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Experimental Study on Cracks of CFRP Reinforced Prestressed Concrete Beams

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Experimental Study on Cracks of CFRP Reinforced Prestressed Concrete Beams

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Abstract. Ten prestressed concrete beams were designed and manufactured, which were preloaded with 40% and 60% ultimate load to crack. Then the beams were reinforced by CFRP and immersed in chloride condition for 120 days. After that, a four-point bending test was performed. Based on the statistics and fractal theories, the cracking mechanism, distribution and shapes of cracks in mid span were researched, considering the initial cracks, CFRP reinforcement and chloride corrosion. The test results demonstrate that CFRP has a restraining effect on the cracks, and the effect decreases with the increases of heights. The crack widths conform to normal distribution, and the dispersion coefficient, average widths and characteristic widths decrease with the increase of the heights, and the three parameters of CFRP reinforced beams at the same heights are all smaller than those of unreinforced beams. The fractal dimensions of cracks in unreinforced beams and CFRP reinforced beams increase linearly and exponentially with load steps, respectively. CFRP reinforcement and Chloride corrosion makes the fractal dimension increase, respectively. The corrosion effect of chloride can be weakened by CFRP. Therefore, the fractal dimensions of beam cracks can be used to evaluate the damage caused by several coupled load conditions.

1. Introduction

Since the 1930s, reinforced concrete structure was widely promoted because of its convenient, good performance and structure diversification. Due to the composition and mechanical characteristics, concrete structure is easily affected by environment, such as high temperature, freezing, acid rain and deicing salt corrosion, and concrete structure tend to appear the durability problems, such as cracking, peeling and corrosion.

The crack state of concrete structure can indicate the damage degrees, so many scholars carry out the research using different methods. Zhao and Guan [1-3] have studied the influence of concrete cover thickness, section heights, and longitudinal tensile bars to the crack distribution of ordinary reinforced concrete beam. Du [4] et al. made a statistical analysis of crack widths at different position on PC beams, and suggested a new formula to calculate the crack widths. Cao [5], Tan [6], Zhuang [7], Meng [8], Han [9], Vicente [10] and many other scholars studied the cracking performance of CFRP-reinforced concrete beams, PC beams and I-shaped prestressed concrete beams under cyclic load on the basis of experiments, and put forward the corresponding calculation models.

In recent years, fractal theory has been used to analyze the cracking mechanism, distribution characteristics and influencing factors of concrete cracks, and good results have been achieved. Also the fractal theory provides a new approach to study the concrete durability. Fan et al. [11] conducted a fractal description on the cracking of corroded reinforced concrete beams and proposed a prediction

model for the flexural capacity of concrete members. Li[12], Yan[13], Cai[14] and Farhidzadeh[15] conducted a fractal description on the damage process of high strength reinforced concrete beam, reinforced inorganic polymer concrete beams under concentrated load, alkali slag concrete under freeze-thaw cycles and shear walls under cyclic loading, and the results show that the fractal dimension of cracks has a quantitative relationship with the mechanical properties and applied loads of structures. Fooladi[16] made a multifractal analysis on crack propagation in concrete specimens considering the influence of the aggregates' grading. Ebrahimkhanlou[17] made a same analysis on cracks development in shear walls. It can be seen that the effective non-destructive evaluation on concrete specimens can be made according to the accurate fractal description on concrete cracks.

In practical engineering, the damage on concrete structure is often caused by both environmental factors and external loads. At present, there is few research on the cracks of PC beams under the action of multi-factor. Based on this, the effects of initial cracks, chloride corrosion and CFRP reinforcement on crack propagation, evolution characteristics and fractal dimension of PC beams under concentrated load were studied by the methods of statistics and fractal geometry, respectively.

2. Experimental programs

Ten pre-tensioned concrete beams were designed and manufactured. Commercial concrete was adopted, and the concrete strength grade was C40. All beams have the same dimension of 150×250×2200mm. The beams were reinforced by four 14mm deformed bars at top and bottom, seven 6mm stirrups with 100mm at beam end. The beams were pre-tensioned with two 12.7mm strands, and the initial prestress of the strand is 558MPa, which is about 0.3 times of the yield strength. The details are shown in Fig. 1.

The tensile performance of the strands and reinforcing bars were tested. The average yield strength of the prestressing strand, the deformed bars and the 6mm plain bars were 1860MPa, 335MPa and 235MPa, respectively. The elastic modulus of the prestressing strand, the deformed bars and the 6mm plain bars were 195 GPa, 200 GPa and 210 GPa, respectively. The average compressive strength of 28-day concrete for all the beams was 49.4MPa.
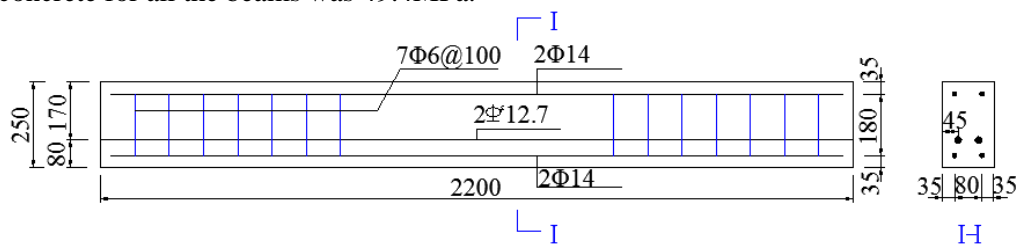

Figure 1. Beam details (unit: mm)

In order to simulate the influence of initial damage on the durability of PC beams, six beams were pre-loaded to crack with 40% and 60% ultimate load. The distributions and parameters of initial cracks are shown in Fig.2 and Tab.1.
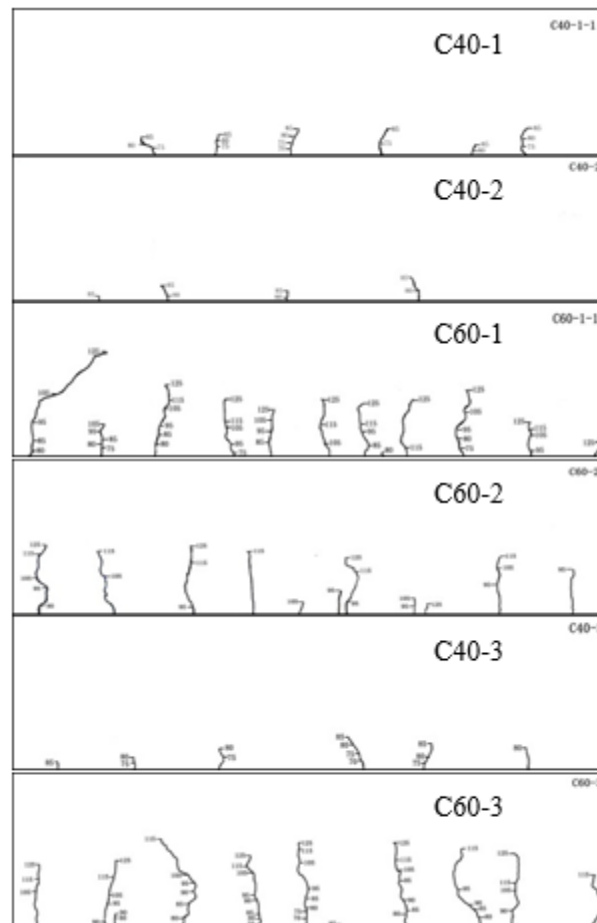
Figure 2. Initial cracks on the PC beams after pre-loading

Table 1. Parameters of initial cracks on mid-span

Beam	Crack number in mid-span	space-ng /mm	Sum of cracks	Crack width at bottom/mm	Crack height/mm
C40-1	4	150	6	0.04	40
C40-2	3	200	4	0.06	45
C40-3	3	170	6	0.06	50
C60-1	8	80	12	0.12	130
C60-2	7	100	11	0.12	125
C60-3	8	80	11	0.15	137

Then the beams were reinforced by CFRP, and U-shaped hoops were set at both ends. The reinforcing scheme of CFRP is shown in Fig.3.
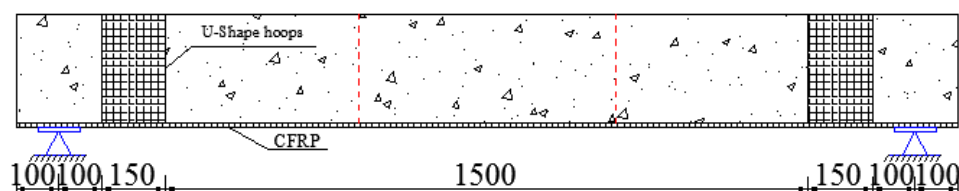

Figure 3. CFRP reinforcing scheme (unit: mm)

After pre-loading and CFRP reinforcing, the beams were immersed in deicing salt solution for 120 days. The components of solution are CaCl2 and MgCl2, and the concentration is 5%. It can be seen in Fig.4. The conditions of all beams are listed in Tab.2.
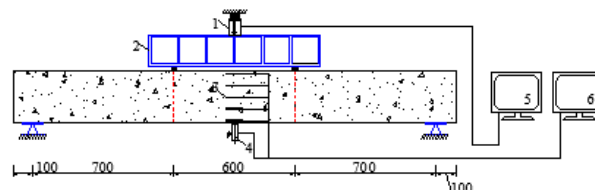

Figure 4. Deicing salt corrosion

Table 2. Test conditions

Beam	Pre-loading/kN	Reinforcement	Environment condition
A1	—	—	—
B1	0		
C40-3	85	—	Chloride corrosion for 120d
C60-3	125		
A2	0		
C40-1	85	CFRP reinforcement	—
C60-1	125		
B2	0		
C40-2	85	CFRP reinforcement	Chloride corrosion for 120d
C60-2	125		

The action of multi-factor results, such as initial damage, CFRP reinforcement and chloride corrosion change the bond performance between steel bars and concrete, and affect the propagation of bending cracks. The design codes are very difficult to predict the flexural behavior and crack widths of these PC beams. The four-point bending tests were employed to study the effects of multi-factor on the flexural behavior in the current study. Each beam was simply supported, and had a pure bending span of 600mm and two shear span of 700mm. Fig.5 shows the details of loading set-up.

The loading process was divided into two stages. The first stage was controlled by the load until reaching 85% ultimate load of beam. The load was applied step by step at a rate of 5 kN per step until crack load, then the rate was 10kN per step. The second stage was controlled by deflection, and the loading increment was 0.6mm per step. The loading test was stopped when the carrying capacity dropped to 75% of ultimate load.

The vertical deflections at the mid-span were measured by a displacement sensor. Electrical resistance strain gauges were pasted on the mid-span section to measure concrete strains. Arrangement of the gauges is shown in Fig. 5. One side of the beam was painted white and was marked with 5×5 cm grids to facilitate the detection of cracks.

Note: 1. Load cell; 2.Steel spreader beam; 3. Strain gauge; 4. Displacement sensor; 5.Computer; 6. Data acquisition system
Figure 5. Loading test set-up (unit: mm)

3. Test results and discussion

3.1 crack patterns

During the loading process, new cracks appeared successively in the middle span and below the loading points of the test beams. As the load grade increased, the cracks developed vertically upward. The distribution maps of cracks are shown in Fig. 6.
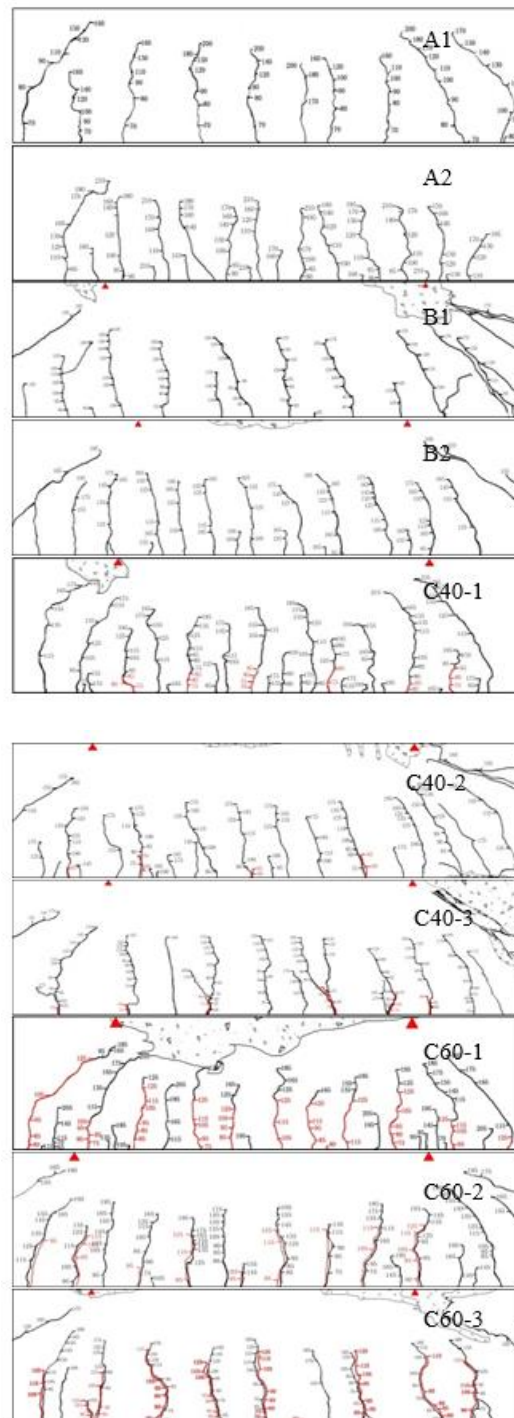

Figure 6. Distribution maps of cracks

At the same time, initial cracks, CFRP reinforcing and chloride corrosion all have impacts on the cracks of PC beams. According to their locations and causes, the cracks in Fig. 6 are divided into three categories, it can be seen in Fig.7.

（1）Major cracks caused by bending stress appear in the mid-span and below the loading points of the test beams. And the distribution of major cracks depends on the comprehensive bonding properties between steel bar, concrete and CFRP. Corrosion of steel bars caused by chloride leads to micro-cracks surrounded the steel bars. Bending stress makes the micro-cracks continue to develop and form the second type of major cracks. Therefore, such cracks occur above the corroded steel bars.

（2）Minor cracks occur near the major cracks. The local bond stress between concrete and CFRP increases with the increases of load. When the local tensile stress of concrete between major cracks reaches the ultimate tensile strength, the minor cracks appears between major cracks. Due to the low influence height of bond stress, such cracks are relatively short.

（3）CFRP peeling cracks is the third kind of cracks. Arriving at the ultimate load, there has a tendency of local peeling between CFRP and concrete at the bottoms, and the peeling cracks are short and inclined or even parallel to the bottom surface, and intersects with the major crack, and then causes the peeling off of the concrete.
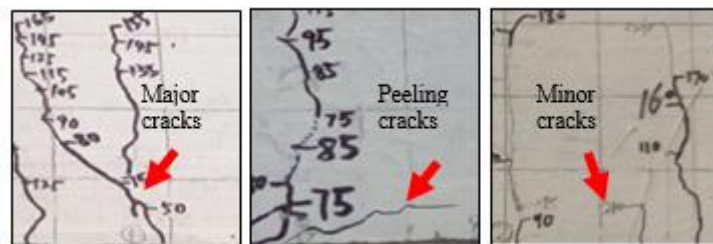

Figure 7. Classification of cracks

The parameters of cracks in the mid-span of PC beams are shown in Tab.3. It can be known that the numbers of mid-span cracks in the beams with initial damage are close to that of the control beam A1. Under natural conditions, the numbers of mid-span cracks in CFRP strengthened beams are about 1.7~2.3 times that of the control beam A1. Under chloride conditions, the numbers of cracks in CFRP reinforced beams are about 1.5~2 times that of control beam A1. It can be seen that the cracks on the surface of CFRP strengthened beams are denser than that of the control beams.

Table 3. Parameters of cracks on mid span of PC beams

Beam	Numb-er	Average spacing /mm	Height/mm	Max width /mm	crack patte-rns
A1	7	91	170	0.18	MAC
B1	8	80	165	0.24	
A2	15	45	150	0.12	MAC+MIC+ PEC
B2	12	47	155	0.12	
C40-1	16	39	165	0.28	
C60-1	12	52	155	0.25	
C40-2	14	42	150	0.15	
C60-2	12	52	162	0.11	
C40-3	8	77	160	0.22	
C60-3	9	74	155	0.2	

Note: MAC is major crack. MIC is minor cracks. PEC is CFRP peeling crack

3.2 Crack widths and load steps

The average widths of the major cracks on different heights of PC beams are shown in Fig.8. It can be seen that the crack widths increase with the increase of load steps. The average widths of cracks on bottoms of CFRP strengthened beams A2、B2、C40-2、C60-1 and C60-2 are all significantly

smaller than those of unreinforced beams. The cracking widths of CFRP reinforced beams are slightly smaller than that of unreinforced beams at a height of 5cm from the beam bottom. At a height of 10cm from the beam bottom, the gaps of the crack widths between the CFRP reinforced beams and the unreinforced beams are not obvious.
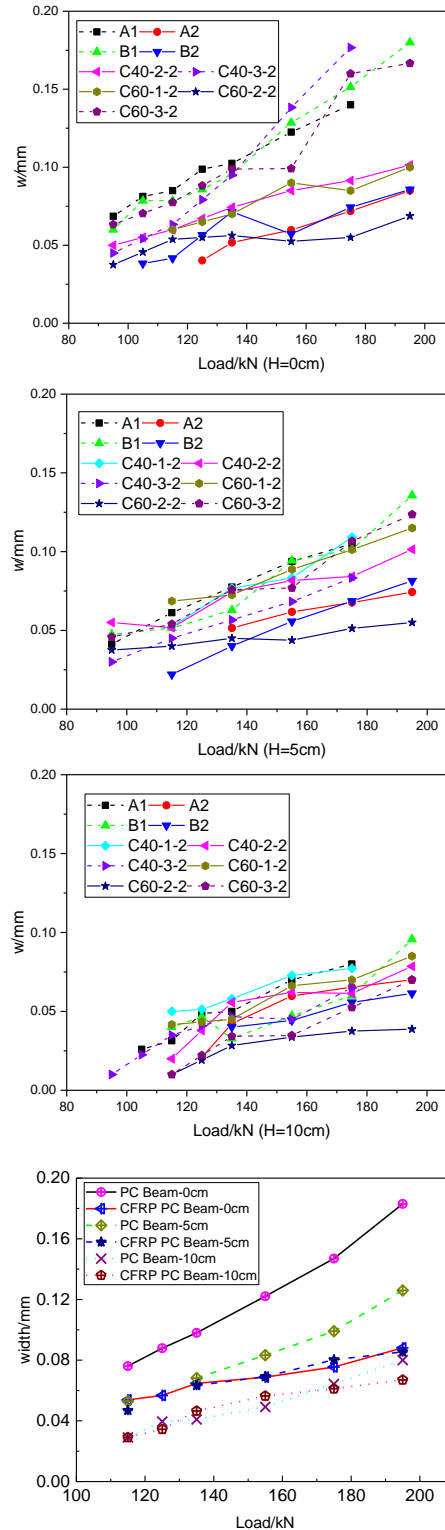

Figure 8. Crack widths and load steps

When the load is 115kN, the average cracks width of CFRP reinforced beams at 0cm、5cm and 10cm from the beam bottom decrease by 29%、11% and 5%, respectively, compared with that of unreinforced beams. When the load is 195kN, they decrease by 52.5%, 32.5% and 17.5%, respectively. So the average crack widths and cracking rates of CFRP reinforced beam are always smaller than that of the unreinforced beams, and the gaps between them increase with the increase of load steps and decreases with the increase of crack heights. At the same time, the average crack widths of unreinforced beams at 5cm and 10cm were 31.1% and 56.3% smaller than those at the bottom, while the average crack widths of CFRP reinforced beams at 5cm and 10cm were only 3.1% and 24% smaller than those at the bottom. In conclusion, CFRP has an effect of constraint on the development of cracks, and the effect decreases with the increase of crack heights. The influence height of constrain is related to its thickness and layer numbers and other factors, which need to be proved by the further tests.

3.3. Probability distribution of crack widths

In order to analyze the probability distribution of crack widths at different heights, 113 major cracks in the mid-span of test beams were summarized, and the probability histograms of the ratio of measured value and the average value of crack widths at the same heights, w_i/w_m, were made, as shown in figure 9.

The statistical analysis shows that the average widths of cracks at 0cm、5cm and 10cm from the bottom of PC beams all conform to normal distribution. It can be seen from table 4 that the dispersion coefficient, average widths and characteristic width of cracks all decrease with the increase of its heights. Due to the constraint of CFRP, the three parameters of CFRP reinforced PC beams are all smaller than those of unreinforced PC beams at the same heights.
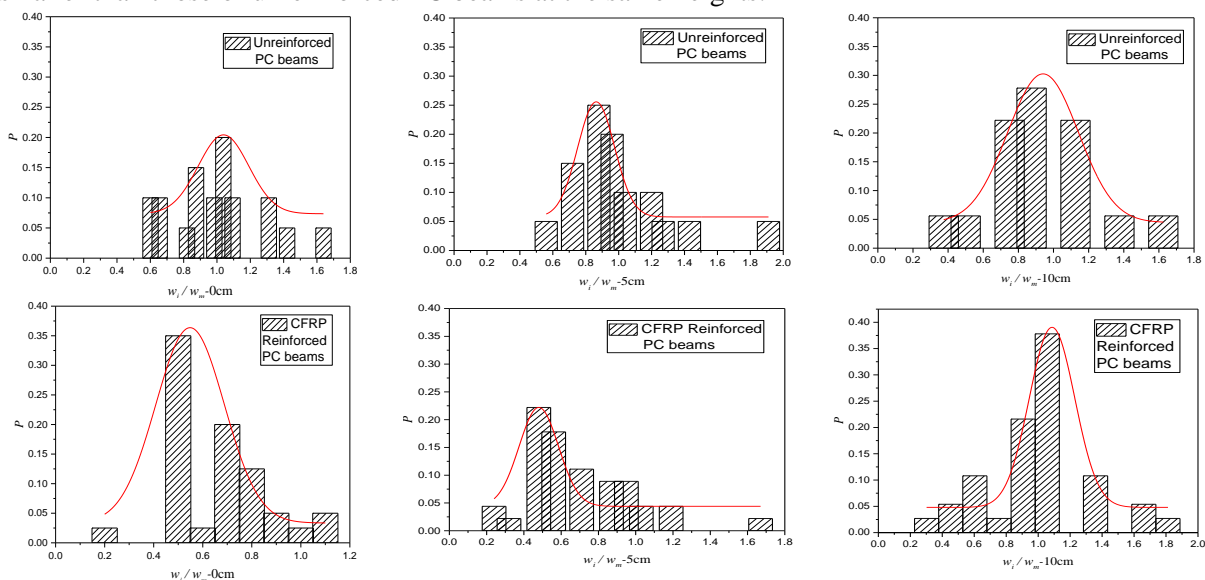

Figure 9. Frequency distribution histograms of crack widths

Table 4. Statistical analysis of crack widths

classification		population mean μ	population standard deviation σ	dispersion coefficient σ/μ	Discrete expansion coefficient α	characteristic width δ_{fk}/mm	average widths δ_{fm}/mm
Unreinforced beam	0cm	1.039	0.303	0.292	1.538	0.281	0.183
	5cm	0.864	0.224	0.259	1.227	0.154	0.126
	10cm	0.952	0.209	0.214	1.296	0.104	0.080
CFRP	0cm	0.941	0.242	0.257	1.338	0.116	0.087

reinforcement	5cm	0.823	0.159	0.193	1.094	0.092	0.085
beam	10cm	1.061	0.162	0.153	1.328	0.088	0.066

3.4. Crack fractal dimension

Previous studies have shown that the concrete structure has fractal characteristics. Therefore, the simple box dimension is adopted to calculate the fractal dimension D_f of the cracks on test beams under the conditions of initial cracks, chloride corrosion, CFRP reinforcement and external loads. So the fractal dimension can be used to characterize the damage degree of PC beams under different working conditions, as shown in equation 1.

$$D_f = log\ (N)\ /\ log(1/r) \qquad (1)$$

Fig. 10 shows the relationship between crack fractal dimension Df and load steps in pure bending section of PC beams. The regular of fractal dimension of cracks in unreinforced PC beam is similar to that of ordinary concrete beam, and the fractal dimension increases linearly with load steps. The fractal dimension of cracks in CFRP reinforced PC beams increases exponentially with the load steps. Due to the constraint of CFRP, cracks

in CFRP reinforced beams are relatively denser, and the fractal dimension increases rapidly in the early stage of loading process. In the late stage of loading process, the development of cracks is inhibited, the gradient of fractal dimension decreases gradually, and the curve tends to flattens out. The relevant parameters of the fitting curve are shown in Tab.7. It can be seen that CFRP has a great influence on the fractal dimension of cracks, and the effect of initial cracks and chloride corrosion on the fractal dimension needs to be further studied.

Due to the different initial cracks on the surface of PC beams, the corrosion degrees of chloride are different. The CFRP at the bottom of the beam can improve the flexural capacity of the structure. Because of the combined action of these three factors, the distribution patterns of surface cracks are different and the fractal dimensions are complex. Fig.11 is the fractal dimension histogram of surface cracks in 195kN. The influences of various factors are as follows:
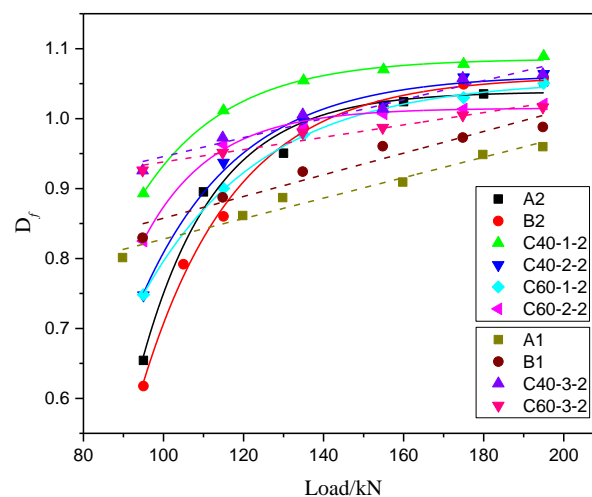

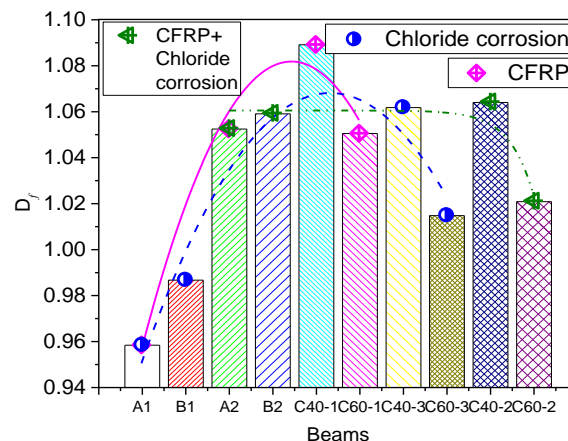Figure 10. Load steps and fractal dimensions of cracks

Figure 11. Fractal dimensions of cracks at 195kN

(1)   Under natural conditions, the fractal dimensions of CFRP strengthened beams, such as A2, C40-1 and C60-1 increase by 9.8%, 13.6% and 9.6%, respectively, compared with that of control beam A1. It can be seen that CFRP reinforcement makes the cracks be denser and the fractal dimension increase.

(2)   After the chloride corrosion for 120d, the fractal dimensions of beam B1, C40-3 and C60-3 were increased by 3.0%, 10.8% and 5.6%, respectively, compared with that of control beam A1. It can be seen that the micro-cracks caused by rust expansion of steel bars had an impact on the bending cracks of beams, which makes the fractal dimension increase.

(3)   Under the condition of chloride corrosion, the effect of CFRP reinforcement reduces the penetration of chloride, weakens the influence of chloride corrosion on the steel bars, and reduces the micro-cracks caused by corrosion. Therefore, the fractal dimension of beam B2 is similar to that of beam A2.

(4)   Different initial damages have different effects on fractal dimension of bending cracks, which should be analyzed in combination with test conditions. In this paper, the fractal dimensions of beam C40 with initial cracks are always larger than that of beam C60 under the same working condition. Since there are few comparison test groups with different initial damage degrees in this paper, its influence on the fractal dimension of cracks needs to be demonstrated by subsequent tests.

4. conclusions

Ten pre-tensioned concrete beams designed with different test conditions were tested to investigate the cracking characteristics. The effects of initial cracks, CFRP reinforcement and chloride corrosion to the crack propagation, probability distribution and fractal dimension of cracks were discussed. The following conclusions can be drawn based on the test.

(1) CFRP reinforcement has a constrain effect on the development of cracks, and the effect decreases with the increases of crack heights. At 195kN, the average crack widths of CFRP reinforced beams decrease by 52.5%, 32.5% and 17.5% from low to high, respectively, compared with that of unreinforced beams.

(2) The crack widths at 0cm, 5cm and 10cm from the beam bottom all conform to the normal distribution. The dispersion coefficient, average widths and characteristic crack widths of the cracks all decrease with the increase of the heights, and the three parameters of the CFRP reinforced beams at the same heights are smaller than those of the unreinforced beams.

(3)The cracks of PC beams satisfy the geometric similarity. The fractal dimensions of unreinforced beams increase linearly with load steps, and the fractal dimensions of CFRP reinforced beams increase exponentially with load steps. Therefore, the fractal dimensions of cracks can be used to characterize the damage degree of concrete structures, and provides a basis for predicting their remaining service life.

(4)Under the natural conditions, the reinforcement of CFRP makes the fractal dimensions increase by 7.3%~13.6%. Chloride corrosion (120d) increases the fractal dimensions of cracks by 3.6%~10.8%. Under the chloride condition, CFRP weakens the corrosion effect of chloride, so the effect of chloride corrosion on fractal dimension of cracks is not obvious.

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