Experimental Study on Post-peak Cyclic Characteristics of Self-compacting Concrete Combined with AE and DIC Techniques

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Abstract

As a kind of concrete material, the self-compacting concrete (SCC) is usually subjected to external cyclic load after cracking. In this paper, three-point bending tests were carried out for SCC specimens with different notch-to-depth ratios. The whole loading process was monitored by acoustic emission (AE) technology and digital image correlation (DIC) method. The post-peak cyclic characteristics of SCC were analyzed, and the effects of notch-to-depth ratios on mechanical performance of SCC were explored. The change rules of acoustic emission energy, b-value and Ib-value were obtained by processing the collected acoustic emission signal data. Besides, the development law of internal damage for SCC specimens was elaborated and the active cracks were classified according to the ratio of RA value to AF. In addition, the strain field diagrams of specimens with notch-to-depth ratio were displayed and analyzed, and the propagation laws of effective crack length and crack tip opening displacement (CTOD) of SCC concrete with different notch-to-depth ratios were obtained based on DIC technology.

1. Introduction

Self-compacting concrete (SCC) has high fluidity without segregation and bleeding, which can easily pass through the gap between the aggregates (Omrane et al. 2017; Rath et al. 2017; Shi et al. 2015). Because of its unique advantages, SCC has been more and more widely used in civil engineering (Mohseni et al. 2017). In practical application, concrete structures often suffer from damage or even local cracking due to external loads (Chen et al. 2016). However, concrete structures can still be subjected to cyclic loads after cracking, especially under the strong earthquake action (Chen et al. 2017). Therefore, it is essential to investigate the post-peak cyclic response of concrete. At present, most of the studies are focusing on the performances of concrete under static and dynamic monotonic loading (Ring et al. 2013; Alhussainy et al. 2016), while there are few studies on the post-peak cyclic response of SCC concrete (Cifuentes et al. 2013; Noorsuhada 2016).

The interior of concrete structure would experience the dynamic damage procedure during mechanical loading. In order to correctly identify the internal damage and fracture location, it is significant to solve the problem in concrete fracture by tracking the whole damage evolution process in real time. As a real-time and dynamic nondestructive testing method, Acoustic Emission (AE) technology has been applied to monitor the loading process of quasi-brittle materials such as concrete and rock (Prem and Murthy 2017; Su et al. 2012), including detecting damage (Behnia et al. 2016), assessing concrete deformation (Sagaidak and Elizaroy 2007; Chen et al. 2019) and monitoring concrete creep (Rossi et al. 1994). Compared with other nondestructive testing technology, the advantage of AE technology is that the position of developing crack can be determined and the entire structure can be tested without interrupting its function and integrity. Shahidan et al. (2013) classified the damage and characterized the damage degree of concrete by acoustic emission technology. Behnia et al. (2014) used the nondestructive method to evaluate the cracks development of concrete under bending test and investigate the relationship between acoustic emission frequency and damage of concrete beams. Nguyen-Tat et al. (2018) used the AE parameters as the indicator to characterize the damage of concrete beams under cyclic loading quantitatively. AE technology, which can record the damage process in the entire load history, is often used to determine the onset of fracture and tracking of all subsequent failure stages. Hu et al. (2013) carried out the fracture tests under different loading rates for concrete with AE technology and evaluated the characteristics of onset of fracture and instability of the specimen based on the characteristics of AE signals.

With the continuous improvement and optimization
of Digital Image Correlation (DIC) algorithm, DIC technology has been widely used in the field of civil engineering for structure health monitoring. As an optical monitoring method, its remarkable advantage is that it can provide continuous and accurate full-field monitoring of surface strain and crack under non-contact condition. Nowadays, DIC technology has become an effective experimental means to study the fracture mechanism of concrete materials (Dzaye et al. 2019). By DIC technology, the full-field strain distribution and the variation of the crack tip opening displacement can be obtained, which bring about a great increase in the convenience to research. (Wu et al. 2011; Skarżyński et al. 2011). Xie et al. (2017) investigated the crack extension length and elaborated crack growth behavior by DIC technology. Fayyad and Lees (2017) carried out three-point bending tests on reinforced concrete beams, and deduced the surface strain and crack opening of specimens. Besides, DIC technology has also been applied to the study of fracture characteristics of concrete under fatigue loading. Mahal et al. (2015) analyzed displacement fields obtained from digital images recorded in fatigue tests to obtain the information on crack width, beam deflection and curvature, and major principal strains for crack detection.

At present, the combination of AE and DIC technologies to explore the fracture mechanics characteristics of cement-based materials deeply can be found in some existing literature. The damage characteristics of fiber reinforced cement under tensile conditions were investigated by Rouchier et al. (2014). Alam et al. (2014) combined AE and DIC technologies to identify fracture parameters such as the openings of crack and the size of fracture process zone. Omondi et al. (2016) used parameter analysis to study the progressive failure of the prestressed concrete under three-point bending with the combination of DIC and AE technologies.

Since self-compacting concrete (SCC) is self-leveling and non-vibrated, it has been widely concerned with and applied in civil engineering. During service, SCC is often subjected to cyclic loading after cracking, such as earthquake. However, few scholars have studied the post-peak cyclic response of SCC specimens. In this paper, post-peak cyclic bending tests were carried on SCC specimens with three different notch-to-depth ratios. The AE characteristics and crack development process were investigated to state the post-peak cyclic response and fracture mechanism of SCC. The relationship between the mechanical performance and the notch-to-depth ratio of SCC specimens was studied. By processing the collected AE signal data, the variations of acoustic emission energy, $b$-value and $I_b$-value during loading were analyzed. Besides, the development law of internal damage for SCC specimens using strength analysis was elaborated and the mode of the active cracks was classified by the ratio of RA value (ratio of the rise time to peak amplitude) to AF (ratio of AE ringdown counts to duration time). In addition, the propagation laws of effective crack length and crack tip opening displacement of SCC concrete with different notch-to-depth ratios were obtained based on DIC technology.

2. Experimental scheme

2.1 Materials and specimens

The chemical composition and physical properties of ordinary Portland cement with grade 42.5 and those of grade I fine fly ash used in this study are shown in Tables 1 and 2, respectively.

The coarse aggregate was crushed limestone with maximum particle size of 15 mm. The apparent density and crushing index of coarse aggregate were 2650 kg/m$^3$ and 8.27%, respectively. The river sand with fineness modulus of 2.9 was used as fine aggregate in this test. The apparent density and bulk density of river sand are 2600 kg/m$^3$ and 1487 kg/m$^3$, respectively. The particle size distributions of aggregates are presented in Fig. 1.

Water is the laboratory tap water. In order to enhance
the fluidity of concrete, polycarboxylate superplasticizer was added into the mixture. The mix proportion of SCC is shown in Table 3. The water-binder ratio and sand ratio of SCC casted in this test were 0.36 and 0.56, respectively.

The work performance of fresh SCC was evaluated according to the Chinese technical specification for the application of self-compacting concrete (China JGJ/T 283-2012 2012). The experimental data obtained are listed in Table 4, showing that the workability of fresh SCC met the requirements of the above technical standard.

The size of casting mould for SCC specimens was 400 mm × 100 mm × 100 mm. One day after casting, the specimens were unmolded and cured in water for 28 days. A prefabricated notch was cut along the midline of the SCC specimen on one forming side. The notch lengths were 10, 20 and 30 mm, respectively. The cutting area was washed by tap water after cutting.

### 2.2 Loading system

In this study, the hydraulic closed-loop servo material testing machine MTS322 was used to conduct post-peak cyclic bending test for SCC specimens. The clip gauge was fixed at the bottom of the specimen, which can monitor the crack mouth opening displacement of SCC specimen in real time. The loading rate was 0.0005 mm/s under COD control. The loading-unloading test was carried out in the period of post-peak. The reloading stage was under COD control, and the loading rate was 0.0005 mm/s. The unloading stage was under force control and the loading rate was 100 N/s. The minimum load is 0.05 kN. After 9 cycles of loading-unloading test, monotonous loading was carried out. When the crack opening displacement reached 0.5 mm, the loading was stopped. In other words, the specimen has been damaged at this time.

The load data were collected by the load sensor inside the MTS machine and recorded simultaneously with the displacement obtained from the extensometers with a sampling frequency of 100 Hz.

The camera with 5 million pixels and a resolution of 2048 × 2048 was fixed in the proper position with a tripod. Two LED cold lights, as light source, were installed on both sides of the camera. In order to de-noise as much as possible, Vic-3D system was used for calibration. The camera was set to take one picture every five seconds.

The DIC device photographing and mechanical loading started at the same time and end when the specimen broke. Digital images and data were collected by Vic-Snap software. By comparing the photos taken at different times, the displacement of each point and the full-field strain on the specimens’ surface can be obtained. The test equipment is shown in Fig. 2.

The Sensor Highway II AE device produced by American Physical Acoustics Company was utilized in this study. The preamplifier gain and threshold value of AE device were set to 40 dB and 35 dB respectively. The data sampling frequency was 1 MHz and the position of AE detectors is shown in Fig. 3.
3. Results and discussions

3.1 Peak load
According to the experimental result, it can obtain that the peak loads of the specimen were 12.89 kN, 10.86 kN and 8.78 kN when the notch-to-depth ratio were 0.1, 0.2 and 0.3, respectively. In other words, when the notch depth increased from 10 mm to 30 mm, the bearing capacity of the specimen decreased by 32.2%. The reason is that with the increasing of the notch-to-depth ratio, the effective height of the mid span section of the concrete beam decreased, and thus the peak load decreased.

3.2 AE Energy
By processing and analyzing the AE parameters collected during loading, the histograms of AE energy verse time of SCC specimens with different notch-to-depth ratios are drawn, as shown in Fig. 4. At the early stage of loading, AE energy of SCC specimens was generally smaller, which indicates that the internal damage of the specimen was slight at this time. Each peak value of energy corresponded to the maximum load at each loading cycle. It can be found that the change of energy value was obviously discontinuous because few AE signals produced in the loading stage of the certain loading cycles. However, by comparing Figs. 4(a), 4(b) and 4(c), the maximum energy value increased with the increase of notch-to-depth ratio. Besides, the occurrence time of maximum energy value was earlier. At the last stage of loading, acoustic emission activity increased significantly, and the energy value remained high until the specimen failed.

3.3 b-value and Ib-value
Based on the Gutenberg-Richter relationship in seismology (Gutenberg and Richter 1944), b-value can be calculated according to the raw AE data, which can reflect the development of micro-cracks inside the concrete materials. When the b-value decreases, it means that the number of AE events with small amplitude decreases and the proportion of large events increases. On the contrary, the increase of b-value represents the number of AE events with small amplitude increases (Han et al. 2019; Li et al. 2016). Therefore, when the b-value kept a steady change and the range of change was small, it states that the occurrence frequency of events with big amplitude and events with small amplitude was comparable. In other words, the crack propagation inside the specimens was stable. When the b-value decreases significantly, it means that the crack expands rapidly. The calculation formula for b-value is as follows:

\[ \log_{10} N = a - b(A_{ab}/20) \]  

where \( A_{ab} \) is the amplitude, \( N \) is the number of events whose amplitude exceeds \( A_{ab} \), a is the empirical value, and \( b \) represents the proportion of acoustic emission events with large and small amplitude.

Some studies (Kawasaki et al. 2013; Aggelis et al. 2009) have shown that although the amplitudes of AE signal are disorderly, the relationship between the number of AE hits and amplitudes basically obeys the normal distribution. Thus, on the basis of b-value, Shiotani et al. (2017) proposed an improved parameter to characterize the concrete failure process, which is Ib-value. The increase of Ib-value indicates that a number of small cracks appear, and these cracks cause stress concentration. The decrease of Ib-value indicates that large cracks forms due to stress release. The stability of Ib-value indicates that a large number of cracks inside the specimen under loading have developed. The for-
mula for $I_b$-value is as follows:

$$I_b = \log N(\mu - \alpha_1 \sigma) - \log N(\mu - \alpha_2 \sigma)$$

(2)

In this study, parameters $\alpha_1$ and $\alpha_2$ are both 0.5.

According to the above method, variations of $b$-values and $I_b$-values for the SCC specimens with three different notch-to-depth ratios can be obtained, as shown in Fig. 5.

In Fig. 5, it can be seen that the $b$-value fluctuated with the loading and unloading, and the range of variation was between 0.9 and 1.5. The peak and valley of $I_b$-value fluctuated with the loading and unloading, and the range of variation was between 0.3 and 0.6. The peak and valley of $I_b$-value fluctuated more with the loading-unloading cycles, which indicates that the larger the notch-to-depth ratio was, the faster the cracks would develop inside the SCC specimen.

By observing the variation trend of $I_b$-value for SCC specimens with three notch-to-depth ratios, it can be found that the $I_b$-value decreased during loading stage, which illustrates that the proportion of AE events with large amplitude increased and macro-cracks propagated. On the contrary, at the unloading stage, the development of the micro-cracks produced a large number of AE events with small amplitude, which caused the increase of $I_b$-value.

In Figs. 5(a), 6(b) and 6(c), comparing the change curves of $b$-value and $I_b$-value in the same condition, it can be obtained that the changes of $b$-value and $I_b$-value have obvious periodicity, but the change rule of $I_b$-value was more regular. This may be related to the number of AE data selected in calculations. Therefore, $I_b$-value analysis was more effective than $b$-value analysis in cyclic loading conditions.

3.4 Intensity analysis

Intensity analysis evaluates the damage degree of materials by processing the signal intensity of acoustic emission data (Kawasaki et al. 2013). History Index ($HI$) is the representative parameter used to characterize intensity analysis, and the calculation formula is shown as follows:

$$HI(t) = \frac{N}{N - K} \sum_{i=1}^{N-K} S_{io}$$

(3)

where $HI(t)$ represents Historic Index, $N$ represents number of AE hits up to time $t$, $S_{io}$ represents signal strength of the $i$th AE hit, $K$ is empirically derived constant based on material. The value of $K$ is related to the number of AE hits, as shown in Table 5.

The $HI(t)$ values of specimens with different notch-to-depth ratios are obtained and plotted in Fig. 6. Each peak represents the formation of the new damage, and the magnitude of peak value corresponds to the severity of the damage.

It can be seen from the figure that there were many peak values of $HI(t)$ with the cyclic loading and unloading. When the notch length was 10 mm, the value of $HI(t)$ remained basically stable during the loading, and the peak values were not high. However, the peaks of $HI(t)$ occur at high frequencies. This illustrates that when the notch-to-depth ratio was small, more micro-cracks can appear inside the specimen, and then gradually developed into macro-cracks. Therefore, there was much damage accumulated inside the SCC speci-
mens, and the cracks inside the specimens became more fully developed. This is because the smaller the initial notch length is, the farther the crack tip is from the upper boundary of the specimen, and the weaker is the restriction of the boundary on the fracture process area. Therefore, crack propagation becomes easier.

The maximum peak values of $HI(t)$ under three notch-to-depth ratios are circled by dotted wire frame. The maximum of $HI(t)$ appeared earlier with the increase of notch-to-depth ratios. Besides, with the increase of notch-to-depth ratios, the number of peak values larger than 3 increased. It states that the severity of the damage caused by cyclic loading and unloading increased with the increase of the notch-to-depth ratios. The reason for the above phenomenon may be that the specimens with large notch-to-depth ratios had more serious initial damage and lower bearing capacity. Thus, the damage caused by loads on SCC specimens with larger notch-to-depth ratio was more obvious, and the corresponding specimens were easier to be destroyed.

### 3.5 Crack modes

Cracks modes can be divided into the tensile crack and the shear crack because of different stress types (Aggelis et al. 2009). As a result, different crack modes can correspond to different acoustic emission waveform parameters. In AE analysis, RA value represents the ratio of the rise time to peak amplitude and average frequency (AF) represents the ratio of AE ringdown counts to duration time.

According to the ratio of AF to RA value, the crack modes and fracture characteristics of SCC specimens with different notch-to-depth ratios can be analyzed. Fig. 7 presents the scatter plots of AF-RA value of SCC specimens with three different notch-to-depth ratios, where the ratio of RA value (abscissa scale) to AF (ordinate scale) was selected as 20 in advance to the classification of active cracks.

Based on the definition, ratio values for each hit that were larger than 20 correspond to shear crack, otherwise the hit corresponds to tensile crack. The ratios of tensile crack and shear crack indicated by AE hits are obtained and shown in Fig. 8. It should be noted that the ratios were calculated by rolling the 100 AE hits.

During the whole loading procedure, the alternative change of the ratios of shear hits and tension hits can be observed in Fig. 8. However, the ratio of tensile hits remained large. As a result, it proves that the failure of specimens under three-point bending was still dominated by tensile crack.

In Fig. 8, the shear hit ratios at the beginning were 0.43, 0.38 and 0.26 for notch-to-depths of 0.3, 0.2 and 0.1, respectively. These shear hit ratios were also the highest during the whole loading process, which indicates that the specimens with large notch-to-depth ratios tended to fail in shear under initial loading. In addition, as the loading proceeds, the tensile hit ratio increased rapidly. When the notch-to-depth ratio was 0.3, the tensile hit ratio was as high as 99% at the normalization time of 0.2.

![Fig. 6 Variations of $HI(t)$ of SCC specimens with different notch-to-depth ratios.](image1)

![Fig. 7 Scatter plots of AF-RA value of SCC specimens with different notch-to-depths.](image2)

![Fig. 8 Ratios of tensile hits and shear hits.](image3)

| $N$ | $\leq 50$ | 51 to 200 | 201 to 500 | $\geq 500$ |
|-----|-----------|-----------|------------|-----------|
| $K$ | 0         | $N-30$    | 0.85N      | $N-30$    |
Thereafter, the shear hit ratio and the tensile hit ratio changed in a smaller range. In the late loading stage, it can also be seen from the figure that the shear hit ratio increased significantly and rose to 0.22 when the notch-to-depth ratio was 0.3. This phenomenon indicated that the greater the notch length, the greater the brittleness would be when the specimen failed.

3.6 Crack propagation analysis

In order to facilitate the analysis of full-field strain evolution and crack propagation of SCC specimens, the following definitions are made for different loading stages, shown as Fig. 9. $P_i$ ($i = 1, 2, 3...)$ represents the unloading point of each post-peak loading cycle, and the corresponding lowest unloading point is $P_{i1}$ ($i = 1, 2, 3...$). And then, when the crack mouth opening displacement of the point is again the same as the unloading point, the intersection point is called the reloading point $P_{i2}$ ($i = 1, 2, 3...$). Besides, Post$70$, Post$80$ and Post$90$ represent the points that were unloaded to 70%, 80% and 90% of the peak load, respectively.

3.6.1 Variation of strain field

In this paper, the variation of strain field of SCC specimens with notch length of 10 mm is analyzed as example. The strain field diagrams of 1, 3, 6 and 9 loading cycles are presented in Fig. 10. The maximum strain of points $P_{i0}$, $P_{i1}$ and $P_{i2}$ ($i = 1, 2, 3...$) are obtained and listed in the Table 6.

It can be found that with the increase of loading cycles, the length of crack became larger and strain at the notch tip increased. Comparing the strain field diagrams at points $P_{i0}$ and $P_{i1}$ in the same loading cycles, it can be seen that when the specimen was unloaded to the lowest point $P_{i1}$, the strain recovered obviously and that the phenomenon of stress concentration still existed. When the specimen was loaded to the reloading point $P_{i2}$, although the crack mouth opening displacements were the same at the points $P_{i0}$ and $P_{i2}$, the maximum strain at the notch tip of $P_{i2}$ exceeded that of $P_{i0}$.

| Points | Loading cycles | $i = 1$ | $i = 3$ | $i = 6$ | $i = 9$
|--------|----------------|---------|---------|---------|---------|
| $P_{i0}$ | $3.5 \times 10^{-3}$ | $5.5 \times 10^{-3}$ | $10^{-2}$ | $1.65 \times 10^{-2}$ |
| $P_{i1}$ | $1.5 \times 10^{-3}$ | $3 \times 10^{-3}$ | $6 \times 10^{-4}$ | $1.2 \times 10^{-2}$ |
| $P_{i2}$ | $4 \times 10^{-3}$ | $6 \times 10^{-3}$ | $1.2 \times 10^{-2}$ | $1.8 \times 10^{-2}$ |

Table 6 Maximum strains at the notch tip under different loading points.

Fig. 9 Selection of analytical points in different stages of cyclic loading.

Fig. 10 Strain field diagrams under 1, 3, 6 and 9 loading cycles.
In Table 6, with the increase of the loading cycles, the strain values at points \( P_{01}, P_{11} \) and \( P_{21} \) all increased, which indicates that the damage accumulated continuously inside the SCC specimens. Besides, according to the data in Table 6, the recovery rates of strain at the point \( P_{11} \) under different unloading-reloading cycles can be calculated and there are 57%, 45%, 40% and 27%, respectively. It can be seen that with the increase of loading cycles, the recovery rates of strain decreased, and the irrecoverable deformation increased.

3.6.2 Effective crack length
The data collected by DIC method were processed using MATLAB program compiled by the authors, and the variation of effective crack lengths of SCC specimens with three different notch-to-depth ratios with time can be obtained, as shown in Fig. 11.

From the figure, it can be seen that the effective crack length did not always increase as loading proceeds. By observing the local enlarged drawing of the effective crack lengths during the first unloading-reloading cycle, it can be found that the effective crack length at point \( P_{11} \) was smaller than that at point \( P_{01} \). The reason is that when the SCC specimen was in the unloading stage, the tip of effective crack was re-compacted and the effective crack length decreased. However, this rule did not exist in every loading cycle and became unapparent with the increase of the loading cycles, this rule was not obvious. This is due to the irrecoverable increasing deformation caused by loading on the specimens. Even if the force was removed, the deformation and cracking of the specimens cannot be restored.

In Fig. 11, the effective crack lengths under peak load of SCC specimens are marked, which states that the effective crack lengths under peak load increases with the increase of notch-to-depth ratio. It can also be seen from the figure that the effective crack length changed little after 9 loading cycles. What’s more, it can be seen in figure that with the increase of the notch-to-depth ratio, the effective crack length became shorter. This states that the crack of the specimen with low notch-to-depth ratio can get more fully developed and the energy absorbed by the specimen during loading was larger. Therefore, it is considered that the specimen with low notch-to-depth ratio had greater “ductility”.

3.6.3 Crack tip opening displacement
The crack tip opening displacements of SCC specimens with three different notch-to-depth ratios are shown in Fig. 12. The change of the crack tip opening displacement shows obvious regularity with the loading. In the same loading cycles, the crack tip opening displacement at point \( P_{12} \) was the largest and the crack tip opening displacement at point \( P_{01} \) was the smallest, which was consistent with the rule of the maximum strain at the notch tip.

With the continuous loading, the crack tip opening displacement of SCC specimen gradually increased. The crack tip opening displacements are 0.278 mm, 0.345 mm and 0.455 mm respectively when the SCC specimens were destroyed. This is mainly because the larger the notch-to-depth ratio was, the closer the crack tip was to the upper boundary. Thus, the crack propagation is limited due to the restriction of the boundary. In addition, it can be seen from the graph that the crack tip opening displacement almost linearly increased with time after 9 loading cycles, and the smaller the notch-to-depth ratio was, the more obvious was the linearity.

4. Conclusions
In this study, three-point bending tests of self-compacting concrete beams with three different notch-to-depth ratios under the loading rate of 0.0005 mm/s were carried out. The fracture characteristics of self-compacting concrete under cyclic loading were investigated by combination of the acoustic emission technology and digital image correlation method. The main conclusions are as follows:

(1) Peak loads of SCC specimens decreased with the increasing of the notch-to-depth ratios, and the peak loads of the specimen with different notch-to-depth ratios were 12.89 kN, 10.86 kN and 8.78 kN, respec-
vatively.
(2) At the early stage of loading, the AE energy of the SCC specimens was generally small. At the final stage of loading, the energy of AE signal remained high until the specimen was destroyed. With the increase of notch-to-depth ratio, the maximum energy increased and the occurrence time was earlier.
(3) Under the three-point bending test, both the $b$-value and the $Ib$-value of the SCC specimen showed the fluctuation trend, but the variation rule of $Ib$-value was more regular than that of $b$-value. With the progress of loading, both the peak and valley values of $b$-value decreased.
(4) The maximum $H(\bullet)$ of SCC specimens appeared earlier with the increase of the notch-to-depth ratio. At the same time, with the increase of the notch-to-depth ratio, the number of peak values larger than 3 increased.
(5) In the whole loading process, the tensile hit ratio was more than 50% and shear hit only accounted for a large proportion at the early loading stage. During the loading procedure, the shear hit ratio decreased rapidly. At the later stage of loading, the shear hit ratio showed a slight upward trend.
(6) With the increase of notch-to-depth ratio, the effective crack length under peak load of SCC specimens increased, while the effective crack length and crack tip opening displacement decreased when the SCC specimens were destroyed. In each unloading-reloading cycle, when the SCC specimen was unloaded to the lowest point $P_{III}$, the effective crack tip closed to a certain extent.

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