Corrosion monitoring of PC beams with a novel type of HCFRP sensors

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ABSTRACT: In this contribution, the corrosion monitoring function of PC structures is demonstrated using a novel type of hybrid carbon fiber reinforced polymer (HCFRP) composite sensors. The HCFRP sensors are designed to consist of three types of carbon tows of different strength and moduli as active materials. The HCFRP sensors with different gauge lengths are mounted on PC tendon, steel bar, and embedded in compressive and tensile sides of the PC beam to monitor the corrosion of PC tendons. To accelerate the corrosion, a distinct current of 3A is introduced into one PC tendon of the PC beam, and the tests are performed under a load of about 54kN. The experimental results show that the corrosion of PC tendon can be effectively monitored both in tensile and compressive sides. For the sensors embedded in tensile side of the PC beam, the electrical resistance increases as corrosion progresses; while for those embedded in compressive side, the electrical resistance decreases with corrosion time. Moreover, it is shown that the electrical behaviors of the zones where the corrosion is performed are much different from those of the other zones. In these zones, either there exist jumps in electrical resistance, or the electrical resistance increases with a much larger increasing rate than those of the other zones. Thus, a distributed corrosion monitoring function of PC beams is demonstrated.

Keywords: HCFRP sensor, corrosion monitoring, electrical resistance, PC structures

1 INSTRUCTIONS

Corrosion of steel reinforcements embedded in concrete plays a vital role in the determination of life span and durability of concrete structures. The corrosion of steel reinforcements can result in an unanticipated and premature degradation of concrete structures. In most cases, water-soluble chlorides induce the corrosion of the reinforcing steels. As the corrosion of the embedded steel progresses, an enormous stress may be exerted on the surrounding concrete, which may lead to cracking and later spalling of the concrete. The stress due to the corrosion of steel might be as high as 450 MPa (Hoke, 1980). In fact, the corrosion of steel in concrete can be retarded by the passivating ferric oxide film (γ-FeOOH) formed in the concrete medium with a pH around 12.5. However, the chlorides can break the passive film when the ratio between the chloride and hydroxide in concrete exceeds 0.6 (Sagフトs, 1993). And then, the corrosion is facilitated.

Consequently, the corrosion monitoring of steel reinforcements is a tough and necessary task. The corrosion of the embedded steel can be monitored through measuring the potential of the steel. The measured potential is compared with standard ones and the condition of steel reinforcements is deduced. It was also reported that the embeddable reference electrodes were very useful for long-term corrosion monitoring of concrete structures. (Ha, 2004; Montemor, 2003; Mccarter, 2004; Andrade, 1978)

The carbon fiber reinforced polymer (CFRP) is characterized by good electrical conductivity and piezoresistivity as well as excellent mechanical properties, high resistance to chemical corrosion etc. The CFRP composite has been used widely as sensing materials to monitor the damage inside the composite-self or CFRP-based structures (Abry, 2001; Kupke, 2001; Yang and Wu, 2003). For the CFRP with only one type of carbon fibers as reinforcing and conductive phase, there are some concerns impairing its mechanical and sensing properties. The CFRP is inherently fragile, so it is prone to sudden rupture. Moreover, the variation of electrical resistance is small until the final rupture of the composite, as impairs greatly the sensitivity of the composite. To overcome the disadvantages of CFRP composite, the authors have developed hybrid CFRP (HCFRP)

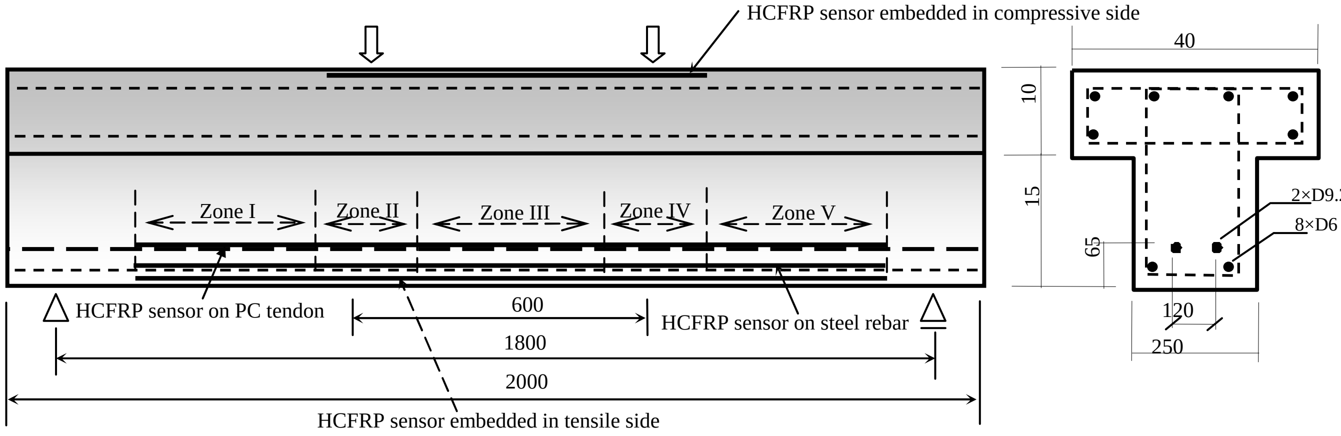

Figure 1. Schematic dimension of the PC beam and distributions of HCFRP sensors

composites and sensors from several types of carbon fibers of different strength and moduli (Wu and Yang, 2004a, 2004b, 2004c, 2005a, 2005b; Yang and Wu, 2005). To the authors' best acknowledge, there are no papers published on the corrosion monitoring of concrete structures with CFRP sensors.

In the present study, a novel type of HCFRP composite sensors is addressed to monitor the corrosion of steel reinforcements in PC structures. Artificial breaking of one of two PC tendons in the PC beam is performed using electrolytic accelerated corrosion. The results demonstrate that the corrosion of PC tendons can be monitoring with the HCRP sensors. Moreover, the corrosion can be located through a proper division of the HCFRP sensors.

Table 1 Properties of used carbon tows, concrete PC tendon and steel rebars

Material Types	Tensile strengthen (Gpa)	Young's Modulus (Gpa)	Resistivity (10^{-3} Ω .cm)	Elongation (%)
C1	3.40	230	1.6	2.1
C5	2.75	392	0.8	1.0
C8	1.90	590	0.66	0.6
PC tendon	1.20	200		
Steel bar	0.6	200		
Concrete	50MPa	33.9		

2 EXPERIMENTAL DETAILS

2.1 *Preparation of HCFRP sensors*

The HCFRP sensors are fabricated with three types of carbon tows, C1, C5 and C8. They are used as high strength (HS), middle modulus (MM) and high modulus (HM) carbon tows, respectively. The mechanical properties of the used carbon tows are shown in table 1. FR-E3P standard epoxy resins and hardeners with a mix ratio by weight 2:1, were used to impregnate the carbon tows. For the HCFRP sensors bonded on PC tendons, they are directly fabricated on the surface of the PC tendon with a lay-up process. While for those bonded on steel rebars, embedded in top and bottom surfaces of the beam, the fabrication was a little complicated. Firstly, C8, C5 and C1 are separately impregnated with epoxy resins and cured. Then, the impregnated C8 and C5 are pretreated, that is, they are pulled repeatedly through a roller with a diameter of about 5cm. Such a process is called pretreatment of C8 and C5 in this study. Finally, the HCFRP sensors are fabricated with the impregnated C8, C5 and C1 with the lay-up process.

2.2 *Preparation of PC beam*

Accelerated cement was used, the compressive strength of concrete made of which are about 50MPa. The cement, water and other admixtures were mixed with a rotary mixer. The mixed slurries were poured into the oiled molds after the steel rebars bonded with HCFRP sensors were placed. An external electrical vibrator was used to facilitate compaction and decrease the amount of air bubbles. The concrete beams were demolded after 10 days. Then, two PC tendons were prestressed to a strain of 3,500με and placed into the beams, which were fully grouted in duct. The material properties of concrete, PC tendons, steel rebars, are given in Table 1. The schematic dimension of the PC beam is shown in figure 1. Moreover, rectangular grooves were chiseled in both top and bottom surfaces of the beam. The HCFRP sensors were embedded into the grooves with epoxy resins and putty. For simplicity, the HCFRP sensors bonded on PC tendon, steel rebar, tensile and compressive side of the beam, are indi-

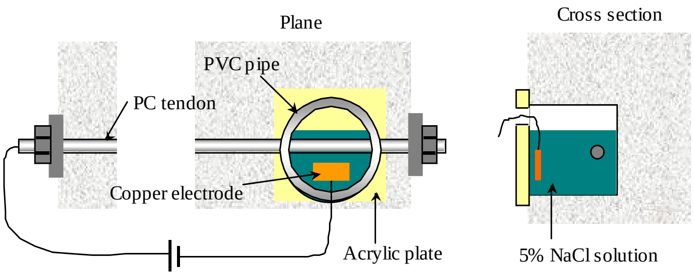

Figure2. Schematic illustration of corrosion system

cated as Sensor I, II, III and IV, respectively. The full lengths of sensors I-III are 170cm. To provide a distributed sensing for the PC structures, sensors I~III are divided into five zones indicated as zones I, II, III, IV and V, as shown in figure 1. The gauge lengths of these five zones are, individually, 45, 20, 40, 20 and 45cm. At the mid-span of every zone, a conventional strain gauge was used to measure the strain. Only the gauge length of Sensor IV embedded in compressive side of the PC beam is 80cm, and there is no division for this sensor.

2.3 *Corrosion and measuring systems*

The breakage of PC tendon was achieved by the electrical corrosion. The corrosion system is schematically shown in figure 2. The PC tendon was used as anodic electrode, and a copper plate was used as cathodic electrode. A DC of 3A was introduced into the PC tendon as shown in figure 2.

The electrical resistance, R, along the stress axis was measured with the four-probe method. Silver adhesive was applied in order to ensure a good electrical contact. A small current of 5mA was introduced into the HCFRP sensors from electrodes. The voltages and strain were continuously measured with Data Logger 302. According to Ohm's law, the axial electrical resistance can be obtained. Moreover, the strains of PC tendon, rebar and HCFRP sensor were measured using conventional strain gauges. The deformation of the beam was measured by means of displacement transducers. A hydraulic universal machine was used to load the beam.

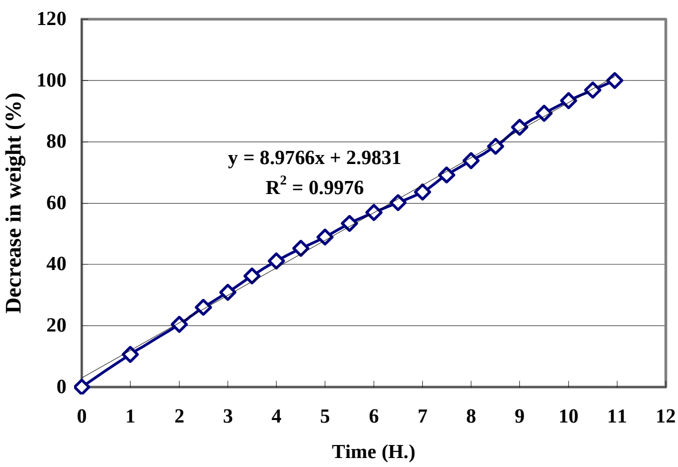

Figure 3. Relationship between decrease in weight and time under a DC of 3A

3 RESULTS AND DISCUSSION

When the specimen was loaded to about 55kN, the load was held. Then, the corrosion of PC tendon was carried out at the left loading point that is the mid-span of Zone II. In the following sections, the responds of each sensor to the corrosion are investigated and discussed.

3.1 *Decrease in weight under a DC of 3A*

The relationship between fractional change in weight and time is shown in figure 3. It shown that the weight of PC tendon decreases with corrosion time linearly. The curve of decrease in weight vs. time can be fitted with a straight line with a correlation coefficient of 0.9976.

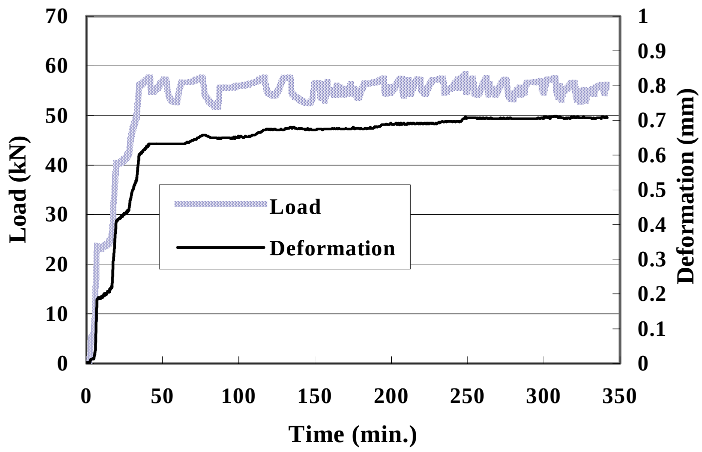

Figure 4. Variations of load and deformation of the beam with time

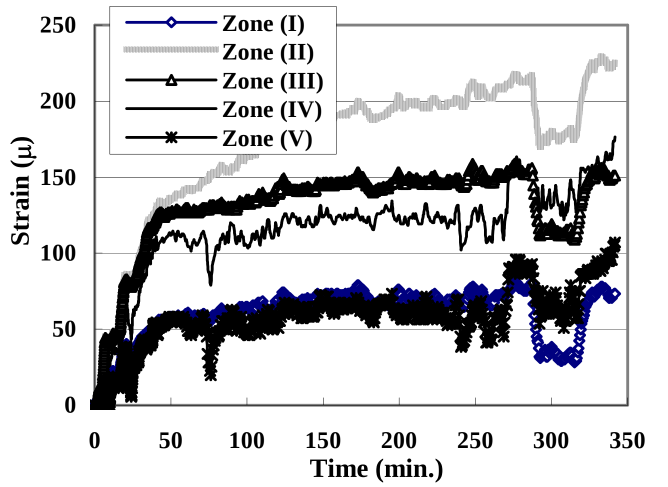

Figure 5. Strain distribution along Sensor III with time

3.2 *Mechanical behaviors of the PC beam*

The variations of load and deformation with time are shown in figure 4. It is shown that the load was not ideally held, which ranges from 51.62 to 57.25kN. The deformation of the beam increases monotonically as electrical corrosion progresses.

Factually, the strains at the mid-span of every zone of the HCFRP sensors and the strains of PC tendon and steel rebars at the mid-span and loading points are measured. In this paper, only the strains along Sensor II bonded on steel rebar are shown to display the strain distribution and discuss the influence of corrosion on the strain distribution. The changes of strain along Sensor II are shown in figure

5. The strain gauges were adhered on the mid-spans of each zone of the sensor. It is seen that the strains increase with corrosion time. The reason is due to that the cross-section of the PC tendon decreases while the stress increase gradually with the increase of corrosion time. The strain of Zone II where the corrosion was carried out is much larger than those of the other zones. The strain of Zone III is a little larger than that of Zone IV. The strains of Zone I and V are very small compared with those of the other zones. The results clearly show the strain distribution along the beam.

3.3 *Distributed sensing results of Sensor I bonded on PC tendon*

The variations of electrical resistance for each zone of Sensor I are shown in figure 6. Generally, it is shown that the electrical resistance increases with the increase of corrosion time. However, for zone II and III, the electrical resistance decreases at the first period of corrosion, as shown in figure 6. The reason is probably attributed to the undulation of load that ranges from 57.65 to 51.62kN. However, the reason is not well understood.

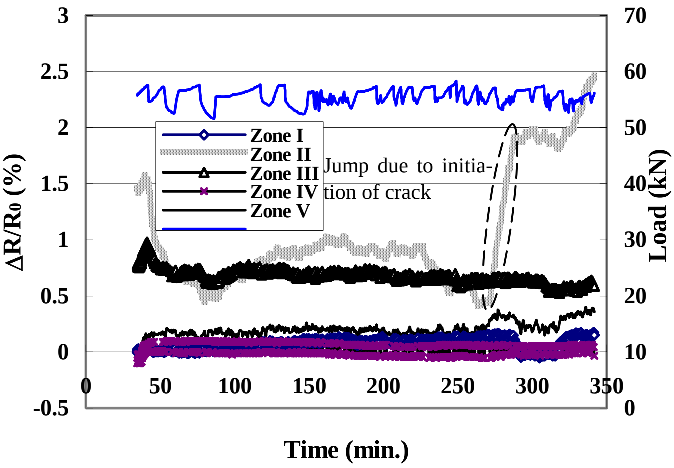

Figure 6. Distributed sensing of Sensor II bonded on PC tendon

It is shown in figure 6 that the changes in electrical resistance of Zones I, IV and V are not distinct. The influence of corrosion is lesser on the other zones than that on Zone II, since the corrosion was carried out in Zone II. The sensing results accord with the strain distribution tendency along the PC beam as shown in figure 5.

At a time of about 271 min., there exists a jump in electrical resistance in Zone II of 1.479%. The observation shows that two micro-crack occurred in the concrete of the beam around the corrosion place. Photo demonstrates the crack condition. Compared with the weight decrease vs. time curve shown in figure 3, 45% cross-section of PC tendon was corroded at the jump in electrical resistance.

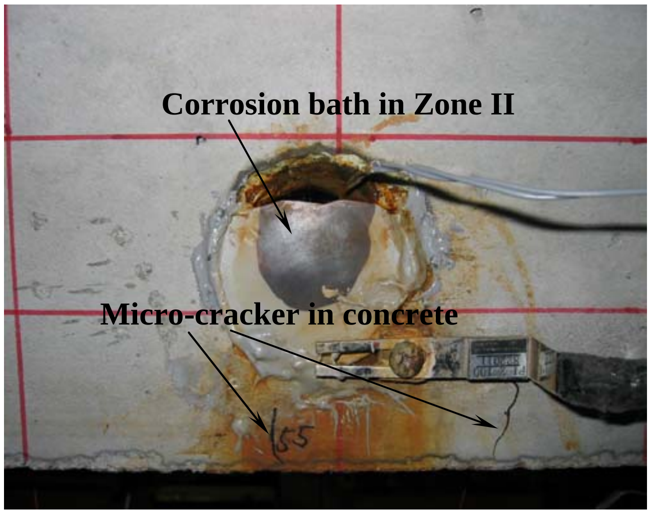

Photo 1. Initiation of micro-cracks and corrosion condition in Zone II

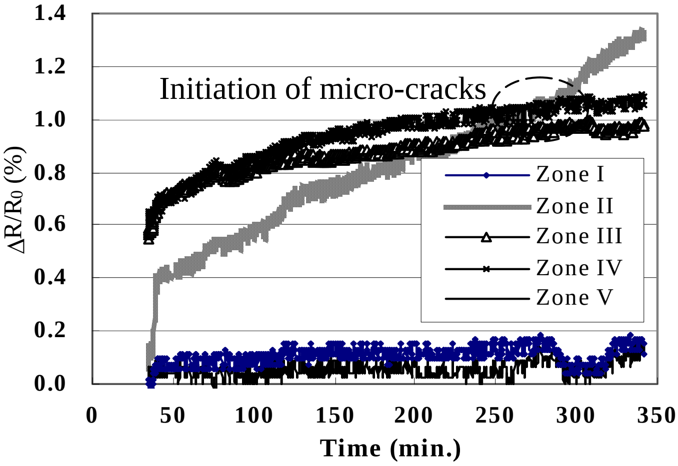

Figure 7. Distributed sensing of Sensor III bonded on steel rebar

3.4 *Distributed sensing results of Sensor II bonded on steel rebar*

The sensing results of Sensor II bonded on steel rebar are shown in figure 7. The changes in electrical resistance of Zones I and V are not so distinct as the electrical resistance change of Sensor I.

The electrical resistance of Zone II, III and IV increases with corrosion time quickly. Not similar to the electrical behavior of Zone II of Sensor I, the electrical resistance changes with corrosion time linearly without jumps in electrical resistance at the initiation of concrete cracks. The reason may be due to the fabrication process. The HM and MM carbon tows of Sensor I were not pretreated; while those of the other sensors were pretreated. The previous investigation (Yang and Wu, 2005) showed that the pretreatment of HM and MM carbon tows was in favoring of improving the values of $\Delta R/R_0$.

Since the corrosion was carried out in Zone II, the electrical resistance of this zone increases more quickly than that of the other zones, as shown in figure 7. Though no jumps in electrical resistance can be found for Sensor II, the changing rate in electrical resistance of Zone II is distinctly enhanced after the initiation of micro-cracks in the concrete. The observations show that the micro-fractures of concrete initiated at a time of 271 min. where the there is a sudden jump in resistance increasing rate of Zone II of this sensor. The results indicate that the HCFRP sensors can be used to monitor the corrosion of steel reinforcements effectively.

3.5 *Distributed sensing results of Sensor III embedded in tensile side of PC beam*

Figure 8 demonstrates the distributed sensing results of Sensor III embedded in the tensile side of the PC beam. Generally, the corresponding values of $\Delta R/R_0$ are much larger than those of the sensors bonded on PC tendon and steel rebar. It is attributed to that Sensor III is embedded in the bottom surface of the PC beams. Therefore, the corresponding strains of Sensor III are larger than those of the other two sensors even at the same load amplitude and corrosion time. Unlike the electrical behaviors of Sensor I and II, the electrical resistance of Zones I and V increases distinctly and linearly from the beginning of corrosion, as shown in figure 8. Compared the electrical behaviors of the other zones, the electrical resistance of Zone II increases with corrosion time at a much larger increasing rate. The reason is due to that the corrosion was carried out in this zone.

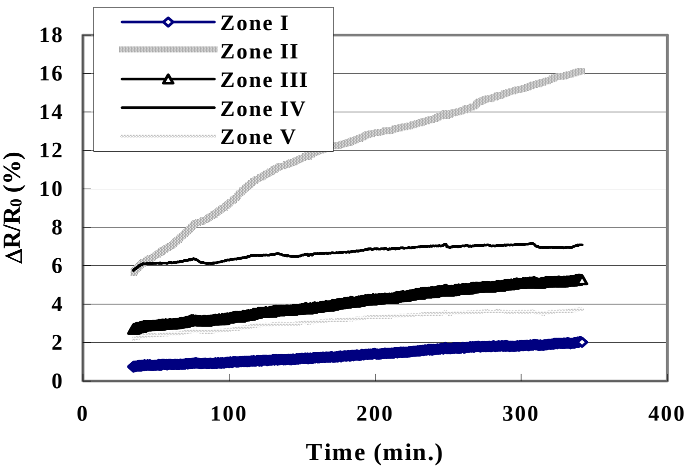

Figure 8. Distributed sensing of Sensor IV embedded in tensile side of the PC beam

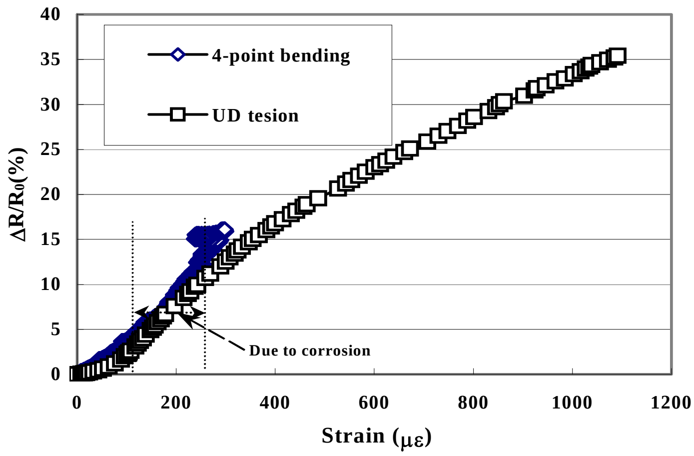

Figure 9. Sensing comparison of Zone II of Sensor III subjected to 4-point bending and UD tension

In fact, before the placement of these sensors into concrete beam, all the sensors have been tested subjected to unidirectional (UD) tension. In this study, only the results of zone II of Sensor III are compared between the 4-point bending and unidirectional tests. The results of both types of experiments are shown in figure 9. It is demonstrated that the electrical behaviors are similar for both types of experiments. However, the values of $\Delta R/R_0$ are a little larger for the 4-point bending than for the UN tension. The reason may be due to that the sensors as well as concrete beam are compressed after the placement of PC tendons. From the results, one can obtain that through a proper calibration the HCFRP can be used to monitor the structural health of concrete structures including the corrosion of steel reinforcement.

It is shown from the results of Sensor I, II and III that the electrical behavior of the zone where the corrosion of PC tendon was carried out is much different from the electrical behaviors of the other zones. For the electrical behaviors in Zone II, either there exists a jump in electrical resistance at the initiation of micro-cracks of concrete, or the electrical resistance increases much faster than those of the other zones. These indicate that a distributed sensing of corrosion of PC tendon can be realized through a proper distribution of the HCFRP sensors.

The comparison of the results of Sensor I without pretreatment of HM and MM carbon tows with the results of Sensor II and III with pretreatment indicates that there may exist some jumps in electrical resistance due to the initiation of micro-cracks in concrete for the HCFRP sensors without pretreatment. But no jumps can be found for the HCFRP sensors with pretreatment due to the initiation of micro-cracks in concrete. However, at the same corrosion time and load amplitude, the corresponding vales of $\Delta R/R_0$ of the HCFRP sensors with pretreatment are larger than those without pretreatment.

3.6 *Sensing result of Sensor IV embedded in the compressive side of PC beam*

In addition to tension, the compression of the PC beam can also be monitored. The sensing result of Sensor IV embedded in the compressive side of the beam is shown in figure 10. It is demonstrated from this figure that with the increase of corrosion time, the electrical resistance decreases, gradually. During the period of corrosion, the electrical resistance decreases by about 2.4%. From figure 10, it is seen that around the beginning of corrosion and initiation of crack, the electrical resistance decreases at a high rate. The results indicate that the compression of concrete can be monitored with the application of HCFRP sensors. On opposition to the electrical behavior of HCFRP sensors subjected to tension (Wu and Yang, 2004a,b, 2005a,b; Yang and Wu, 2005), the electrical resistance of Sensor IV subjected to compression decreases gradually as the corrosion processes.

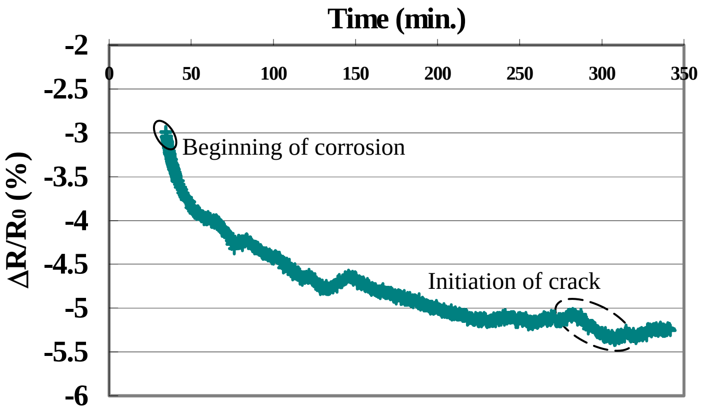

Figure 10. Results of Sensor IV in compressive side

4 CONCLUSIONS

In conclusion, an intrinsic corrosion monitoring function of PC beams is realized with the application of HCFRP sensors. The most advantages of such kind of sensors are their low cost, long-term durability and simplicity in technology and measuring systems.

The compression of concrete due to the evolution of corrosion can be detected with the application of HCFRP sensor. Under tension, the electrical resistance increases with the corrosion progresses; while under compression, the electrical resistance decreases gradually with the corrosion time.

The electrical behaviors of the zones where the corrosion was carried out are different from the other zones. In these zones, either there exist jumps in electrical resistance or the electrical resistance increases with a much larger increasing rate than those of the other zones. Thus, a distributed sensing of corrosion of the PC beam is demonstrated.

Moreover, it is found that the corresponding values of $\Delta R/R_0$ of the HCFRP sensors with pretreatment are larger than those without any pretreatment even at the same corrosion time and load amplitude.

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