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Research on the Residual Strength of Cracked Plate Considering Fatigue Crack Propagation under Cyclic Load

Qin Dong [1,*], Geng Xu [2], Yaoyu Hu [3] and Ziya Peng [1]

1 Key Laboratory of High Performance Ship Technology, Wuhan University of Technology, Ministry of Education, Wuhan 430063, China
2 School of Naval Architecture and Navigation, Wuhan Technical College of Communications, Wuhan 430065, China
3 Marine Equipment and Technology Institute, Jiangsu University of Science and Technology, Zhenjiang 212000, China
* Correspondence: qdong26@163.com

Abstract: Fatigue damage caused by cyclic loading is a major concern in engineering applications. Cracks propagated by cyclic loading can lead to catastrophic failure, which can have severe consequences in safety-critical systems. The main objective of the paper is to investigate the residual strength of cracked plate considering fatigue crack propagation under cyclic loading. In this study, a cracked plate model is proposed to study the difference of compressive and tensile residual strength with pre-crack and fatigue crack. The influence factors such as crack length, number of cycles, tensile/compressive cyclic loads, and out-of-plane deformation are considered in the residual strength study of cracked plate. The numerical results can gain insight into the effect of crack propagation on the structural residual strength, with the aim of providing guidance for evaluating the residual strength of cracked components.

Keywords: residual strength; cyclic load; fatigue crack; crack propagation

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1. Introduction

When the hull structure is subjected to large cyclic bending loads under adverse sea conditions, some longitudinal members at the dangerous section of the hull beam will buckle or yield. If the number of load cycles continues to increase, the plastic deformation at the dangerous section will continue to accumulate, which will continuously reduce the ultimate bearing capacity of the dangerous section of the hull beam until the hull structure breaks. This will reduce the ultimate load capacity of the dangerous section of the hull beam until the hull structure is fractured. In addition, in the local stress concentration area of the hull structure, the stress level is near or exceeds the yield strength of the material, and the increase of the number of load cycles will cause cracks to sprout and expand in the stress concentration area, thus reducing the effective bearing area of the structure and reducing the ultimate bearing capacity of the structure to a certain extent.

The study of fatigue crack propagation in hull structures is primarily intended to predict the service life of the structure as well as the load bearing capacity, which is of great importance for the structural safety of ships. A great deal of research has been carried out on the residual strength of hull structures containing crack damage. Paik [1,2] analyzed the ultimate strength characteristics of steel plates containing cracks under axial compression or tensile loading by numerical simulations and model tests, and investigated the effects of crack length, crack distribution, crack direction angle, plate thickness, and other factors to the results by parametric approach. The simplified theoretical equations are proposed based on the results of numerical calculations and model tests for predicting the ultimate strength of cracked plates under axial compression or tension. Margaritis [3] made a numerical study on the effect of crack closure on the ultimate strength of stiffened plates with cracks at the plate-web intersection, and found that the crack configuration has little impact on the reduction in ultimate strength when the crack length is short. Shi and Wang [4,5] investigated the reduced ultimate strength of open box girders with crack damage by numerical method, the effects of crack length and locations were analyzed. Huang [6] evaluated the residual strength of thin-walled structures containing cracks using the crack opening angle criterion, and improved the prediction accuracy of the residual strength of multi-cracked thin-walled structures effectively by adding unit constraints around the crack tip and adopting a plane strain kernel model. Saad-Eldeen [7] tested the residual strength of cracked plates with a large opening, subjected to uniaxial compressive load. It is concluded that when the crack length is along the diagonal direction of the applied load, the reduction in the ultimate strength is almost linear. Hu [8] used nonlinear finite element method to study the residual ultimate strength of large open box girder with cracks under torsion and bending load, three types of crack are considered include longitudinal crack, transverse crack, and inclined crack. Shi [9] experimentally and numerically investigated on the effects of orientation, length, and location of the crack to the residual strength of steel stiffened plate under gradual compression load, and indicated that initial weld-induced deformations should be considered in the ultimate strength analysis. Li [10] analyzed the influence of crack length, angle and positions, plate aspect, and slenderness ratios to the ultimate strength of plate with transverse or inclined cracks, and proposed that the slenderness significantly affects the ultimate strength reduction rate of transverse cracked plate. Chen [11–13] conducted numerical study on the stress intensity factor and fatigue life of CFRP repaired steel plates with inclined central cracks subjected to tensile fatigue loading.

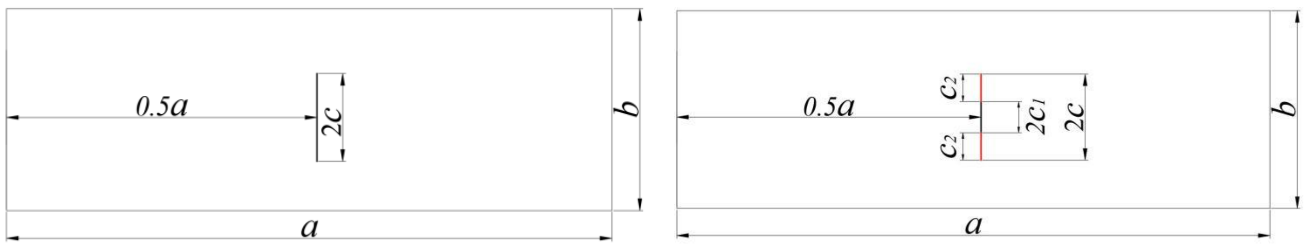
The above studies mainly consider the ultimate load-bearing capacity of the structure under one-time collapse, while the case of cyclic loading is less studied. The fatigue crack propagation is usually ignored in the ultimate strength assessment. This may not reflect the true collapse behavior of the cracked components. For a cracked plate, severe stress concentrations near the crack tip induce a plastic zone in a localized region, which will reduce the stiffness of the cracked plate and lead to serious structural damage. Xia [14] investigated the ultimate strength and post-ultimate strength behavior of hull plates with cumulative plastic damage and fatigue cracks under ultimate longitudinal cyclic load, factors affecting the compressive ultimate strength values were analyzed. Paik [15] conducted a detailed collapse testing of hull girder to obtained the ultimate strength of a bottom stiffened plate structure of an as-built 1900 TEU containership under cyclic axial compressive loading. Cui [16] made some explorations on the ultimate strength and fracture failure of stiffened plate under cyclic load, and discussed the influences of material models under different cyclic load patterns. Hu [17] used the element erosion method to simulate the propagation the crack under extreme cyclic load, and proposed simplified formula to evaluate the ultimate strength of cracked plate under cyclic load. However, in their study, the number of cycles and the load conditions are not considered. Therefore, there is a strong need to conduct further research.

The main objective of the paper is to investigate the residual strength of cracked plate considering fatigue crack propagation under cyclic loading. In this study, a cracked plate model is proposed to study the difference of compressive and tensile residual strength with pre-crack and fatigue crack. The influence factors such as crack length, number of cycles, tensile/compressive cyclic loads, and out-of-plane deformation are considered in the residual strength study of cracked plate. The numerical results can gain insight into the effect of crack propagation on the structural residual strength, with the aim of providing guidance for evaluating the residual strength of cracked components.

2. Numerical Analysis

2.1. Geometric Model and Material Parameters

The specimens are divided into prefabricated crack specimens and fatigue crack specimens. The crack of the prefabricated crack specimen is directly made by wire cutting as shown in Figure 1a, while the crack of fatigue crack specimen is formed by the propagation of specific crack as shown in the Figure 1b ($2c1$ represents prefabricated crack, while $2c2$ represents fatigue crack formed on the basis of prefabricated crack). Ideal elastic-plastic material model and von Mises yield criterion are adopted for analysis, the dimension and material parameters of the model are shown in Tables 1 and 2.



(**a**) (**b**)

Figure 1. (**a**) plate with prefabricated crack; (**b**) plate with fatigue crack.

Table 1. Geometry parameters of the cracked plate.

Plate Length	Plate Width	Plate Thickness	Crack Width
a/mm	b/mm	t/mm	G/mm
2550	850	11	3

Table 2. Material parameters of the cracked plate.

Elastic Modulus	Poisson's Ratio	Yield Strength
E/MPa	v	σ_y/MPa
205,800	0.3	313.6

In this paper, tensile and compressive residual strength analyses are carried out for pre-fabricated and fatigue crack specimen, respectively. The range of size for pre-fabricated crack is $\frac{2c}{b} = 0.1 \sim 0.4$. For fatigue crack, the initial crack size is $2c_1/b = 0.07$, and then gradually extended by cyclic loading to the same length as the crack in the prefabricated crack specimen. Finally, the residual tensile and compressive strengths of the cracked plate are calculated separately for the relative crack lengths at this point. As shown in the Figure 2a,b, as tensile stresses are more likely to cause crack propagation, the loads during the cycle are mainly tensile loads, while the residual ultimate strength of the cracked plate is calculated in the last instance. After the last load cycle, the remaining ultimate strength of the cracked plate is calculated.

2.2. The Initial Welding Deformation

Electroplating structures are usually cut with flame fusion welding in manufacturing. During these processes, imperfections will generate in the form of initial deformation. It has been known that the initial imperfections have significant influence on the ultimate strength behavior of steel plate, which should be taken into account in the ultimate strength assessment. Weld residual stresses are a self-balancing force system, the beneficial effects and the adverse effects of residual stresses can also counterbalance each other. Therefore, the effects of weld residual stresses are not considered in this paper. However, the initial welding deformation must be considered [9], eigenvalue buckling is used to model the initial deformation of the hull plate, using the lowest order buckling mode as the shape of the initial deformation, which can be described by Equation (1) [18]:

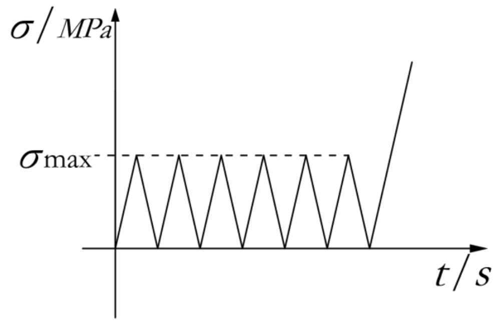


Figure 2. The load forms: (**a**) cyclic load, and end with tensile load; (**b**) cyclic load, and end with compressive load.

$$w = A_0 sin\frac{m\pi x}{a} sin\frac{\pi y}{b} \tag{1}$$

where w is the buckling mode of initial deformation, m is longitudinal flexural half-wave number. When a/b is an integer, $m = a/b$, when a/b is not an integer, the value of m is the smallest integer satisfying the following inequality:

$$a/b \leq \sqrt{m(m+1)} \tag{2}$$

where, A_0 is the amplitude of initial deformation, the value is taken as an average, $A_0 = 0.1\beta^2 t$. β is the flexibility factor, and $\beta = b/t\sqrt{\sigma_y/E}$, t is plate width, E is elastic modulus.

2.3. Mesh and Boundary Conditions

The cracked plate is modeled by ABAQUS as shown in Figure 3, the type of element is taken as four-node shell element S4R. The elements near the crack are refined to simulate the changes of stress field near the fatigue crack, and then gradually transition to a coarse mesh.

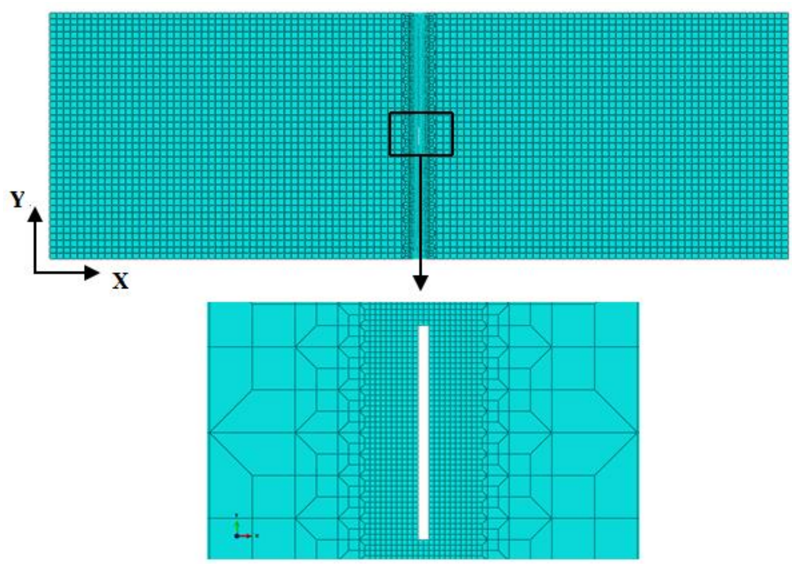


Figure 3. Finite element model.

In the hull structure, the hull plate can be considered to be supported by the longitudinal and transverse bones all around, and the constraint at the junction of plate and tendons is generally between simple support and rigid fixation. For conservative reasons, most cases are taken as simply supported, and Figure 4 shows the specific boundary conditions.

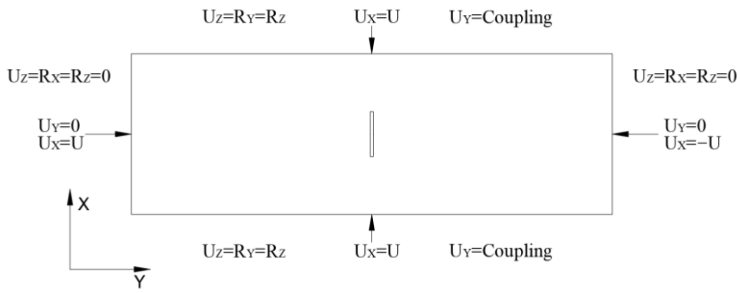


Figure 4. Boundary Conditions.

(1) The surrounding boundary of the plate constrains z-directional displacement Uz, which is simply supported along z direction.

(2) The loaded and unloaded edges are kept with straight boundary conditions, and the unloaded edge of the plate is set with coupling constraints so that it has the same displacement in the y-direction; the loaded edge of the plate is set with rigid constraints along the x-direction, and the middle node is used as the main node to simulate uniaxial compression and uniaxial tension loads by applying forced displacements.

(3) The midpoint of the longitudinal boundary of the plate constrains the displacement Ux in the x-direction, and the midpoint of the transverse boundary of the plate constrains the displacement Uy in the y-direction to limit the rigid body displacement.

To accurately simulate the collapse behavior of cracked plate in finite element (FE) model, a fine mesh size is required. However, this also increases computational efforts, necessitating a balance between accuracy and computational time. For a cracked plate, two regions, near crack tip and away from crack tip, should be treated separately and assigned with different mesh. Due to the need to simulate the stress change at the crack tip, the mesh near the crack tip needs to be refined. Xu [19] considered that the mesh size at the crack tip had little effect on the ultimate strength, so only the convergence of the mesh far from the crack tip region was studied. As can be seen from Table 3 and Figure 5, there types of mesh were considered to calculate the residual strength, and the difference in residual strength between the three mesh size was relatively small. Although the economy is good by using coarse mesh, the change of stress distribution cannot be simulated well. Therefore, the FE model adopts the refined mesh for simulation, which can not only save the calculation time but also simulate the stress distribution well. The size of refined element is 1.5 mm × 1.5 mm, and the size of coarse element is 24 mm × 24 mm. Further, three different frequencies were used for analysis, and the differences were found to be small. Therefore, each FE model was modeled using a 1 Hz frequency sine wave, because it can represent real engineering loading conditions more closely [20].

Table 3. Results of convergence study.

Case	N_x	N_y	N_{sum}	σ_u/MPa	Difference/%
Coarse mesh	80	18	15,392	170.71	−0.15
Middle mesh	130	36	18,092	170.96	-
Refined mesh	232	68	29,036	171.01	0.029

Note: N_x and N_y are the number of elements along longitudinal and transverse edges, respectively. N_{sum} is the total number of elements.

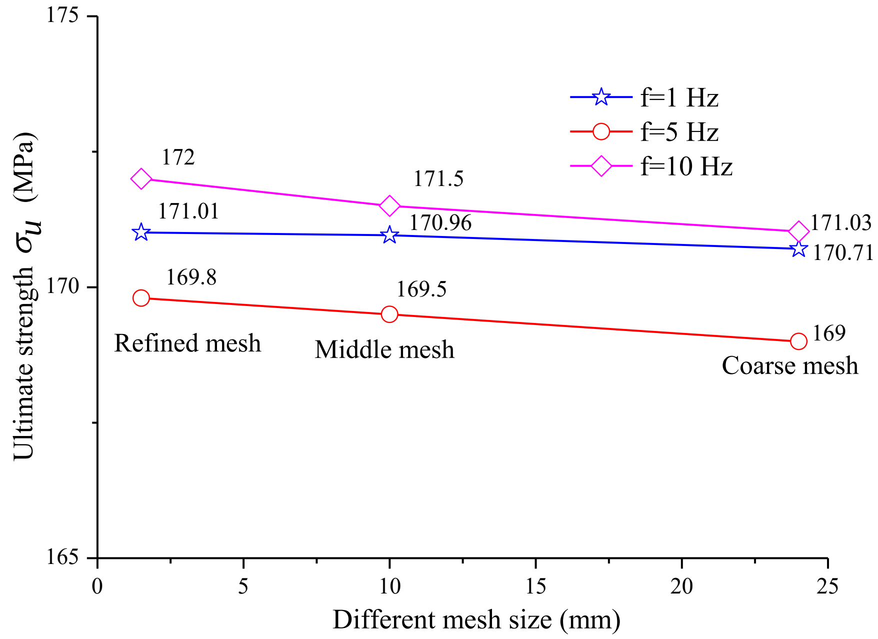


Figure 5. The time and mesh convergence analysis.

In order to verify the validation of finite element method (FEM) modeling, the ultimate compressive strength of an intact plate is predicted by the FEM using the present element type and boundary conditions, the result obtained is compared with Faulkner [21] formula and Cui's [22] FEM results. In Faulkner formula, the ultimate strength of the plate can be expressed as:

$$\frac{\sigma_u}{\sigma_y} = \frac{2}{\beta} - \frac{1}{\beta^2} \tag{3}$$

where, σ_u is the ultimate stress of the plate, σ_y is the yield stress of the material, and β is the flexibility factor of the board.

The results of the comparison are shown in the Figure 6 and Table 4.

It can be found that the result obtained from finite element method is close to the formula and reference, so it can be considered that the finite element model is reasonable in terms of element mesh and boundary conditions.

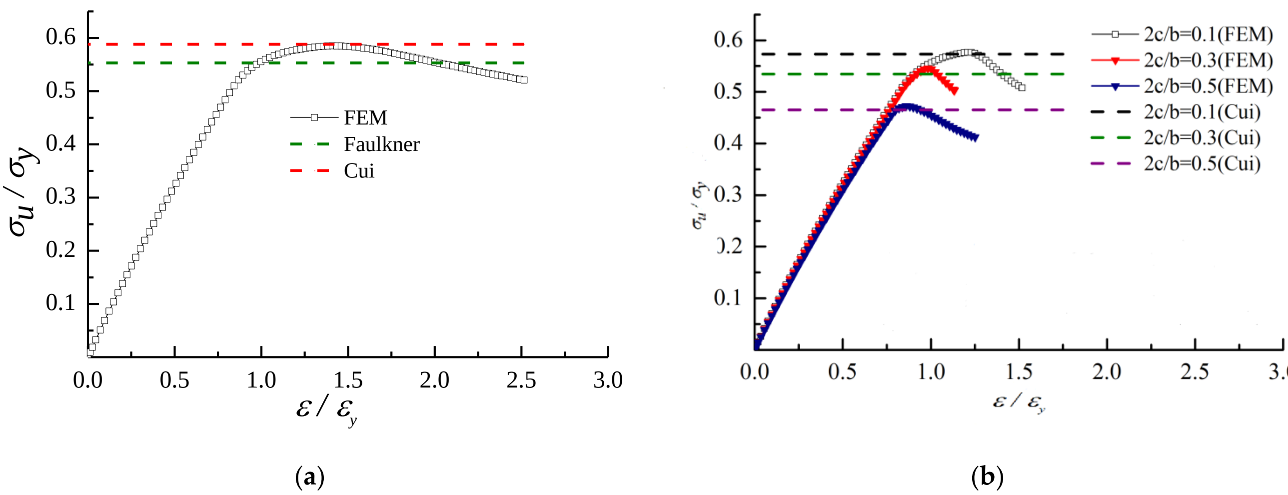


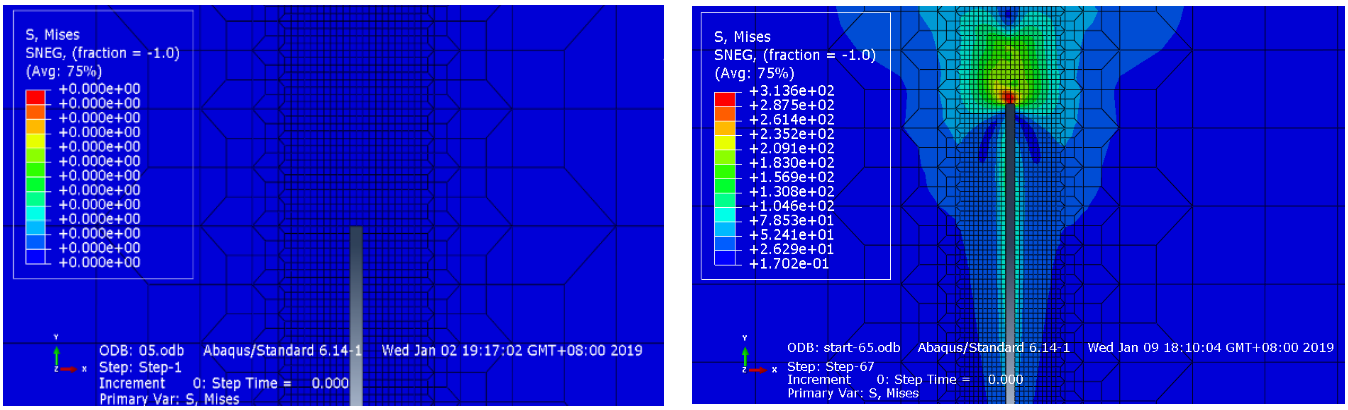
Figure 6. The stress-strain curve of (**a**) intact plate and (**b**) cracked plates.

Table 4. Comparison of finite element method and formula.

Analysis Method		σ_u/σ_y	Error (%)
FEM method	Intact plate	0.585	-
	$2c/b = 0.1$	0.576	0.61
	$2c/b = 0.3$	0.545	1.6
	$2c/b = 0.5$	0.472	1.49
Cui	Intact plate	0.588	0.51
	$2c/b = 0.1$	0.573	-
	$2c/b = 0.3$	0.537	-
	$2c/b = 0.5$	0.465	-
Faulkner formula	Intact plate	0.553	5.79

2.4. The Simulation Method of Crack Propagation

In order to study the effect of crack formation by fatigue crack propagation on the residual strength of structures containing crack damage, it will be important to select a suitable crack propagation method. The residual strength of cracked plates is significantly related to factors such as initial defects, the larger the initial defects, the smaller the residual strength, it is necessary to consider the initial defects. For the initial defect problem, first of all, the difference between fatigue crack and prefabricated crack must be clarified. As shown in Figure 7a,b, there is a clear difference between the two kinds of crack. The fatigue crack expands under the action of cyclic load, there will be residual strain in the trailing area behind the crack tip, and the residual strain will generate residual tensile or compressive stress, while the prefabricated crack has no residual strain.



(**a**) (**b**)

Figure 7. The initial stress distribution: (**a**) plate with prefabricated crack; (**b**) plate with fatigue crack (When cyclic tensile load unloading to zero).

Figure 8a shows that the initial displacement of the cracked plate is zero, this is the initial displacement of the crack when the plate is assumed to have initial deformation but not subject to external load. On the other hand, fatigue crack has an out-of-plane deformation based on the initial deformation due to relative displacement caused by crack propagation as shown in Figure 8b.

In this paper, the "model change command" in ABAQUS is used to simulate the crack propagation by remove elements under a certain condition criterion, which is similar to the raw and dead element method. The raw and dead element method [23] is used in finite element analysis to control the activation and deactivation of specific elements based on certain parameters, such as fracture strain. This method does not add or remove elements, but rather modifies their stiffness matrix and load. When elements are activated, their stiffness matrix and load are assembled into the global matrix and load, and when they are deactivated, their stiffness matrix and load are not included. The raw and dead element method can be used to simulate the crack propagation, a fracture strain is defined, and when the strain at the crack tip reaches the defined value, the element at the crack tip is deactivated and the crack propagates forward.

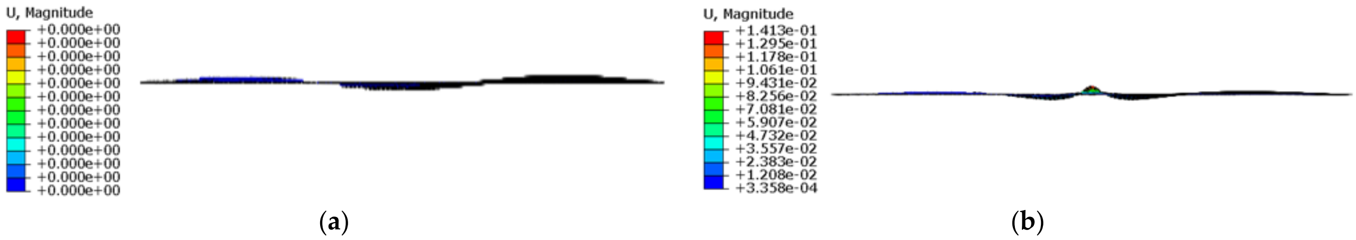


Figure 8. The initial deformation: (**a**) plate with prefabricated crack; (**b**) plate with fatigue crack (When cyclic tensile load unloading to zero).

3. Results and Discussion

3.1. The Effect of the Number of Load Cycles

The number of load cycles may have some influence on the evaluation of crack propagation and residual ultimate strength of cracked plate. Therefore, it needs to be explored specifically. In this paper, crack growth and residual strength are evaluated at different number of load cycles (2, 5, 10) for a certain load level. As shown in Figure 9a,b, under the same crack length, the tensile and compressive residual strength values of the cracked plate do not change significantly with the increase of the number of cycles, and it can be seen that the effect of the number of cycles has little impact on the residual strength. Considering the computational efficiency of the model, the subsequent calculations in this chapter are analyzed using 2 cycles.

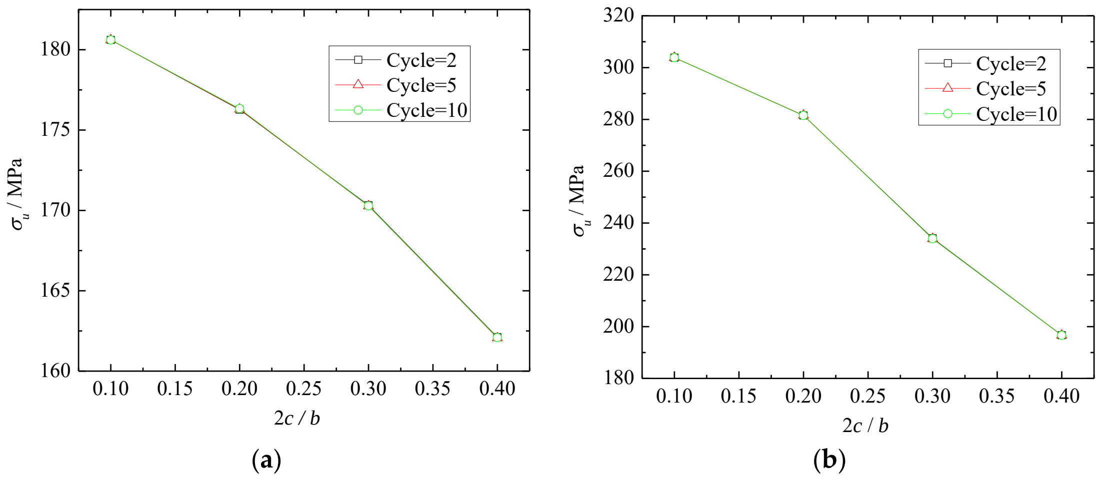


Figure 9. Residual strength at different number of cycles: (**a**) compressive residual strength; (**b**) tensile residual strength.

3.2. Effect of the Magnitude of the Cyclic Load

The magnitude of the cyclic tensile load is an important factor in crack propagation, which affects the crack tip trailing zone, out-of-plane deformation, and crack length, etc. Therefore, it is necessary to analyze different cyclic load magnitudes. Three different load levels of 0.7, 0.8, 0.9 are selected for the analysis. As shown in Figure 10, although the magnitude of the cyclic load has a certain degree of effect on the residual strength, but the effect is very little. Therefore, in order to better investigate the difference between fatigue cracks and prefabricated cracks on the residual strength, the larger cyclic load magnitude of 0.9 is used in this study.

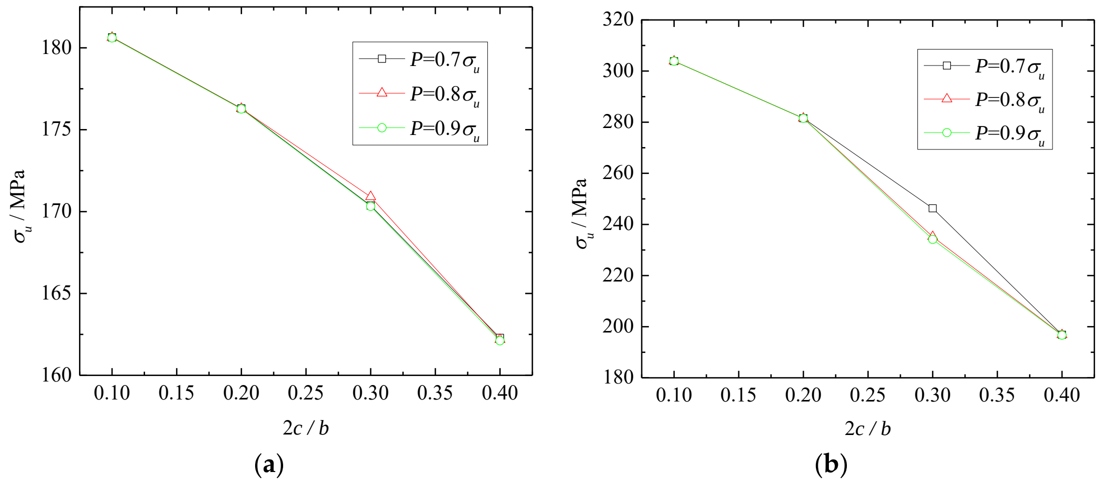


Figure 10. Residual strength at different cyclic load magnitudes: (**a**) compressive residual strength; (**b**) tensile residual strength.

3.3. Results of Stress Field Distribution

In order to study the changes of stress field near the crack tip with the crack propagation, the stress field distributions at the minimum load for different crack propagation lengths are extracted and analyzed under the external load of 0.9. Figure 11 presents the distribution of the normal stress σ_y in the y = 0 plane at minimum applied load. Extract the compressive stress near the crack tip, as shown in Figure 10a–d, the stress field distribution is different for different crack propagation lengths Δc. The maximum compressive stresses at the crack tip increased with the expansion of the crack and their values are −208.921 MPa, −308.483 MPa, −341.513 MPa, and −352.598 MPa, respectively. In addition, the range of compressive stress field in the crack wake area is also different. When the crack length increases, the influence range of the compressive and tensile stress field near the crack tip also increases. In addition, even though crack propagation occurs, a small compressive stress field still exists within a certain range from the initial crack, and the magnitude of its value does not change significantly.

The level of load also affects the stress field distribution in the crack area. Figure 12 shows the stress field distribution curves of the crack tip corresponding to the crack propagation length of 90 mm at different load levels. It can be seen that the higher the load level is, the higher compressive stress in the small area near the crack, but the overall residual compressive stress after the distance from the crack tip is decreasing. This is mainly because the large load level offsets part of the residual compressive stress on the crack surface, and in contrast, the overall tensile stress before the crack tip is increasing. Although the effect of load level on the residual stress field distribution near the crack tip is obvious, the difference between the two calculated residual strength values is not significant, which indicates that the residual stress field distribution near the crack tip in crack propagation has little effect on the residual strength.

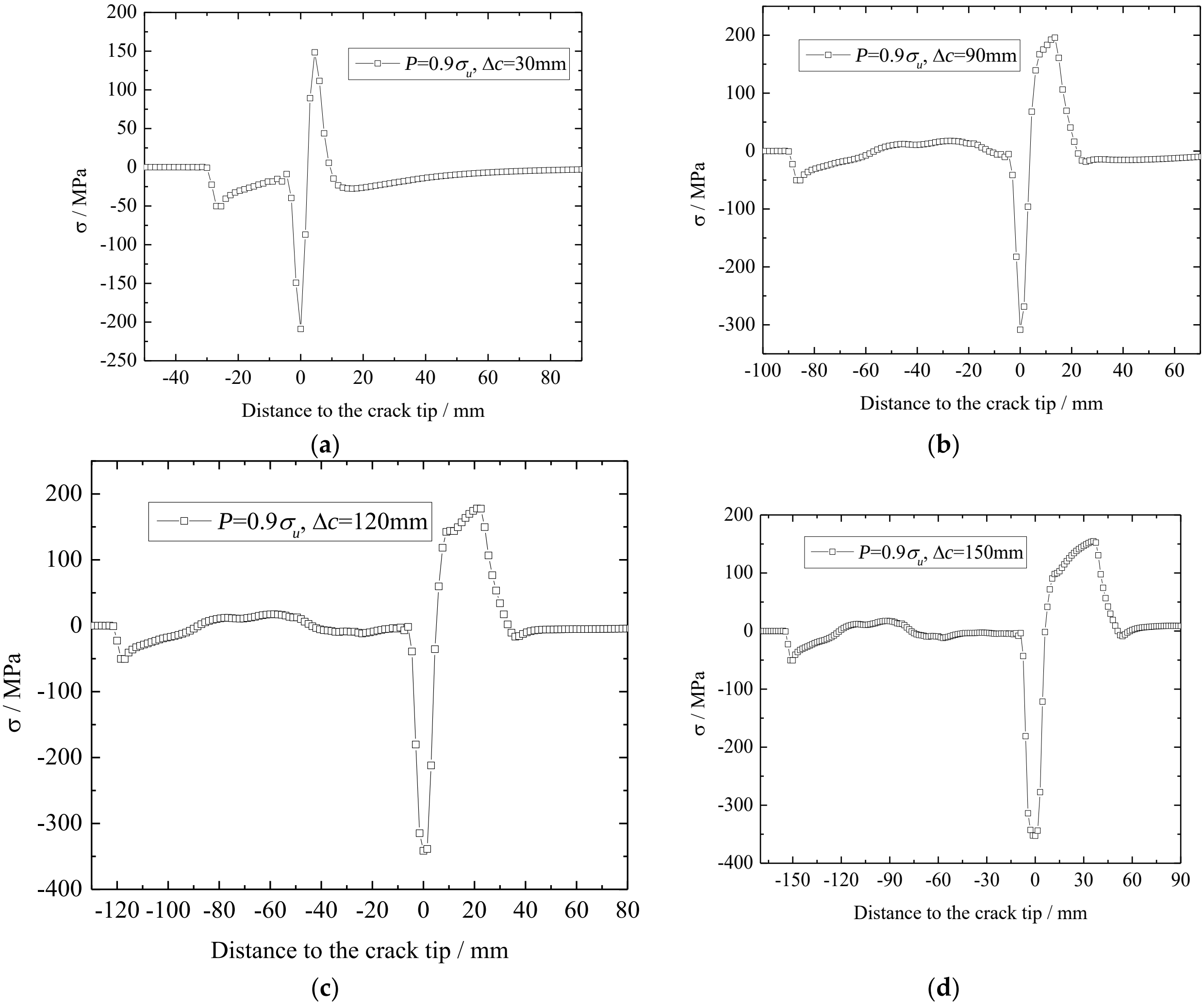


Figure 11. Compressive stress values for different crack propagation lengths: (**a**) $\Delta c = 30$ mm; (**b**) $\Delta c = 90$ mm; (**c**) $\Delta c = 120$ mm; (**d**) $\Delta c = 150$ mm.

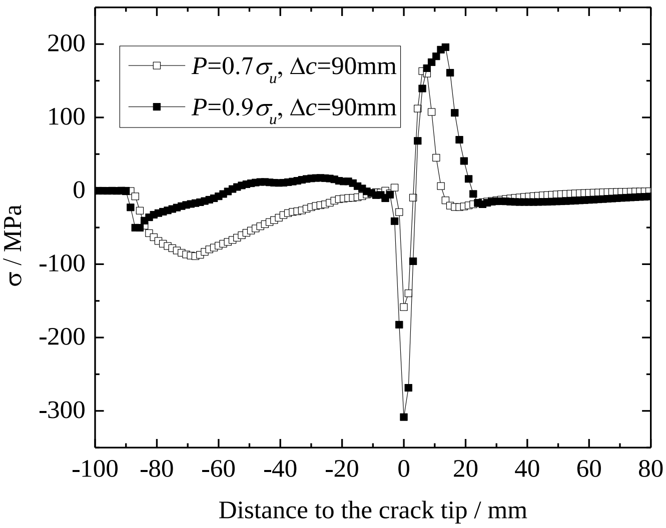


Figure 12. Stress distribution curve of the crack tip at different load levels for crack propagation length $\Delta c = 90$ mm.

3.4. Results of Out-of-Plane Deformation Distribution

In order to study the changes of out-of-plane deformation during crack propagation, the out-of-plane deformation corresponding to the minimum load at different crack lengths (load unloaded to zero) are extracted under the condition of cyclic tensile load of 0.9. Figure 13 shows the displacement clouds of the out-of-plane deformation distribution under different crack propagation lengths. It can be seen that as the number of cycles increases, the crack grows, the out-of-plane deformation of the cracked plate changes to some extent, and the residual strength of the cracked plate gradually decreases. In addition, as shown in Figure 14, the change in out-of-plane deformation increases with the increase in applied load.

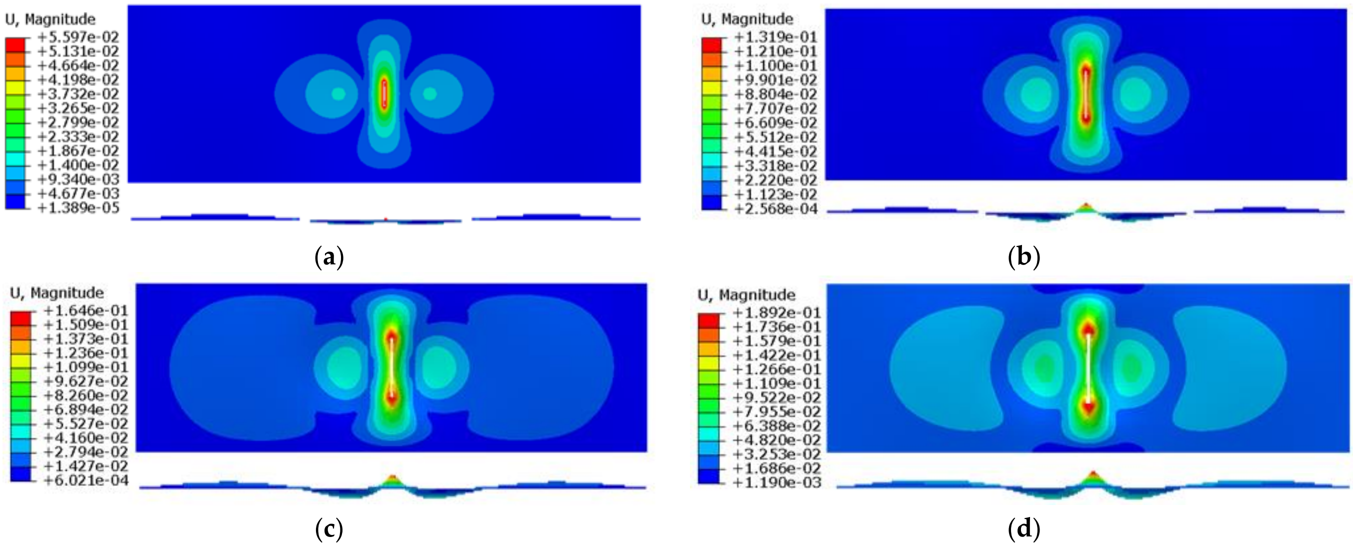


Figure 13. Out-of-plane deformation distribution of cracked plate at minimum load: (**a**) $\Delta c = 30$ mm; (**b**) $\Delta c = 90$ mm; (**c**) $\Delta c = 120$ mm; (**d**) $\Delta c = 150$ mm.

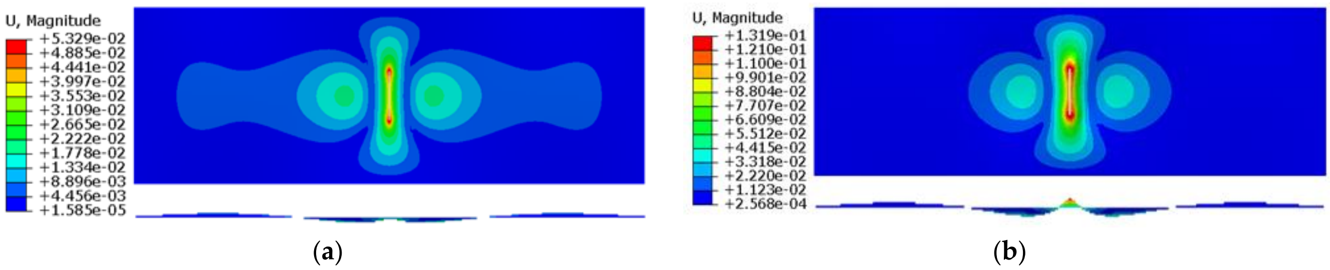
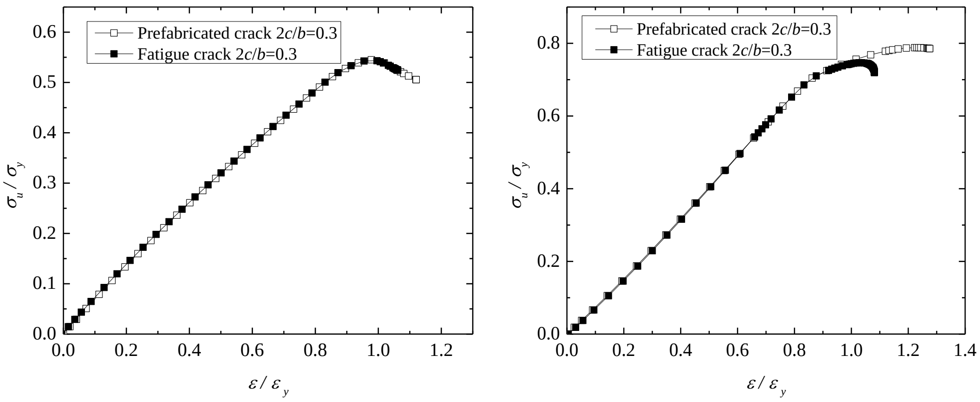


Figure 14. Out-of-plane deformation distribution of cracked plate at minimum load: (**a**) $P = 0.7\sigma_u$, $\Delta c = 90$ mm; (**b**) $P = 0.9\sigma_u$, $\Delta c = 90$ mm.

3.5. Effect of Crack Type

To investigate the effect of crack type on the residual strength of cracked plate, the load-displacement curves of the tensile and compressive residual strength corresponding to the prefabricated crack specimen and the fatigue crack specimen at crack length of $2c/b = 0.3$ are extracted, respectively.

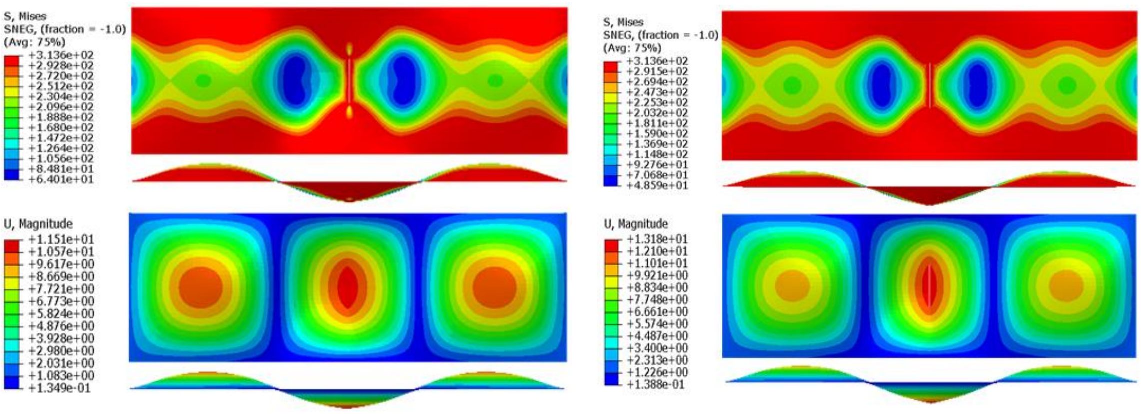
From Figure 15a,b, it can be seen that for the compressive residual strength, the load-displacement curves corresponding to both are approximately the same, while for the tensile residual strength, the residual strength value corresponding to the fatigue crack is reduced.



(**a**) (**b**)

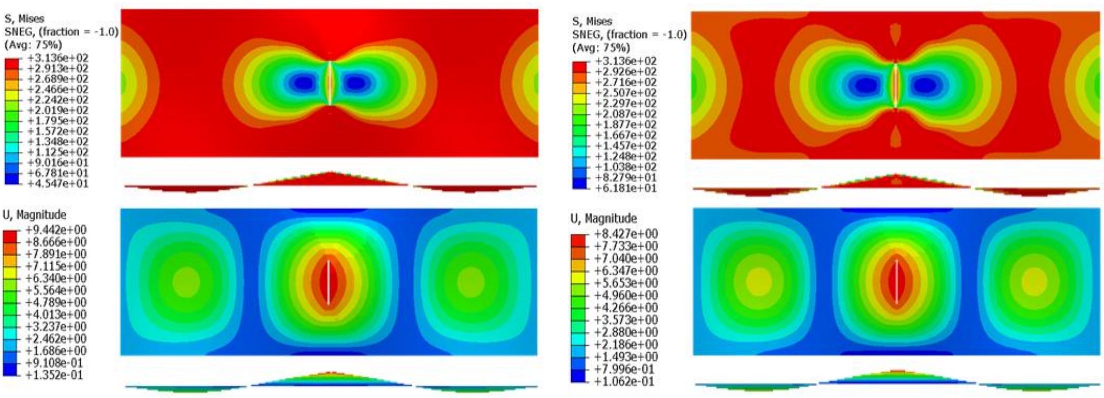
Figure 15. Load-displacement curves of plate with prefabricated crack and fatigue crack at $2c/b = 0.3$: (**a**) Compressive residual strength; (**b**) Tensile residual strength.

In addition, the stress distribution and out-of-plane deformation of the prefabricated crack model when it reaches the limit state are also similar to the crack formed by crack propagation, as shown in Figures 16 and 17. Therefore, from the above analysis, it can be seen that crack propagation has little impact on the residual strength assessment of cracked plates.



(**a**) (**b**)

Figure 16. The stress distribution and out-of-plane deformation at the compressive limit: (**a**) plate with prefabricated crack; (**b**) plate with fatigue crack.

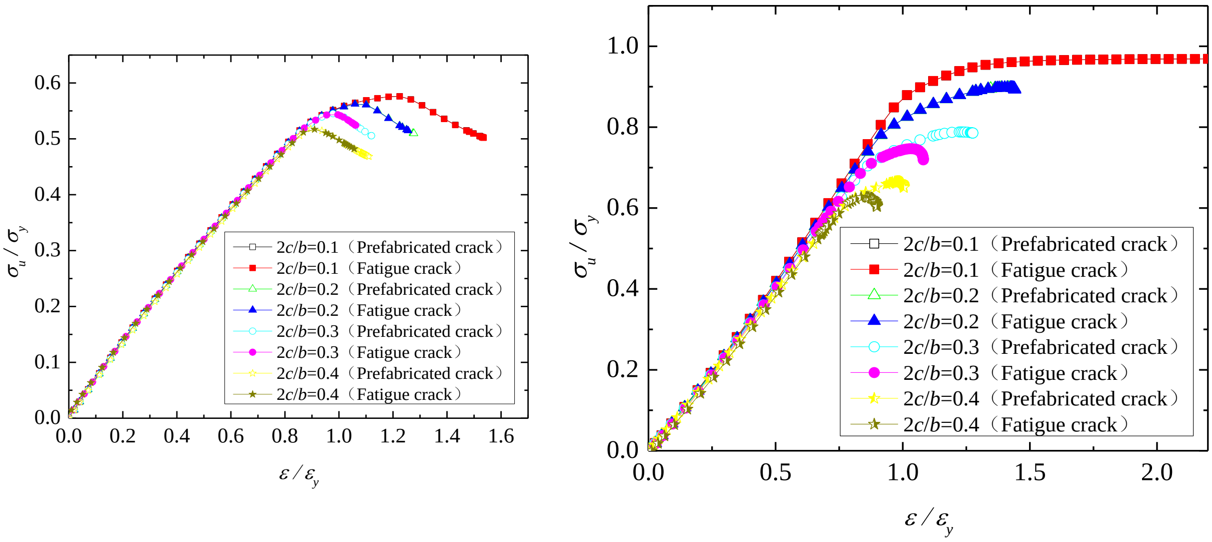


(**a**) (**b**)

Figure 17. The stress distribution and out-of-plane deformation at the tensile limit: (**a**) plate with prefabricated crack; (**b**) plate with fatigue crack.

3.6. Effect of Crack Length

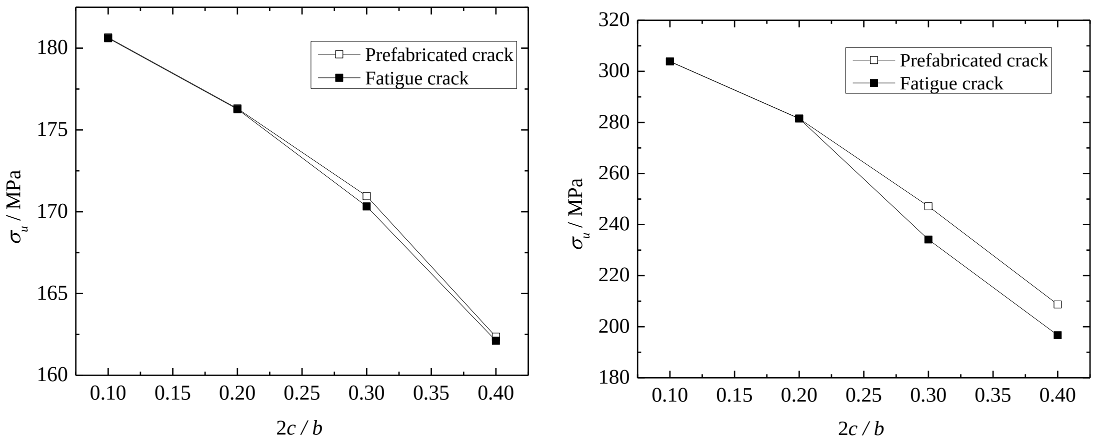
In order to study the effect of crack length, different loading conditions with initial crack length $2c/b = 0.1 \sim 0.4$ and external load $P = 0.9$ are selected for analysis. As shown in Figure 18a,b, the obtained load-displacement curves show that the compressive and tensile residual strength of the cracked plate decreases continuously with the increase in crack length.



(**a**) (**b**)

Figure 18. Load displacement curves at different crack lengths: (**a**) compressive load; (**b**) tensile load.

Figure 19a,b show the relationship between relative crack length and residual strength. It can be seen that there is no significant difference between the compressive residual strength of fatigue crack and prefabricated crack. For the tensile residual strength, there is no significant difference when the crack length is short. However, with the propagation of crack length, the gap between the two results is gradually clear, and the tensile residual strength of fatigue crack is smaller.



(**a**) (**b**)

Figure 19. Residual strength at different crack lengths: (**a**) compressive residual strength; (**b**) tensile residual strength.

The above analysis shows that under the action of cyclic loading, the crack propagation will increase the crack length, and the residual stress field will be formed in the crack tip trailing area, and the out-of-plane deformation of the cracked plate will change to a certain extent relative to the initial deformation. The deformation can be clearly reflected in Figure 13, but the results from the finite element analysis show that the residual strength results calculated from fatigue crack and prefabricated crack are similar. The influence on the residual strength value is still the size of the effective cross-sectional area of the cracked plate, that is, the crack length, and the rest of the influencing factors are relatively small. The main factor affecting the residual strength is still the size of the effective cross-sectional area of the cracked plate while the rest of the influencing factors have relatively little effect.

4. Conclusions

Through the studies, the magnitude of the residual ultimate strength of prefabricated and fatigue cracks in cracked plates was calculated and analyzed, and the following conclusions are drawn from the discussion of factors such as cyclic load size and crack length:

(1) Prefabricated crack and fatigue crack have obvious differences. Prefabricated crack is formed by wire cutting, and there is almost no residual strain in the crack trailing area. Fatigue crack will expand under the action of cyclic load, a trailing area with residual strain will be formed, and the residual strain will cause a certain tensile or compressive stress field behind the crack tip.

(2) The stress field near the crack tip changes continuously with the crack expansion. When the crack propagates, the range of tensile and compressive stresses near the crack tip increases continuously, and a small compressive stress field exists near the initial crack tip. When the load level increases, the compressive stress in the small area near the crack also increases, but the overall residual compressive stress behind the crack tip decreases, while the overall tensile stress before the crack tip increases. Although the change of stress field is relatively large, its effect on the on the residual strength is not significant, which indicates that the stress field near the crack tip has less influence on the residual strength assessment.

(3) Under the combined effect of crack propagation and cyclic tensile loading, the out-of-plane deformation of the cracked plate will change to a certain extent. However, this change in out-of-plane deformation caused by crack growth has a smaller effect on the remaining strength compared to the same prefabricated crack length.

(4) In this paper, the residual strength of structural with fatigue crack and prefabricated crack are analyzed by crack propagation simulating method using model change command of ABAQUS, and the results show that the corresponding compressive residual strength values of both are approximately the same. However, for tensile residual strength, the value calculated for fatigue crack is relatively smaller than that for prefabricated crack when the crack length is large. In sum, it can be seen that the propagation of cracks has a small effect on the assessment of the residual strength of the structure, and the main factor affecting the magnitude of the remaining ultimate strength of the structure is the size of the effective cross-sectional area, and therefore the longer the length of the crack, the more obvious the reduction in the remaining strength of the structure.

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