

Article

Numerical Investigation of Fatigue Crack Propagation Behaviour of 550E High-Performance Steel

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Abstract: The fatigue crack propagation behaviour of Q550E high-performance steel (HPS) is studied in this paper. Static tensile testing and fatigue crack propagation testing were carried out, and the results were compared with those of Q235. Finite element models were developed and verified against the experimental results. The impacts of the initial crack angle, crack depth ratio, stress ratio, thickness, and corrosion pitting on the fatigue crack propagation behaviour of the HPS were analysed. The results show that the fatigue life of Q550 was reduced by 18% due to the corrosion pitting, but it did not change the crack propagation path. When the stress intensity factor is higher than a certain value, the fatigue performance of Q235 is better than that of Q550E. The initial crack angle of 52.5° is the critical angle of the crack stress intensity factor. The steel tends to fracture as the crack depth ratio increases, and more attention should be paid to the effective crack length in engineering practice. An increasing stress ratio leads to a smaller stress intensity factor, and the thickness affects the stress intensity factor in the later stage. The crack stress intensity factor around the corrosion pits gradually decreases along the thickness direction, and the crack tips around the corrosion pits tend to reach the yield state initially, accelerating the fatigue fracture of the specimen and ultimately leading to a decrease in fatigue life.



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Keywords: bridge engineering; high-performance steel; fatigue crack; numerical simulation; stress intensity factor

1. Introduction

Bridge structures are developing in the direction of large span, high load, light weight, and environmental protection [1]. The performance of steel is also improving with the increasing demands of engineering construction, resulting in high-performance steel for bridges [2,3]. Compared to ordinary steel, high-performance steel (HPS) shows higher strength, higher fracture toughness, and better fatigue resistance [4–7]. As a result, HPS is widely used in various steel bridges [8], such as the sea-crossing bridge, Akashi Kaikyo Bridge.

Long-term stress fatigue often leads to structural fracture failure during the service life of steel bridges [9–12]. Zong et al. [13] conducted an experimental study on the fatigue crack growth rate of Q345qD bridge steel by changing its thicknesses and stress ratios. The results showed that the crack growth rate increased with the stress ratio, and the crack growth rate increased by 7–25%, but the influence of plate thickness change was not noticeable. Liu et al. [14] studied the relationship between the thickness and the stress state of the crack, quantified the thickness effect, and introduced the penetrating crack, but how the thickness affects the stress intensity factor of the crack tip was not clearly pointed out [15]. Li et al. [16] carried out a study on the influence of different surface crack directions on

the change in stress intensity factor during bearing operation. Yaagoubi and Meier [17] studied the relationship between surface cracks with different angles and the J-integral, and they showed that the increase in friction effect in the case of oblique cracks weakened the J-integral at the crack tip. But there has been no in-depth study on penetrating cracks, which are more harmful to the structure; these will be studied in this paper for HPS steel. Although the effective initial crack in the process of crack propagation is very short, it is extremely destructive since there are some invisible initial cracks. Therefore, it is necessary to undertake in-depth study on the crack depth ratio. Meanwhile, most scholars have focused on the fatigue crack propagation behaviour of ordinary steel beams [18,19], and there have been insufficient investigations on fatigue crack failure of high-performance steel. Kang and Hong [20] studied the fatigue properties of HPS, and their results showed that the fatigue strength of Q690D HPS was significantly higher than existing specifications.

It is known that the joint action of a corrosive environment and repeated stress is one of the main reasons for the premature failure of most engineering metals, especially in marine environments [21,22]. This usually leads to the premature initiation of fatigue cracks on the surface of materials, resulting in reductions in fatigue life and resistance [23–25]. The research on the crack growth rate of different kinds of steels is extensive [26], but the driving factors affecting the crack growth rate of HPS are not well understood [27–29]. The effects of the initial crack angle, crack depth ratio, stress ratio, thickness, and corrosion pitting have not attracted enough attention, but they are very important for the fatigue safety of high-performance steel structures [30]. These limited investigations have led to fatigue safety problems in high-performance steel structures.

To investigate the behaviour of fatigue crack propagation, a finite element model of a CT specimen of Q550E HPS is established and verified against experimental results in this paper. The impacts of the initial crack angle, crack depth ratio, stress ratio, thickness, and corrosion pit on crack propagation are studied. This research provides a reliable and practical basis for the theoretical analysis of prefabricated cracks and an anti-fatigue design, which promotes the application of HPS in sea-crossing bridges.

2. Experimental Program

2.1. Specimen Design

Q550E with a thickness of 8 mm was used in the experiment, and Q235 specimens were also made for comparison. The chemical compositions of the steels are shown in Table 1. In order to obtain accurate material parameters of the tensile mechanical properties of the steel, uniaxial tensile tests were carried out before the fatigue crack propagation experiments, and the test results are shown in Table 2.

Table 1. Chemical compositions (%).

Material	C	SI	Mna	Nbb	Vb	Tib	Als	Cr	Ni	Cu	Mo	S	P
Q550E	0.12	0.55	1.255	0.024	0.05	0.016	0.03	0.5	0.5	0.4	0.3	-	-
Q235	0.17	0.35	1.4	-	-	-	-	-	-	-	-	0.045	0.045

Table 2. Basic mechanical properties.

Material	Yield Strength (MPa) <i>R_p</i> (0.2)	Ultimate Strength (MPa) <i>R_m</i>	Modulus of Elasticity (GPa) <i>E</i>
Q550E	665.71	720.43	216.79
Q235	293.91	435.64	213.22

Three C(T) compact tensile samples for each kind of steel were designed for the fatigue test. The prefabricated notch length of the specimen was 8mm, and the toughness zone length *w* was 40 mm, as shown in Figure 1. A corrosion pit was prefabricated manually, and in accordance with the research of other scholars [31], the corrosion pit was a hemisphere

with a radius of 2 mm, positioned 6 mm away from the crack tip of the specimen. The experimental fixture had to be customized, and the specific dimensions are shown in Figure 2.

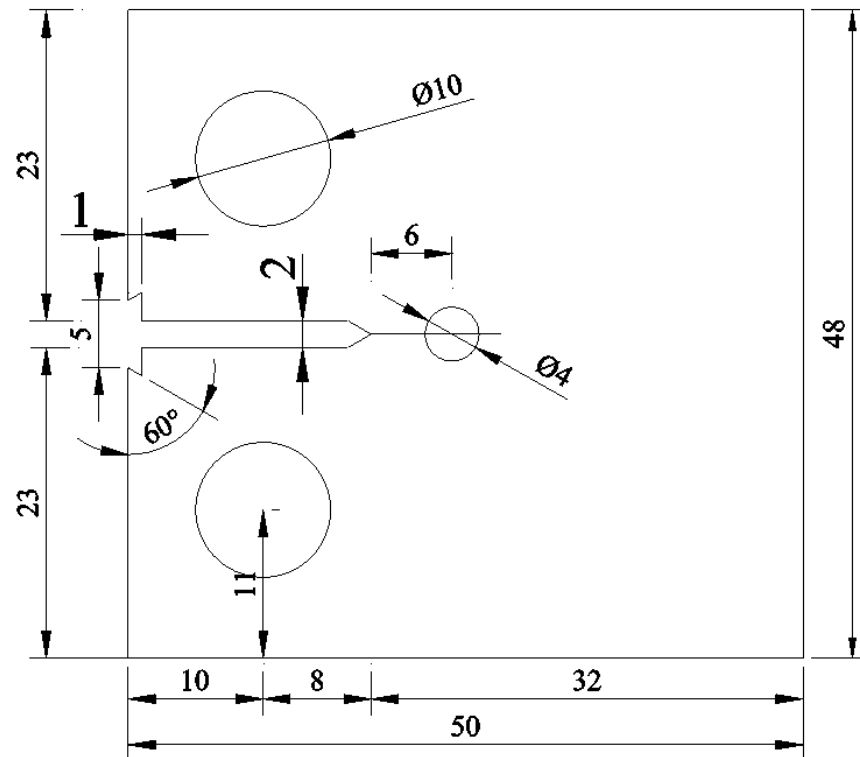


Figure 1. Dimensions of the specimen with a corrosion pit (unit: mm).

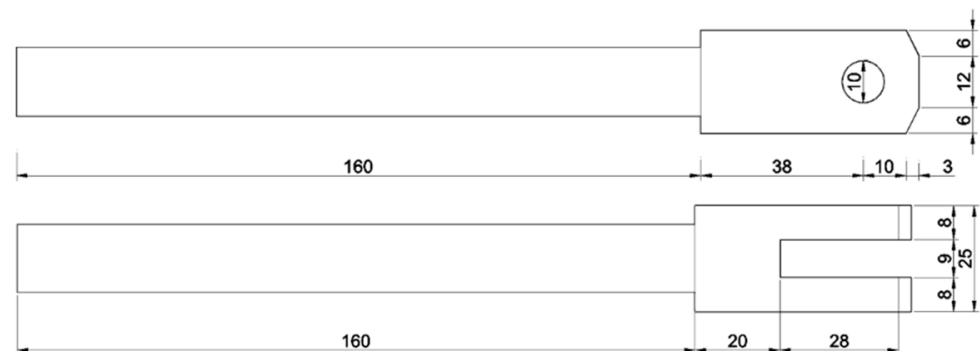


Figure 2. Dimensions of the fixture (unit: mm).

2.2. Fatigue Testing

Figure 3 shows the loading device for fatigue crack growth testing. Sine wave loading with a frequency of 10 Hz was used in the experiment, and the stress ratio was 0.1. A COD extensometer was placed at the notch to continuously record the opening displacement during the test, and an industrial camera with an electron microscope was used to observe the micro-crack propagation. The opening displacement of the specimen was measured by the COD extensometer, and the fatigue crack length was calculated using the formula of the flexibility method. In order to ensure that the crack tip was sharp enough and not affected by the initial notch shape of machining, a 1.5 mm crack was prefabricated via initial machine cutting. In general, the stress intensity factor $K_{\max}$ selected for pre-cracking was higher than the value in the crack growth rate test. If there was no crack initiation after 30–50 thousand cycles, the $K_{\max}$ was increased by 10%.

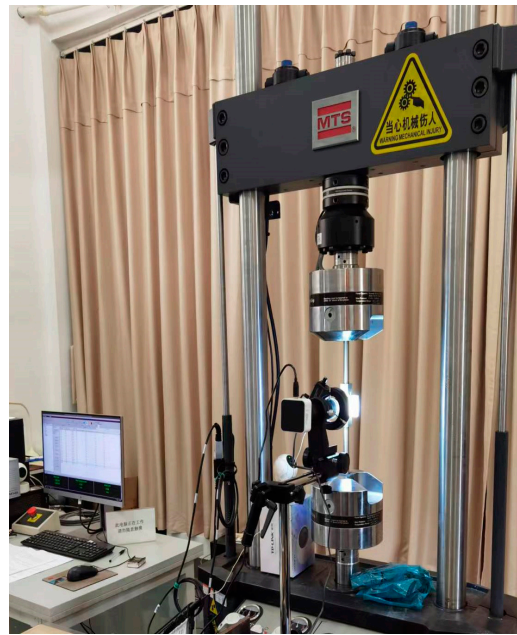


Figure 3. Loading device diagram.

3. Experimental Results and Discussion

3.1. Fatigue Crack Growth Curve

Figure 4 shows the average test results regarding the fatigue crack growth rates of the intact Q550E and Q235. There is no obvious difference in crack growth rate between the two steel specimens in the early stage of crack growth, but the crack growth rate of Q550E is obviously higher than that of Q235 in the late stage of crack growth. The crack growth rate of the two steel specimens in the later stage is much higher than that in the earlier stage.

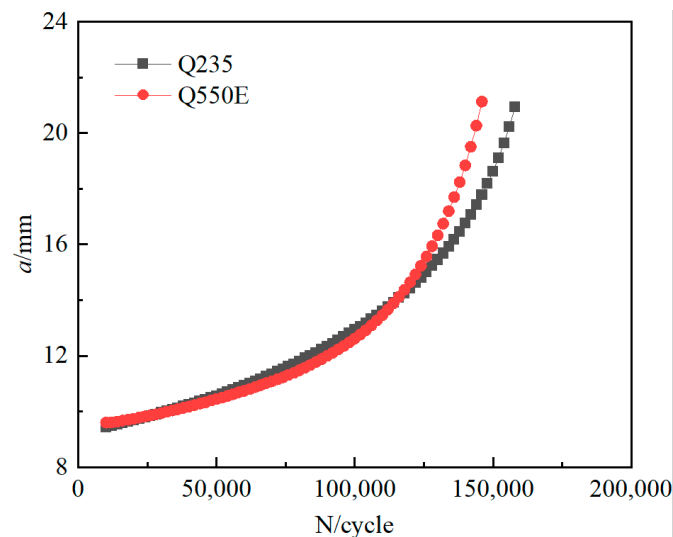


Figure 4. Fatigue crack growth curves of the intact steels.

The influence of corrosion pitting on the crack growth curve based on average results is shown in Figure 5. The curves show three stages and two turning points. The two curves are close in the first stage. After the first turning point, the crack growth rate of Q550 is higher than that of Q235. After entering the third stage, the crack grows sharply, and the specimen fails. The crack propagation lengths of Q235 and Q550E at the first turning point were 11.21 mm and 16.08 mm, respectively. Compared with the curves for the intact

specimens, the presence of turning points in these curves is due to the obvious stress concentration when the crack tip extends to the vicinity of the corrosion pit, which leads to a sudden increase in stress at the crack tip, thus accelerating the crack propagation. The crack propagation life of Q550E was reduced by about 18% from the intact sample to the corroded one. However, the corrosion pit had little influence on the crack propagation curve path, shown in Figure 6; the crack propagation path is along the direction perpendicular to the load line.

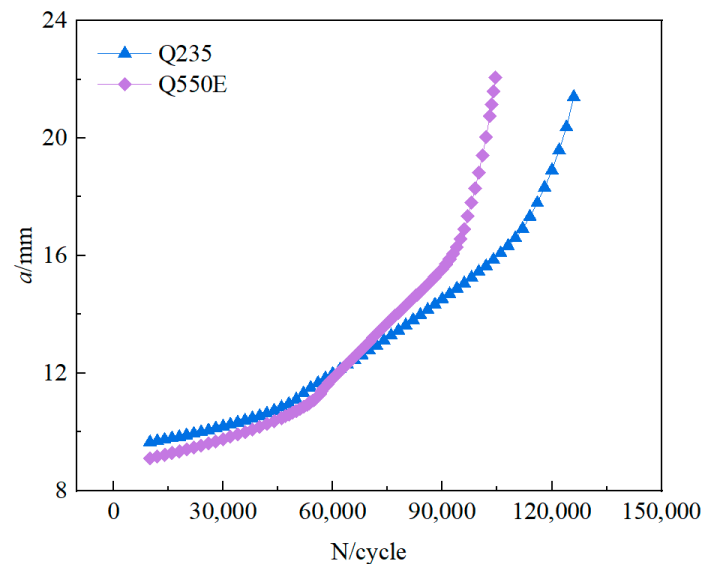
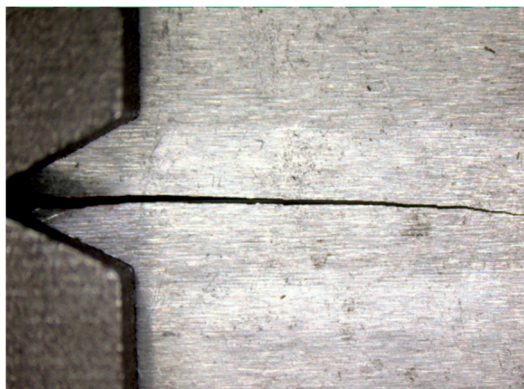
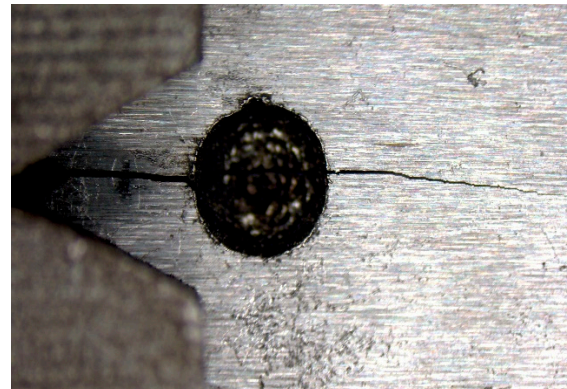


Figure 5. Fatigue crack growth curve of the corroded steels.



(a)



(b)

Figure 6. Crack propagation path: (a) Intact; (b) Corroded.

3.2. Fatigue Crack Growth Rate

The crack growth rate is obtained as the tangential slope of the polynomial fitting curve of crack length a and fatigue cycle number N , expressed as follows:

$$(d_a/d_N)_i = b_1/C_2 + 2b_2(N_i - C_i)/C_2^2 \quad (1)$$

where d_a/d_N is the crack growth rate in mm; C_i terms are the material parameters, such that $C_1 = (N_{i+3} + N_{i-3})/2$, $C_2 = (N_{i+3} - N_{i-3})/2$, and index i indicates the test data point; $\alpha = a/W$, and its value is greater than 0.2; and b_1, b_2 are the regression parameters determined by the least squares method. The stress intensity range ΔK is calculated by Equation (2). By taking the logarithm of the Paris formula, it can be expressed as

Equation (3), and the values of parameters m and c can be obtained by linear fitting as listed in Table 3.

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} \left(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4 \right) \quad (2)$$

$$\lg \frac{da}{dN} = m \lg(\Delta K) + \lg(C) \quad (3)$$

Table 3. Parameter values.

Materials	No	lgC	m	R^2	Mean Value
Q550E	1#	−9.08	3.61	0.98	lgC = −9.11, m = 3.6
	2#	−9.16	3.6	0.98	
	3#	−9.09	3.58	0.99	
Q235	1#	−10.47	4.59	0.98	lgC = −10.45, m = 4.57
	2#	−10.45	4.57	0.98	
	3#	−10.43	4.57	0.97	

Figure 7 shows the crack growth rates of the two steels according to their average values, and an intersection point at a stress intensity factor amplitude of $24.04 \text{ MPa} \cdot \text{m}^{1/2}$ can be observed. After this point, the crack growth rate of Q550E is slightly higher than that of Q235. As shown in this figure, the crack growth rates of the corroded specimens can be roughly divided into three stages in the logarithmic coordinate system, i.e., Stage I of initial crack growth, Stage II of the crack passing through the pit, and Stage III of stable crack growth. When the crack growth length reaches 12 mm, the crack reaches the edge of the corrosion pit, and the crack growth rate then suddenly changes and enters Stage II. When the crack length reaches 16 mm, the crack propagation completely passes through the corrosion pit, and the crack propagation of the specimen reaches a stable stage. The fatigue crack propagation rate is linearly related to the stress intensity factor in the logarithmic coordinate system. The crack growth rate of Q550E in Zones I and II is significantly higher than that of Q235. Once the crack propagates through the corrosion pit, the crack propagation rate of Q550E is slightly higher.

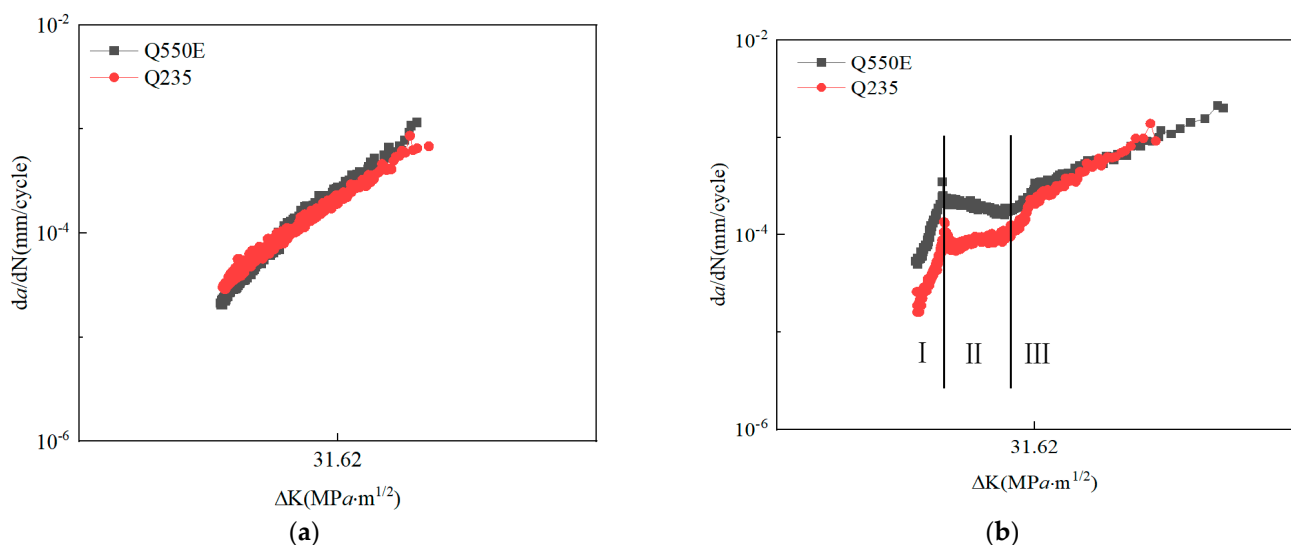


Figure 7. Comparison of crack growth rates: (a) Intact; (b) Corroded.

4. Numerical Investigations

4.1. Finite Element Model

A finite element model was developed by using the commercial software ANSYS workbench. The specimen size, material parameters, and load of the finite element model were consistent with those of the crack propagation test. A tetrahedral mesh and Solid185 elements were adopted, and the overall mesh accuracy was set to 1.5 mm. For a more realistic simulation and considering the requirements of time and accuracy, an influence ball with a radius of 6 mm and a mesh precision of 0.4 mm was set at the crack tip for mesh refinement, as shown in Figure 8. Smart crack growth simulation was adopted in the mesh processing. This process is based on mesh division that simulates the features of fatigue or crack growth morphology in engineering structures, representing separation, deformation, adaptation, and re-division technology. To simulate static or dynamic fatigue crack growth in the solution process, the influence of the crack tip stress singularity on the crack growth rate can be effectively alleviated. Because the grid changes occur at the crack front, the stress state at the crack tip can be well represented in the process of crack propagation, and the high stress intensity factor at the crack tip caused by rough grid division can be avoided.

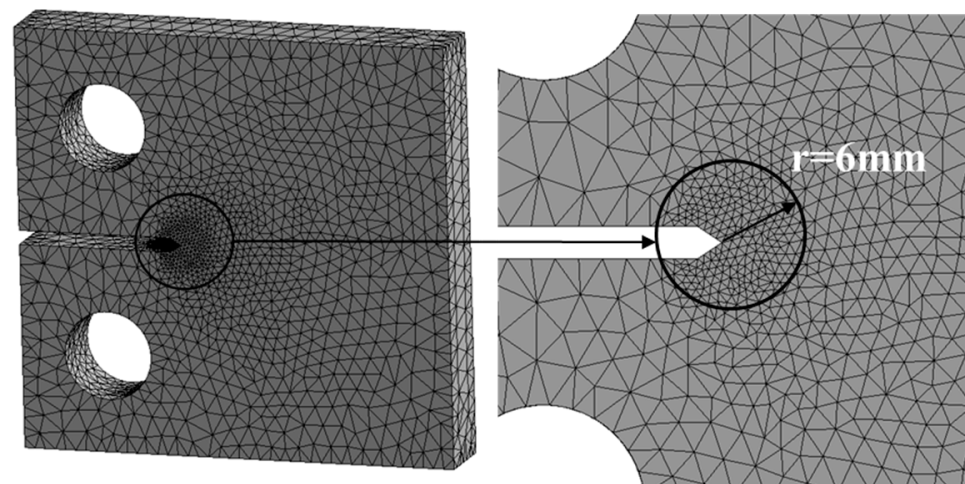


Figure 8. Finite element model.

The X-axis in the FEM indicates the direction of crack propagation, and the Y-axis indicates the crack opening direction. The upper loading hole was divided into upper and lower sides and coupled to the centre for loading. The displacement in the X and Z directions and the rotation in the X and Y directions were fixed at 0. The lower loading hole was coupled with the force, where the displacement in the X, Y, and Z directions and the rotation in the X and Y directions were constrained. The process for developing the finite element model is shown in Figure 9.

4.2. Verification

The results of the finite element simulation were compared with the corresponding experimental values, as shown in Figure 10. The maximum errors of the intact Q550E and Q235 in terms of a - N curves in Figure 10a were 6.53% and 3.4%, respectively. The maximum errors of Q550E and Q235 with corrosion pitting were 9.17% and 8.94%, respectively. Due to the grid division of the crack tip, the error of the specimens with corrosion pitting is relatively high, but the overall error is small, which can truly reflect the crack propagation of CT specimens. Figure 10b shows the crack propagation path, and it can be seen that the experimental value is very close to the simulated value in terms of crack length and angle. Therefore, the developed finite element model was deemed reliable for further parameter analysis.

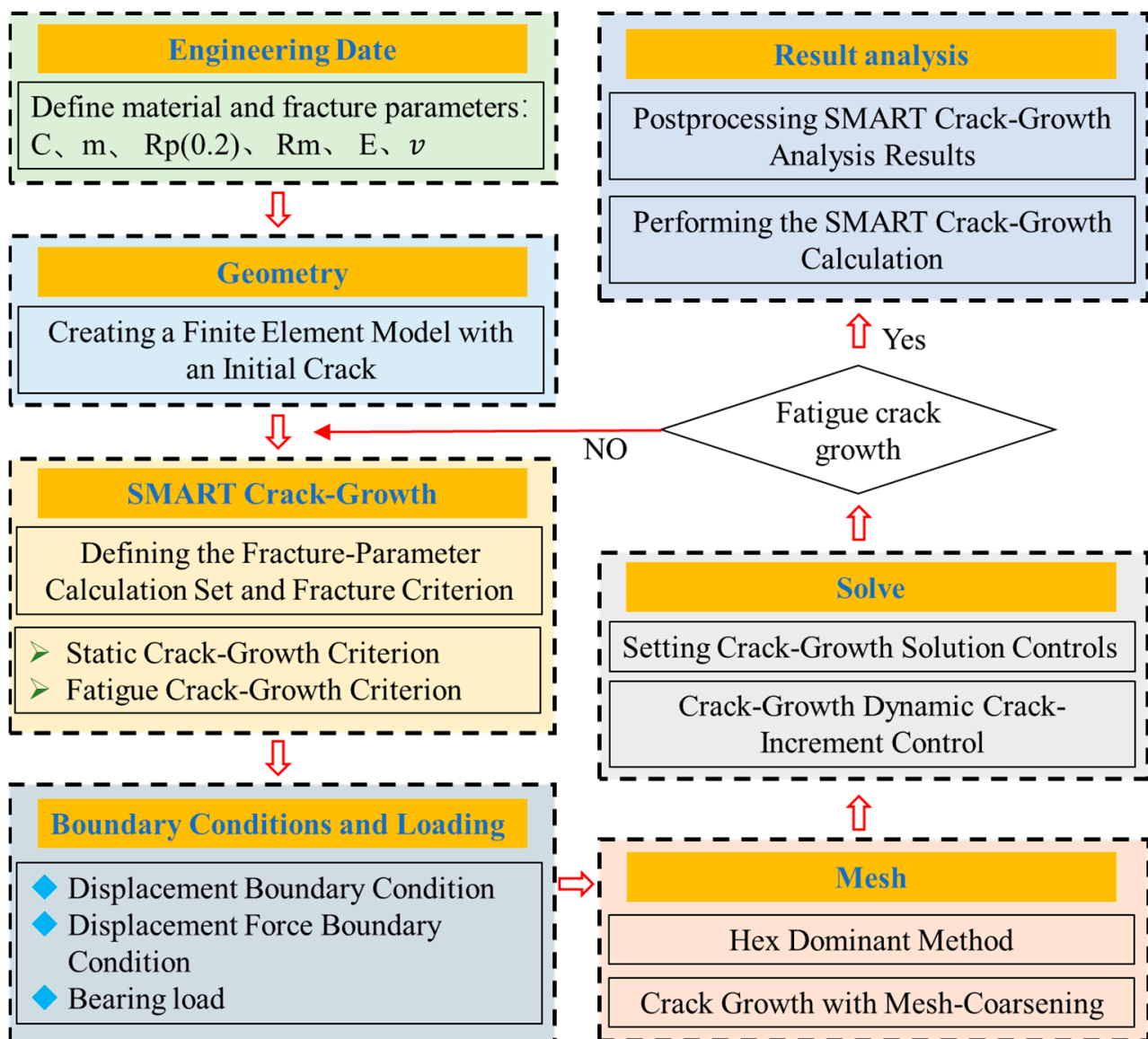


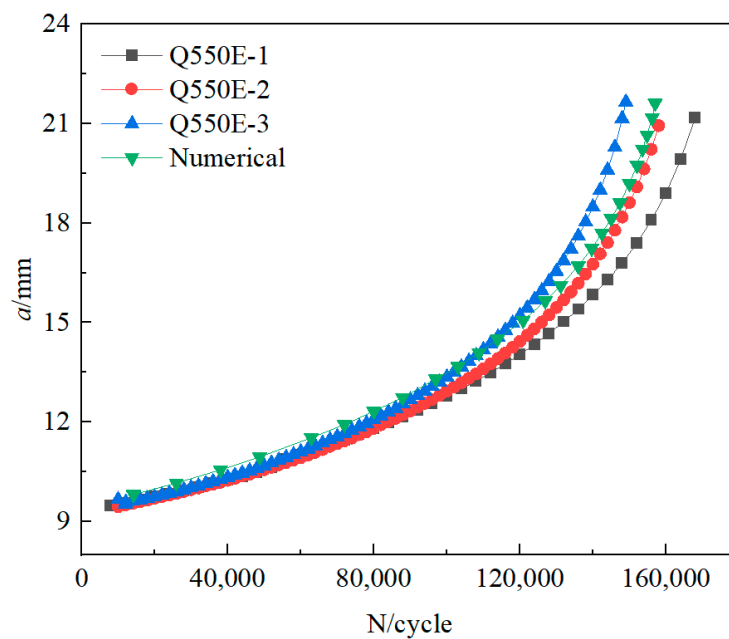
Figure 9. Flowchart for developing the FEM.

4.3. Parametric Analysis

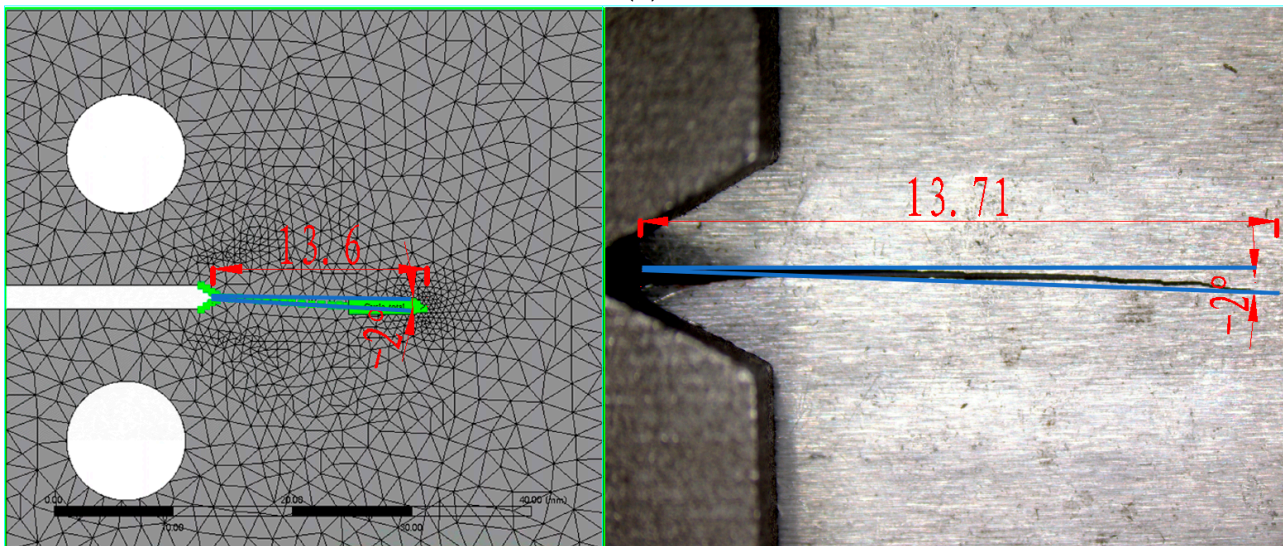
4.3.1. Initial Crack Angle

To study the effect of the initial crack angle on the crack propagation, initial cracks at four angles of 0° , 30° , 45° , and 60° were prefabricated on the specimens in this study. The initial crack length was 1.5 mm with a 7 kN load level, thickness of 8 mm, and stress ratio of 0.1.

As shown in Figure 11, the trends of crack propagation at different angles were the same. The curves are very close to each other when the initial angles are in the range of 0° – 45° , but they change significantly at 60° . Thus, there is a critical angle of crack propagation. An encrypted approximation at 45° – 60° was carried out. It was found that the critical angle was 52.5° , where the crack growth rate suddenly changed. According to the K – N curve, with an increase in the initial crack propagation angle, the stress intensity factor caused by crack tip fracture decreases, and the reduction range is as high as 59%. Therefore, an initial crack angle of 0° is the most unfavourable for crack propagation. The initial crack angle has little effect on the K – a relationship.



(a)

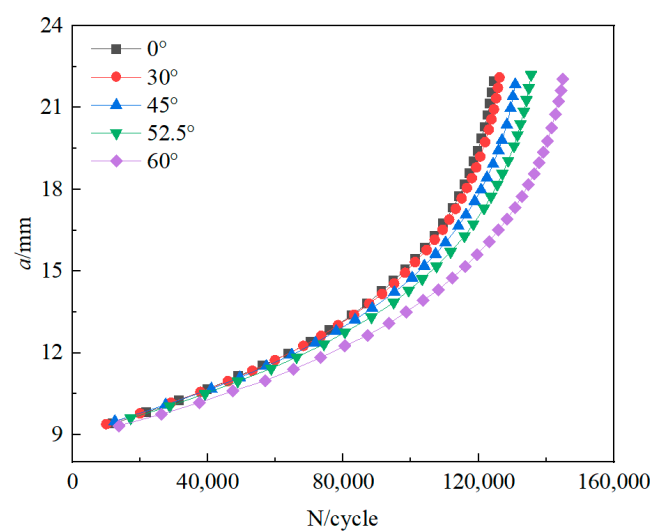


(b)

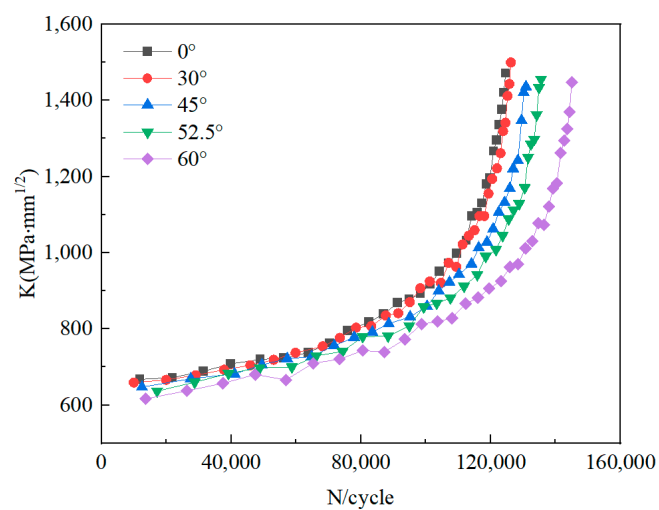
Figure 10. Comparison of experimental and numerical results: (a) $a-N$; (b) Crack propagation path of Q550E-1.

4.3.2. Crack Depth Ratio

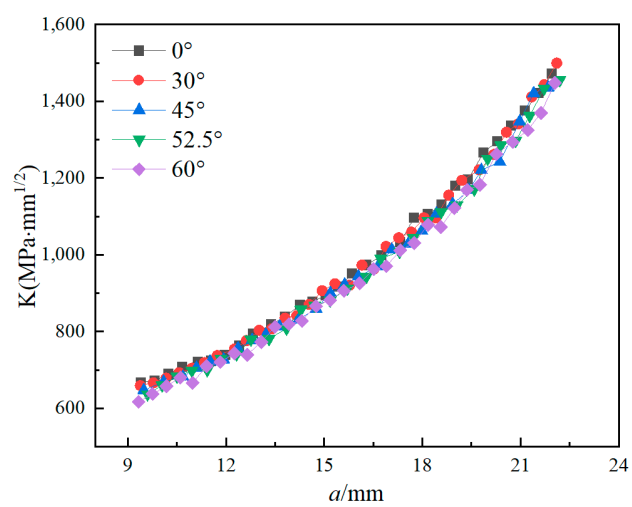
Figure 12 shows the crack growth life curves with six crack depth ratios for a thickness of 8 mm and a stress ratio of 0.1. The fatigue life decreased with increasing depth ratio. When the crack depth ratio was repeatedly increased by 0.05, the fatigue life decreased by 37%, 39%, 49%, 40%, and 54%. The relationship curve between the stress intensity factor and crack length was not affected by the crack depth ratio. The change in the stress ratio did not affect the cracking state under the same crack depth ratio, as shown in Figure 12c. The ratio of the cracking K to the stress ratio R was constant for different crack depth ratios, and the ratio became higher as the depth increased.



(a)



(b)



(c)

Figure 11. Influence of the critical angle: (a) a - N ; (b) K - N ; (c) K - a .

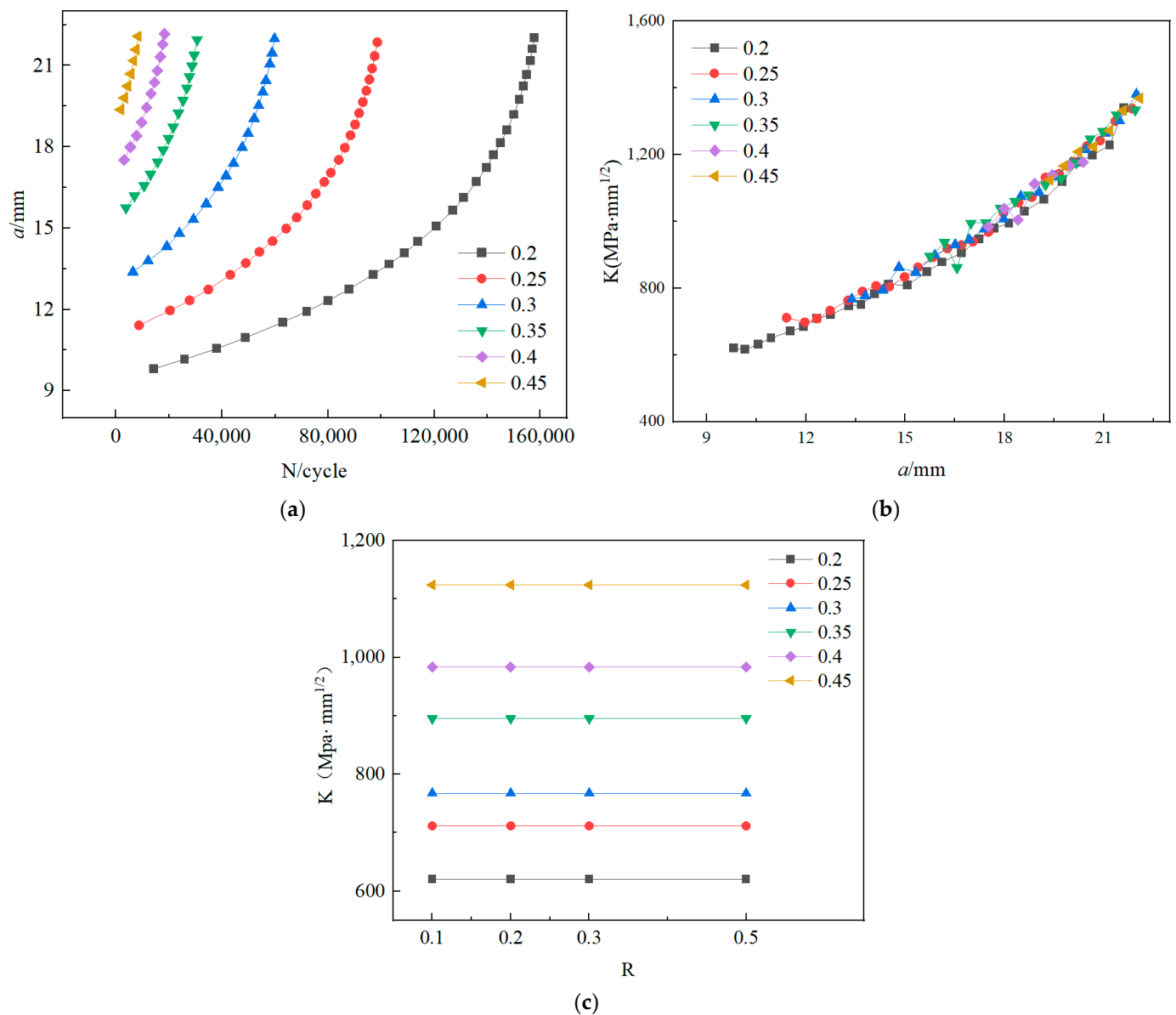


Figure 12. Influence of the crack depth ratio: (a) a - N ; (b) K - a ; (c) K - R .

Figure 13 shows a stress diagram of crack propagation of the crack tip along the thickness direction with different crack depth ratios, where the horizontal direction represents the crack propagation length, the vertical direction represents the specimen thickness, and labels 1–2 represent the path of the crack tip along the thickness direction. In this case, the load was 7 kN, the stress ratio was 0.1, and the thickness was 8 mm. Regardless of the crack depth ratio, the maximum K mainly occurs in the middle position, and a crack initiates in the middle position in the thickness direction and gradually extends to both sides, eventually causing the entire surface to fracture. The K values increase with the crack depth ratio, which leads to a higher possibility of crack tip fracture. In engineering practice, the effective crack length, i.e., the sum of the notch depth and crack length, must be monitored to detect these hidden cracks.

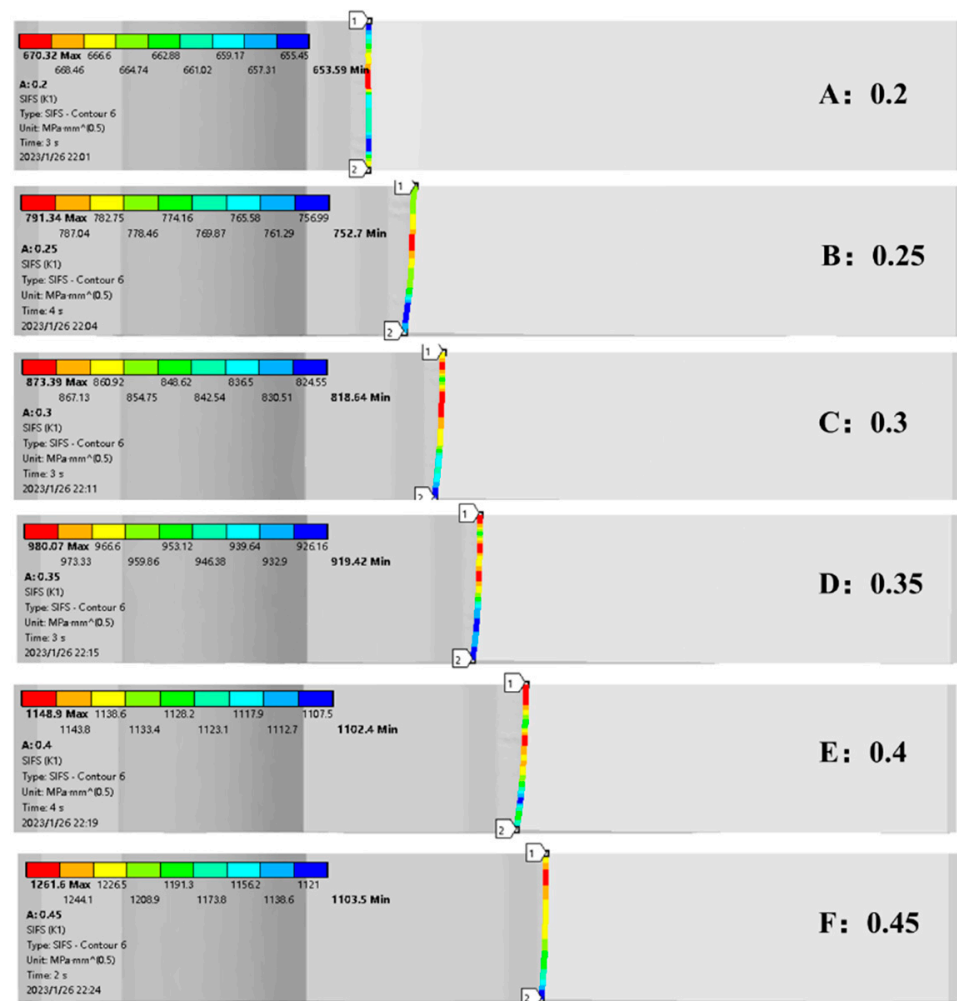


Figure 13. Stress diagram of crack propagation with different crack depth ratios of (A) 0.2, (B) 0.25, (C) 0.3, (D) 0.35, (E) 0.4, and (F) 0.45.

4.3.3. Stress Ratio

Previous studies have shown that stress ratios of 0.1, 0.2, 0.3, and 0.5 can well demonstrate the effect of stress ratios on crack propagation [24]. For this reason, these stress ratios with a thickness of 10 mm and a load of 36 kN were used in the FEM to study the relationship between the crack propagation length, cycle times, and the K value.

As shown in Figure 14, whether the steel is corroded or not, the stress ratio is directly proportional to the crack length and inversely proportional to the stress intensity factor. The curves of corroded specimens fluctuated and experienced a sharp–slow–sharp growth process. This is because the effective length of the crack tip decreases when the crack propagation length is about to reach the corrosion pit. This leads to a sudden increase in crack tip stress and, in turn, to a sudden change in the crack propagation rate.

4.3.4. Thickness

According to ASTM E647-15, the thickness B of the CT specimen should be between $W/20$ and $W/4$. Considering the information in the related literature [24], steel samples with thicknesses of 5 mm, 8 mm, and 10 mm with a load of 7 kN and a stress ratio of 0.1 were used to study the effect of thickness on the crack propagation.

As shown in Figure 15, an increase in thickness leads to a downward curve shift in the K – a relationship, which shows that the thickness is inversely proportional to K . When the thickness was 10 mm, the variation in K was the lowest, and the extreme difference occurred at $595.18 \text{ MPa} \cdot \text{mm}^{1/2}$. For the K – N curves, the stress intensity factors at the initial fracture

of the crack tip for these thicknesses were $923.96 \text{ MPa}\cdot\text{mm}^{1/2}$, $589.01 \text{ MPa}\cdot\text{mm}^{1/2}$, and $482.32 \text{ MPa}\cdot\text{mm}^{1/2}$, respectively. Obviously, halving the thickness from 10 mm to 5 mm led to an increase in K . The numbers of cycles that began to develop rapidly when the thickness reached 8 mm and 10 mm were roughly 133,761 and 335,330, respectively. This indicates that a smaller stress intensity factor of crack tip fracture appears when the thickness is greater, and the critical value of rapid fracture cycles gradually increases, that is, the steel is less likely to fracture. In the a - N relationship, increasing the thickness resulted in a lower crack growth rate. For the same number of cycles, the extension length decreases as the thickness increases. Therefore, as the thickness increases, the K value of the crack tip at the stress concentration position reaches a maximum. Combined with the theoretical formula for K , the thickness affects K in the crack propagation area and significantly affects the crack growth rate. The stress intensity factor changes little in the early stage of crack propagation, but it changes obviously in the later stage.

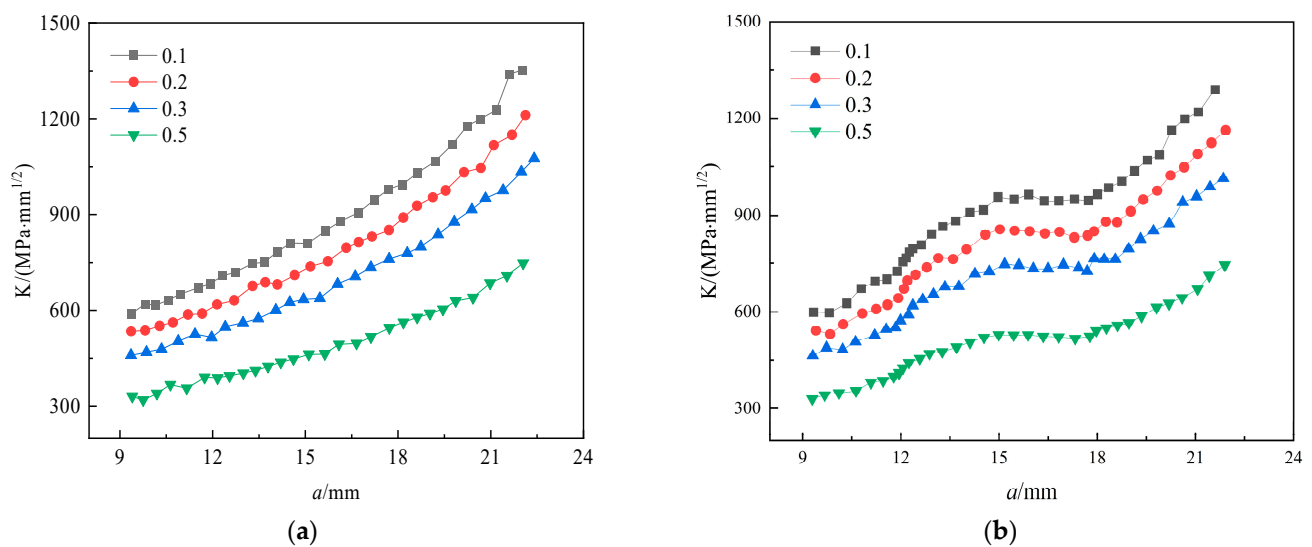


Figure 14. K - a curves of different stress ratios: (a) Intact; (b) Corroded.

4.3.5. Corrosion Pitting

Based on the research described above, a corrosion pit was prefabricated on the crack propagation line. Studies have shown that there are many forms of corrosion pit, such as conical, cylindrical, elliptical, and hemispherical, of which hemispherical corrosion pits are the most widely used [32]. Therefore, a hemispherical corrosion pit with a radius of 2 mm was prefabricated on the specimens based on the existing research [31]. The sine wave continuous load reduction method was adopted to prefabricate an initial 2 mm fatigue crack. The data of the first 2 mm of the initial crack are relatively discrete in the formal propagation process; thus, the centre of the pit was positioned 4 mm away from the crack tip of the specimen. The effects of various pit depths on the crack propagation were analysed for cases of 0.25 B, 0.5 B, and 0.75 B (relative to CT specimen thickness B, namely, 1:1, 2:1, and 3:1).

As shown in Figure 16, before the crack propagation length reaches 12 mm, the corrosion pits do not affect the fatigue life. Then, when the front line of the crack reaches the edge of the pit, the crack propagation rate begins to increase slowly. When the crack propagation length reaches 16 mm, that is, the crack passes through the bottom of the pit, the crack propagation rate increases significantly. Therefore, the corrosion pit has little effect on the crack propagation in the early stage of the corrosion pit (less than 12 mm), and the fatigue life of the specimen is obviously different when the crack passes through the corrosion pit. The maximum difference in fatigue life was 29,252 times when passing through the corrosion pit, accounting for 19% of the total life.

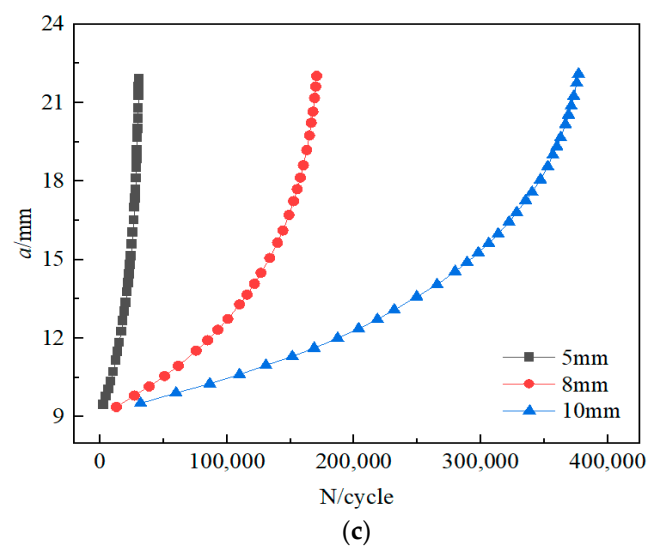
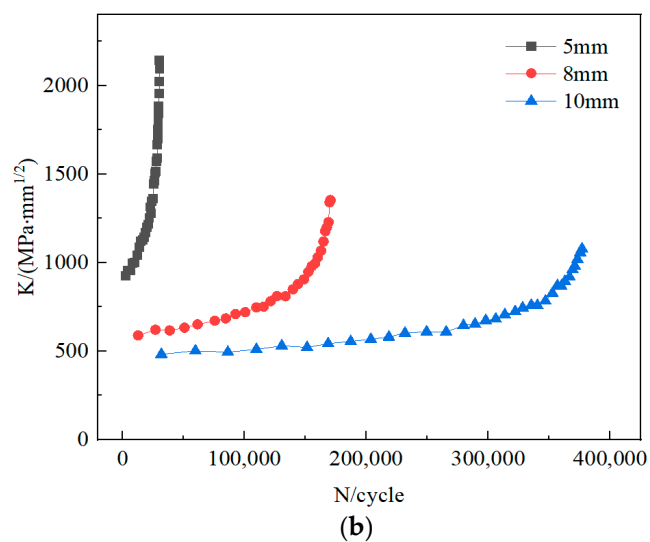
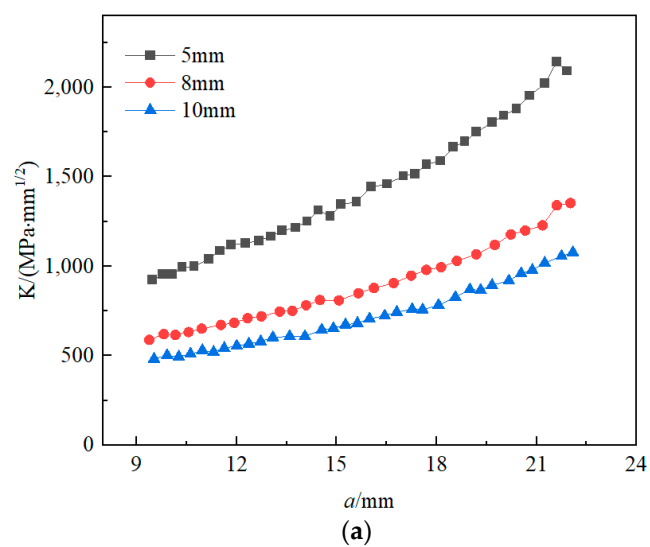


Figure 15. Crack propagation with different thicknesses: (a) K - a ; (b) K - N ; (c) a - N .

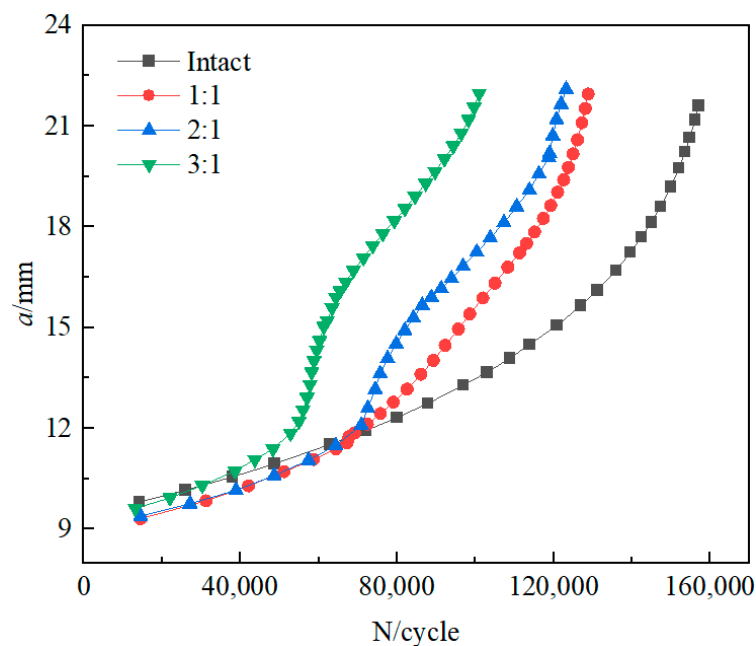


Figure 16. a - N curves of different corrosion pit depths.

Since the crack growth rate for the case with a depth of $0.75 B$ was the fastest, the change in K along the crack propagation direction was further studied. As shown in Figure 17, stress fluctuation occurs when the crack propagates to the vicinity of the pit bottom because of the influence of stress singularity. However, the K value of the crack tip at the bottom of the corrosion pit is always significantly higher than the value at both ends. The crack propagation rate reaches its maximum when it propagates to the bottom of the pit. From the perspective of the whole crack tip section, when the crack tip extends to the left edge of the pit, the K of the crack tip near the pit edge is the highest. This is different from the distribution of K at the crack tip of the non-corroded specimen. This shows that the specimen with a corrosion pit is in a dangerous stress state under the action of fatigue load.

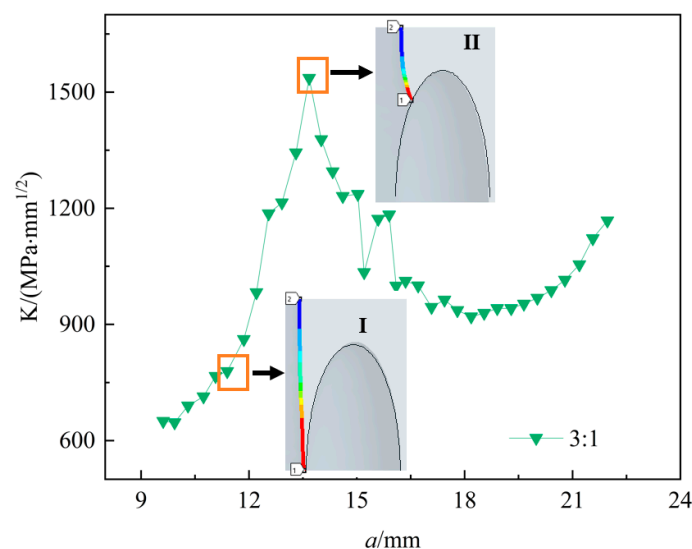


Figure 17. The stress state of the crack tip for the pit at a depth of $0.75 B$.

Figure 18 shows a diagram of the stress state of the crack tip at the end of crack propagation in the corrosion pit. It shows that the K value of the crack tip gradually decreases from the side with the corrosion pit (from 2 or 1 in Figure 17) to the other side,

and the stress is still the highest near the pit. This indicates that the corrosion pit around the crack propagation surface will reach the yield state first, and a stronger stress field can be observed near the crack tip.

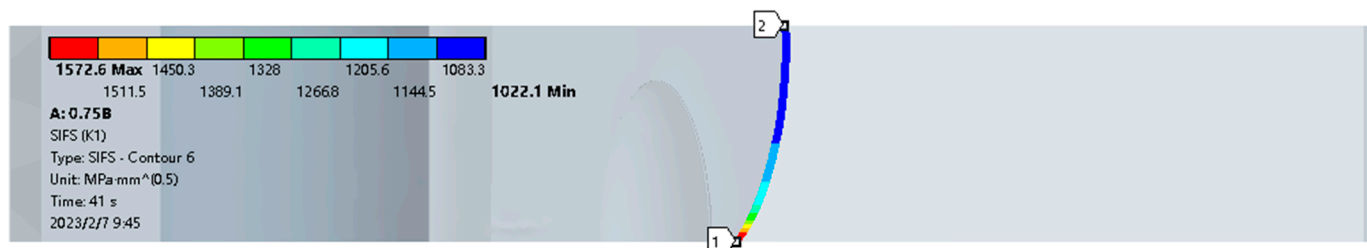


Figure 18. Cloud diagram of the stress state of the final crack tip for the 0.75 B depth pit.

5. Conclusions

In this study, the fatigue crack propagation behaviour of Q550E high-performance steel was experimentally investigated. The fatigue crack growth performance of Q550 was compared with that of Q235. The effects of some factors, such as the initial crack angle, crack depth ratio, stress ratio, thickness, and corrosion pitting, on crack propagation were numerically studied. The main conclusions of this study are as follows:

1. The crack growth rate of Q550E is obviously higher than that of Q235 in the late stage of crack growth. The crack propagation life of Q550E is reduced by about 18% when corroded, as compared to intact specimens. The crack growth curve associated with corrosion pitting is divided into three stages, but it has little influence on the crack propagation path.
2. A higher crack depth ratio easily leads to a higher K value, which, in turn, affects the structural life. The critical angle in the initial crack propagation process is 52.5° , and K is significantly affected by the initial crack angle once this critical value is exceeded. When the initial crack angle is 0° , the crack tip stress is maximized, and fractures are most likely to occur. Otherwise, the crack initiation angle tends to expand perpendicular to the load direction.
3. The stress ratio is directly proportional to the crack length and inversely proportional to the stress intensity factor. The thickness has an obvious impact on the K value in the crack propagation area and significantly affects the crack growth rate.
4. The presence of a corrosion pit has little effect on crack propagation in the early stage of the corrosion pit, but the fatigue life of the specimen is obviously different when the crack passes through the corrosion pit. The corrosion pit around the crack propagation surface reaches the yield state first, and the K value around the corrosion pit gradually decreases along the thickness direction.

It should be noted that these findings are based on limited experimental and numerical results. The comprehensive influence of these parameters needs to be verified and quantified to further promote the application of Q550E in sea-crossing bridges. Therefore, more studies are required to develop a fatigue life model with consideration of these parameters for the guidance of HPS service performance evaluation in marine environments.

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