Effects of loading rate and temperature on crack arrest behavior of hull steel in stiffened plate construction

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Abstract Based on the residual strength diagram of non-stiffened plate construction, a residual strength diagram of hull steel in stiffened plate construction was proposed using the linear-elastic fracture mechanic theory in this work, the effects of loading rate and temperature on the crack arrest behavior of the stiffened plate construction were discussed, the lower limit of the residual strength and the dimension of a valid arrested crack were obtained via the theoretical analysis. The results demonstrated that, whether loading rate or temperature significantly influence the lower limit of the residual strength of the hull steel in a stiffened plate construction; under the conditions of 273K and 293K, the stiffened plate construction is a stiffener critical construction when the applied loading rate $\dot{K}$ is in the order of $\sim 10^5 MPa\sqrt{m}/s$, while under the loading rate of $\sim 10^6 MPa\sqrt{m}/s$, it becomes a skin critical construction due to the decrease of the fracture toughness of the full steel, the lower limit of residual strength is reduced to one fourth of the steel yield strength under this loading condition. In this case, the stiffened shipping construction is no longer adaptable to such a high loading rate, the crack arrest design is therefore highly desirable for protecting the full plate construction.

Keywords stiffened plate, residual strength, crack arrest, loading rate and temperature effect

1. Introduction

In order to enhance strength and stiffness, the stiffened plate construction is always often used in the structure design of the hull. Therefore, it must be considered the effect of stiffener when analyzing the deformation and fracture behavior of hull structure. Vliege and Brock studied the crack propagation behavior and crack arrest characteristic in stiffened plate structure of the plane, and proposed the residual strength diagram of non-stiffened plate structure to analyze and predict the crack propagation characteristic of the stiffened plate structure [1, 2]. The design of crack arrest is an important aspect of ship design, while the study associated with of the crack arrest behavior of hull steel under dynamic loading is quite limited at present. The ships especially naval vessels are often subjected to impact load in their service processing. The fracture toughness of hull steel may be reduced due to the effect of high loading rate, for example, the fracture toughness (K_{IC}) of hull steel used in this paper is $\sim 180MPa\sqrt{m}$ (loading rate $\sim 10^0 MPa\sqrt{m}/s$) under the temperature ~273K, while the fracture toughness decreases to $\sim 64MPa\sqrt{m}$ under the loading rate $\sim 10^6 MPa\sqrt{m}/s$, which is one third of static fracture toughness. Thus, it is essential to design ships in terms of crack arrest principle. Based on the linear-elastic fracture mechanic theory and residual strength diagram (when temperature is 273K, $\sim 10^5 MPa\sqrt{m}/s$ and 293K, $\sim 10^6 MPa\sqrt{m}/s$) of the hull, the present paper discusses the crack arrest behavior of the stiffened plate structure of the hull, the conclusions drawn from this work can be used as the reference for the design of crack arrest of the hull steel.

2 Mechanical properties of materials and stiffened plate construction

The hull steel used for skin plate and stiffener of stiffened plate structure is a low alloy steel in this paper, and its mechanical properties of the hull steel are listed in Table 1,

Table 1 The mechanical properties of hull steel

material	σ_s (MPa)	σ_b (MPa)	δ(%)	φ(%)
hull steel	480	580	21.4	74
weld metal	400	505	28	74

The Charpy impact specimens were used in experiments, which firstly were cut notch ~3mm by EDM (electrical charge machine), and then pre-fatigue for achieving a relative crack length a/W≈0.5. The dynamic fracture toughness of hull steel under different loading rate conditions were tested by pendulum impact test ($\sim 10^5 MPa\sqrt{m}/s$) and Hopkinson bar apparatus ($\sim 10^6 MPa\sqrt{m}/s$), respectively. The experimental results are shown in Table 2. The impact energy tested by pendulum impact experiment can be used to calculate the dynamic fracture toughness by the following Equation [3]:

$$K_{\mathrm{Id}}^2 = 1290.17 + 108.03\mathrm{CVN} \tag{1}$$

It can be seen from Equation (1) that the dynamic fracture toughness under loading rate $\sim 10^5 MPa\sqrt{m}/s$ can be obtained using the value of CVN. The dynamic fracture toughness of tested material under higher loading rate $\sim 10^6 MPa\sqrt{m}/s$ can be gained using Hopkinson bar loading apparatus, details for testing procedures can be found elsewhere [4].

Table 2 The dynamic fracture toughness and dynamic strength of hull steel

loading rate	$\sim 10^5 MPa\sqrt{m}/s$		$\sim 10^6 MPa\sqrt{m}/s$	
Temperature (K)	273	293	273	293
$K_{Id}(MPa\sqrt{m})$	119	128	64	74
$K_d(MPa\sqrt{m})$	282	343	71	89
σ_{Yd} (MPa)	567	565	640	638
$\sigma_b(MPa)$	691	678	774	768

As the dynamic yield strength of tested material is a necessary parameter in next analysis, the dynamic yield strengths under different strain rate and temperature were carried out using dynamic compression test in Hopkisnon bar apparatus in order to investigate the rate sensitivity of this material. Thus the dynamic compression test was carried out on the Hopkinson pressure bar test for determining the dynamic yield strength of hull steel. The relationship between dynamic yield strength and strain rate and temperature can be established as following according to our experimental data:

$$\sigma_{yd} = \sigma_s\left[1+\left(\dot{\varepsilon}/59213\right)^{0.281}\right]\left[1.13\exp(-0.0004T)\right] \tag{2}$$

Where T is the experimental temperature, σ_s is the yield strength under quasi-static, $\dot{\varepsilon}$ is the strain rate. Using the Equation (2), the dynamic yield strengths of hull steel under different strain rate and temperature were evaluated and listed in Table 2.

The data listed in Table 2 and the thickness of skin were confirmed to be meet the plane strain condition in terms of ASTM E-399 standard. Therefore, it needed to use the Irwin Equation to transform the data listed in table 2 to plane stress fracture toughness K_d [5, 6]:

$$\beta_{\mathrm{I\,d}}=\frac{1}{B}\left(\frac{K_{\mathrm{I}d}}{\sigma_{yd}}\right)^2 \quad , \quad K_{\mathrm{d}}^{\ 2}=K_{\mathrm{I}\,d}^{\ 2}(1+1.4\beta_{\mathrm{I\,d}}^{\ 2}) \tag{3}$$

The value of plane stress fracture toughness K_d transformed were also listed in Table 2.

The simple stiffened plate construction with two stiffeners was analyzed, as shown in Figure 1. The stiffeners are symmetrically distributed at both sides of central crack 2a, and the crack plane passes through the rivet hole. The stiffener and skin plate are connected by rigid rivet. The corresponding construction parameters are as following: thickness of the skin plate B=24*mm*, sectional area of stiffener A_s=20*mm*×80*mm*, interval of stiffeners b=600*mm*, interval of rigid rivet p=b/12=50*mm*, modulus of elasticity E_s=E=2.1×10^5*MPa*, Reinforcement ratio [7]:

$$\mu=A_sE_s/(A_sE_s+EbB) \tag{4}$$

where E_s is elastic modulus of stiffeners, E is elastic modulus of skin plate. The value of μ is calculated using Equation (4) to be 0.1.

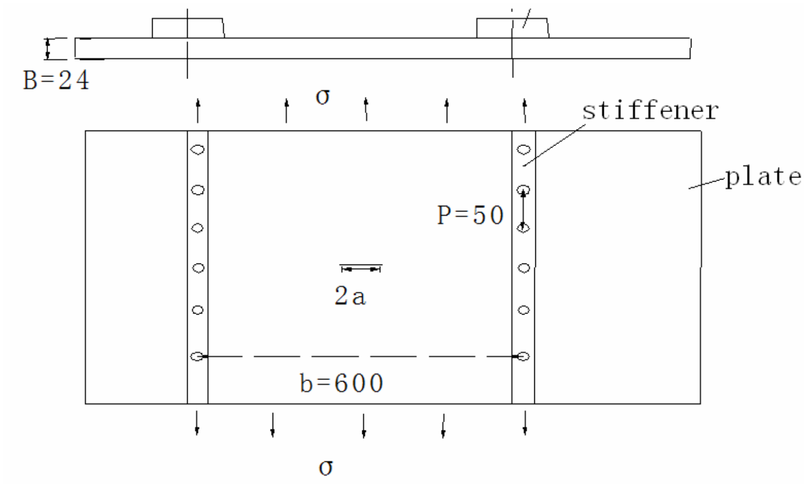

Figure1. Construction diagram of stiffened plate construction

3 The residual strength of stiffened plate construction

According to linear-elastic fracture mechanical theory, the relationship between stress and plane strain fracture toughness is following for the infinite wide plate with a penetrated central crack that bears the average tensile stress in both surface [8].

$$\sigma_c = K_{\mathrm{I}c}/\beta\sqrt{\pi a_c}\ \text{(for infinite width plate, a<<w,}\ \beta=1) \tag{5}$$

Here, σ_c is fracture stress, a_c is the half length of critical crack and $K_{\mathrm{I}c}$ is quasi-static plane strain fracture toughness. If the dynamic fracture toughness does not meet the plane strain condition, the equivalent value must be calculated by Equation (3). According to the Equation (5), the curve of residual strength of non-stiffened plate can be calculated, that is to say the curve of $\sigma_c - a$ can be computed. However, it must be modified by Fedderson revision [9] when the crack length is quite small.

When stiffened plate construction is subjected to load, partial load would transfer to stiffeners by way of rivet, which lower the stress intensity factor in the crack tip of stiffened plate. Simultaneously, the stress concentration occurs around the stiffeners. The decreasing coefficient of stress intensity factor of crack tip of stiffened plate C is calculated as [10,11] ,

$$C = K_{stiffened} / K_{\mathrm{nonstiffened}} \quad (6)$$

where, $K_{stiffened}$ is the stress intensity factor of stiffened plate construction with crack, $K_{nonstiffened}$ is the stress intensity factor of non-stiffened plate construction with crack. It can be seen from Equation (6) that the value of C is less than 1, i.e. C≤1. The coefficient of stress concentration L is written as,

$$L = \sigma_{\max} / \sigma \quad (7)$$

where, σ is nominal stress of stiffened plate construction, $\sigma_{\max}$ is concentrated stress of stiffener, the parameters of C and L can be found in the stress intensity factor manual [8].

If the stiffened plate and non-stiffened plate construction with the same crack length fracture under the same stress intensity factor, the following Equation will be exist:

$$\sigma_{cstiffened} = \sigma_{cnonstiffened} / C \quad (8)$$

where, $\sigma_{\mathrm{cstiffened}}$ is fracture stress of stiffened plate construction, $\sigma_{cnonstiffened}$ is fracture stress of non-stiffened plate construction. It can be seen from Equation (8) that the fracture stress of stiffened plate increases by 1 / C times. Using the Equation (8), the residual strength curve of stiffened plate construction can be calculated by that of non-stiffened plate construction.

Under the non crack condition, when the stress of stiffeners reaches to tensile strength σ_{b}, the stiffeners will fracture. Contrary, if the concentrated stress $\sigma_{\max}$ reaches to tensile strength σ_{b}, stiffeners would fracture. The following Equation can be derived from Equation (7):

$$\sigma = \sigma_{\mathrm{b}} / L \quad (9)$$

Where, σ is nominal stress of stiffeners. According to the Equation (9), failure curve of stiffeners can be attained.

The residual strength curve of stiffened plate construction can be achieved by putting the residual strength curve of non-stiffened plate and stiffened plate construction and the failure curve of stiffener together into a common coordinate system, as shown in Figures 2 and 3.

4 Analysis of the crack arrest behavior of the stiffened plate construction

The residual strength diagram of stiffened plate construction of the hull under the loading rates $\sim 10^5 MPa\sqrt{m}/s$ and $\sim 10^6 MPa\sqrt{m}/s$ at the temperature of 273K and 293K can be determined using the related data listed in table 2 and Equations (3)-(8), as shown in Figures 2 and 3.

Whether Figure 2(a) and (b) or Figure 3(a) and (b), all of them indicate that for stiffened plate construction with penetrable crack in center, the residual strength curve nearly coincides with that of non-stiffened plate construction when the crack length is small, which shows that reinforcement effect of stiffener is not obvious. When the crack propagated near the stiffener, the amplitude decrease of stress intensity factor become larger due to the load beard by stiffeners increasing, and the stress intensity factor reaches to maximum value while the crack propagates to the central line of stiffeners. At the same time, the residual strength curve of stiffened plate construction is much higher than that of non-stiffened plate construction. The reinforcement effect of stiffener decreases again and the residual strength curve of stiffened plate construction falls with increasing crack

According to the relative position between the failure curve of stiffeners and the residual strength diagram of stiffened plate construction, the crack arrest behavior of the stiffened plate construction includes a stiffener critical construction (Figure 2) and a skin critical construction (Figure 3). In skin critical construction (Figure 3), the unstable expansion of crack is arrested when the lengths reaches a_1' under stress state of σ_1 and the initial length of crack satisfying $a_0<a_1< a_s$. Under this condition, the crack is in stable state. That is to say, any expansion of crack would lead to further increase of the fracture resistance. It can be concluded that crack is in controlled state or crack arrest state. As the stress increased to σ_0, crack would steadily spread to a_s and then unsteadily propagate. Following, the stiffener would fracture because of the high stress applied, which results in structural failure. However, in the skin critical construction, as shown in Figure 2, when crack spread to a_s, since the stress of stiffener reaches its fracture stress, fracture would occur and the reinforced influence of stiffener released. As a result, crack of skins spread instability and led to structural failure.

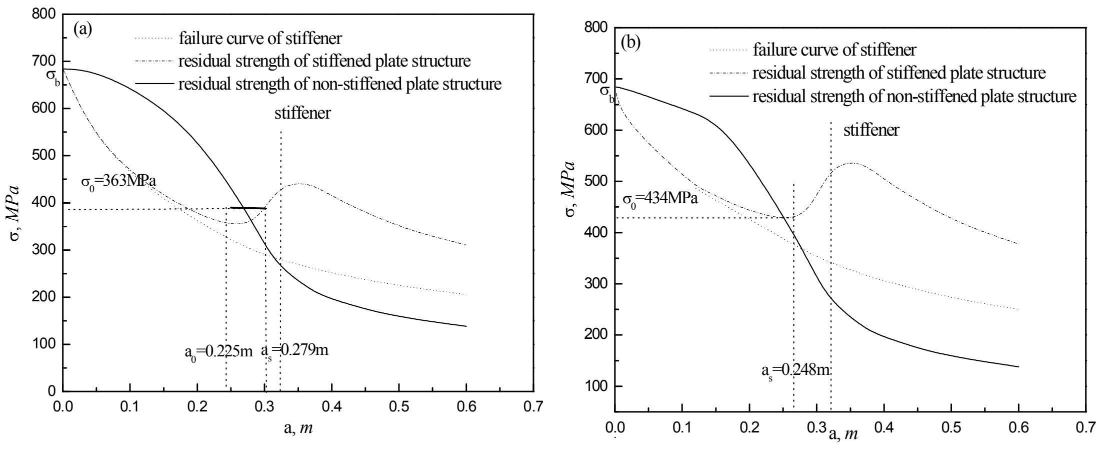

Figure2. Residual strength diagram of stiffened plate construction of the hull under loading rate $\sim 10^5 MPa\sqrt{m}/s$ and temperature 273K (a) and 293K (b)

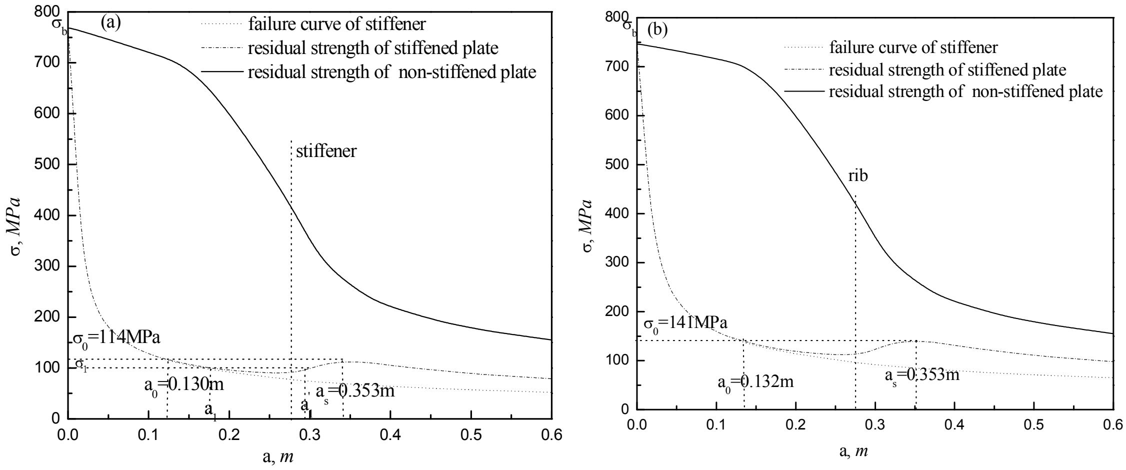

Figure3. Residual strength diagram of stiffened plate construction of the hull under loading rate $\sim 10^6 MPa\sqrt{m}/s$ and temperature 273K (a) and 293K(b)

The above analysis with respect to the crack behavior shows that the residual strength of stiffened plate construction has a "platform" stress σ_0 to which corresponding the range of cracks length $a_0 \sim a_s$. At this scope, the stiffened plate construction can play a part in crack arrest. Therefore, it can be obtained that the lower limiting value of residual strength of stiffened plate construction is σ_0, and the effective range of crack length for crack arrest is $a_0 \sim a_s$.

The stiffened plate construction of the hull analyzed in this paper shows elastic-plastic fracture with large plastic deformation under the loading rate $\sim 10^5 MPa\sqrt{m}/s$ and temperature 273K and 293K. At this condition, the stiffened plate construction belongs to a stiffener critical construction (details seen in Figure 2). For example, when the loading rate is $\sim 10^5 MPa\sqrt{m}/s$, the fracture toughness of hull steel are $282 MPa\sqrt{m}$ and $343 MPa\sqrt{m}$ under temperature 273K and 293K, respectively. While, under the loading rate $\sim 10^6 MPa\sqrt{m}/s$, the fracture toughness obviously decrease to $71 MPa\sqrt{m}$ and $89 MPa\sqrt{m}$, which is only quarter of the fracture toughness under quasi-static loading rate (seen Table 2). Thus, the residual strength curve of stiffened plate construction decreases largely. As a result, under the loading rate $\sim 10^6 MPa\sqrt{m}/s$, the stiffened plate construction belongs to a skin critical construction (Figure 3). The lower limiting value σ_0 and the range of crack length for crack arrest $a_0 \sim a_s$ for stiffened plate construction of the hull are listed in Table 3.

Table 3 $\sigma_0 (MPa)$ and $a_0 \sim a_s$(m) of stiffened plate construction of the hull

loading rate	$\sim 10^5 MPa\sqrt{m}/s$		$\sim 10^6 MPa\sqrt{m}/s$	
temperature (K)	273	293	273	293
$\sigma_0 (MPa)$	363	434	114	141
$a_0 \sim a_s$(m)	0.225-0.279	0.248	0.130-0.353	0.132-0.353

It can be seen from Table 3 that the lower limiting value of residual strength is strongly dependent

upon the loading rate and temperature, which is the same as the fracture toughness of steel. That is to say, at the same loading rate, the lower limiting value of residual strength under temperature 293K is higher than that under temperature 273K; on the other hand, at the same temperature, the lower limiting value of residual strength decreases drastically with increasing loading rate, especially under loading rate $\sim 10^6 MPa\sqrt{m}/s$, the lower limiting value of residual strength reduces to the level of a quarter of σ_s. Suggesting the hull construction is no long suitable for use under impact condition with a loading rate $\sim 10^6 MPa\sqrt{m}/s$. Thus, it is necessary to use stiffened plate construction according to the strength level. However, it is worth noting that the stiffened plate construction is the skin critical construction that has a limit crack arrest capacity. Therefore the stiffened plate construction is needed to modify to enhance the crack arrest performance of the construction.
The data listed in Table 3 indicates that the crack length range of effective crack arrest in the skin critical construction is more than that in the stiffener critical construction. Under the loading rate $\sim 10^5 MPa\sqrt{m}/s$, the crack length range at temperature 273K is 0.225 *m* ~0.279 *m*, while at temperature 293K there is no crack arrest after the crack instable state. Under the loading rate $\sim 10^6 MPa\sqrt{m}/s$, the crack length range of effective crack arrest is 0.130 *m* ~ 0.353 *m* whether temperature 273K or 293K because the stiffened plate construction belongs to the skin critical construction.

5 Conclusions

Based on the linear-elastic fracture mechanic theory and the residual strength diagram of non-stiffened plate construction, the residual strength diagram of stiffened plate construction of the hull was proposed, and the crack arrest behavior, temperature and loading rate effects in the stiffened plate construction were discussed. The following conclusions can be drawn:

(1) The lower limiting value of residual strength of stiffened plate construction is significantly influenced by temperature and loading rate.

(2) The stiffened plate construction belongs to the stiffener critical construction at temperature 273K and 293K under loading rate $\sim 10^5 MPa\sqrt{m}/s$. While stiffened plate construction belongs to the skin critical construction because the fracture toughness of hull steel decreases sharply under loading rate $\sim 10^6 MPa\sqrt{m}/s$.

(3) The lower limiting value of residual strength of stiffened plate construction discussed in this paper and the crack length range of effective crack arrest are found to be 0.225 *m* ~ 0.279 *m* for the loading rate $\sim 10^5 MPa\sqrt{m}/s$ and temperature 273K and 0.130 *m* ~ 0.353 *m* for the loading rate $\sim 10^6 MPa\sqrt{m}/s$ and temperature 273K or 293K.

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