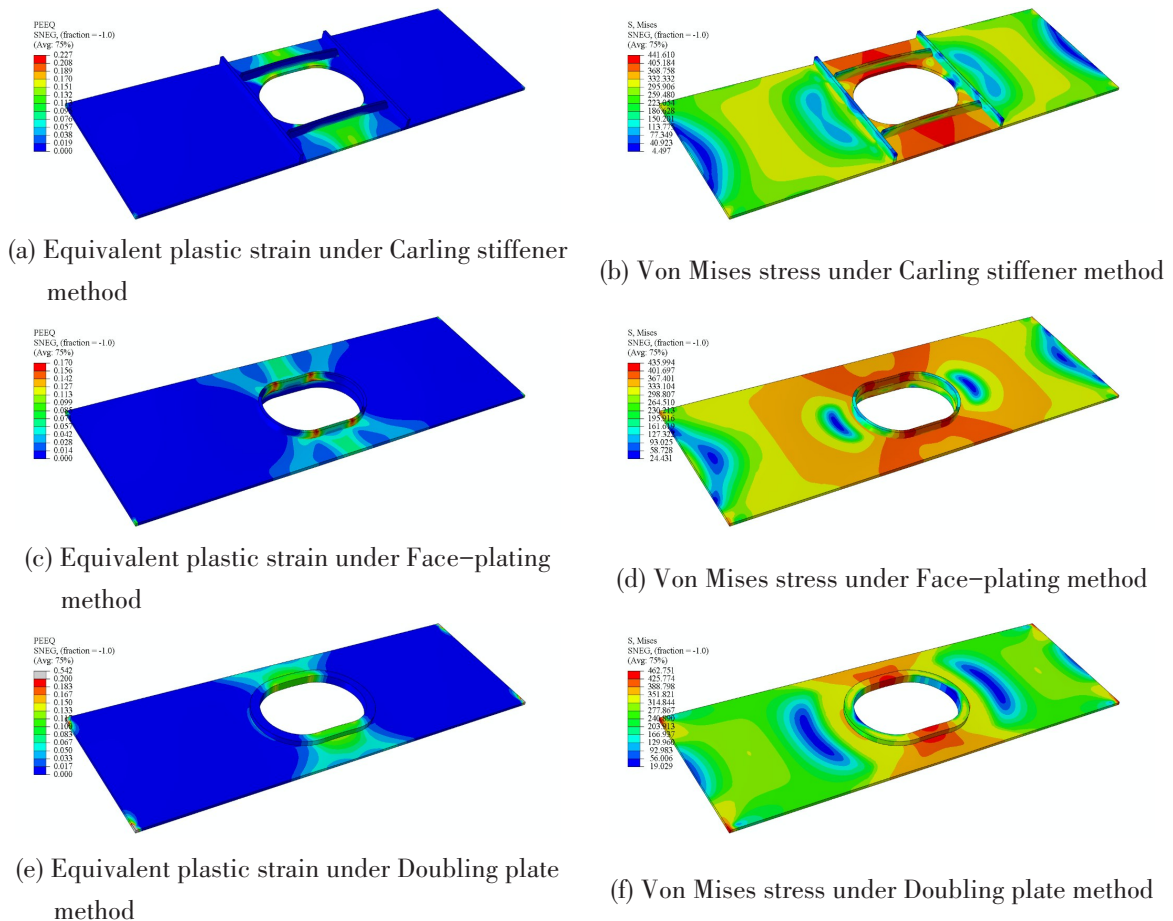


Fig.13 Equivalent plastic strain and Von Mises stress distribution under different reinforcement methods at $p=4$

By comprehensively comparing the strength gains from the three strengthening methods, the total workload should be lower and potentially save shipbuilding costs considering that the Carling method is expected to be simpler and cheaper^[27]. The stiffening ribs required for the doubling method and the face-plating method are limited due to the difficulty in their production^[26], and the use of Carling reinforcement form is the best choice for structures with predominantly longitudinal loads.

3 Conclusions

This paper presents investigation results of the ultimate strength of hull perforated plates after extreme cyclic loading in the longitudinal direction and the influence of parameters on the ultimate strength such as cycle period, opening shape, opening position and type of opening reinforcement. The main conclusions obtained are as follows:

(1) During cycling of extreme loads, a large amount of plastic cumulative damage occurs on both transverse sides of the opening, and the ultimate strength gradually decreases. The ultimate strength of the hull plate decreases mainly due to the damage caused by the first four cycles of loading and stabilizes with the increase of the number of cycles.

(2) Plates with rounded openings show a significant increase in strength compared to plates with right-angled openings. This is due to the strong stress concentration effect at the corners of rectangular openings, which will be attenuated by rounded corners. As the cycle time increases, the strengthening effect shown by rounded openings compared to rectangular openings gradually decreases. With rounded corners, the closer the aspect ratio of the opening is to 1, the more pronounced the strength enhancement is.

(3) Under longitudinal cyclic loading, the plate with the center opening in the longitudinal position has the lowest strength, while the plate with the center opening in the transverse position has the highest strength. The position of the longitudinal opening corresponding to the maximum strength is closer to the longitudinal edge as the cycle period increases. The difference in ultimate strength due to changes in opening position in both directions decreases as the period increases.

(4) Under extreme cyclic load, the ultimate strength of the plate reinforced with Carling method has the gentlest decreasing trend. In addition, considering the low cost and short time of this structure in manufacturing and construction, it can be considered that this strengthening method performs best.

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极端循环载荷下船体开口板的极限强度研究

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摘要: 在材料运动硬化和各向同性硬化存在的情况下, 分析开孔参数对极端循环加载下开口板极限强度的影响。结果

表明:在前四次循环中,开口板的极限强度迅速下降并趋于稳定;与矩形开口相比,长圆形开口的板具有更高的极限强度,而相对强化比随着循环时间的延长而减小;开孔位置也是影响结构强度的重要参数,在纵向上,靠近边缘开孔的板强度较高,而在横向上,靠近中心开孔的板强度较高;对比三种开孔加固方法,Carling加强法在多次循环荷载作用下仍保持较好的加固效果。

关键词: 极端循环载荷; 开口板; 极限强度

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