- Technical Paper -

COVER CRACK-WIDTH PROPAGATION OF REINFORCED CONCRETE MEMBERS INDUCED BY CORROSION

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ABSTRACT

Cover crack-width propagation of reinforced concrete beams caused by corrosion are experimentally investigated through the accelerated corrosion testing. The study evaluates the relative influence of stirrup confinement, bar diameter, and concrete strength. From test, the crack-width propagation increases with increasing of concrete strength. It is also found that stirrups strain rate is closely related to crack propagation rate so that the crack propagation rate can be monitored from the strain rate. Vice versa, corrosion rate and strain of stirrups can be predicted from crack width propagation.

Keywords: crack width, corrosion, reinforced concrete, and serviceability

1. INTRODUCTION

A common problem found on reinforced concrete structures built in the chloride environments is corrosion of reinforcing bar. After corrosion initiated on the surface of reinforcing bar, the corrosion product built up around the surface and penetrate to surrounding concrete generating crack or even more spalling of concrete cover. A small crack around the bar surface mostly do not have a substantial effect on structural capacity. However, as corrosion growing crack propagates to concrete cover and it leads to structural degradation and promotes more damage because the bar became more expose to the environment. Thus, the knowledge of crack initiation and crack growth (propagation) became important due to serviceability requirement. Moreover, for assessment of existing corroded RC structure, the amount of corrosion loss is essential to be determined. While direct measurement of corrosion loss without removing the reinforcement from the structure is difficult and costly, as an alternative way it may be estimated indirectly using the relation between cover crack width and its cross-sectional loss caused by corrosion. There have been number of experimental studies evaluating the cracking behavior (e.g. crack initiation and crack propagation) of concrete under corrosion of reinforcement for past years (Andrade [2], Maruyama [5], Mullard [6], and Vu [8]). However, most of studies used a single bar in concrete prism or cylinder and absence of stirrup bars, which may not represent the real boundary condition of reinforced concrete structures. Many analytical and numerical models have also been developed (Li [4], Shinohara [7]), however, the experimental data is still required as a reference due to multi-aspects affecting the cracking behavior of corroded RC structures, and the limitations of current available models.

It has been known that volume of corrosion products are larger compared to its original volume of steel bar. This corrosion product generates an expansion pressure and produces a ring tension stress on surrounding concrete. The expansion pressure is not only causing the crack of surrounding concrete when reach its tensile strength, but also generate stress on transverse bar or stirrups. This becomes an initial stress on stirrups that should be considered on the assessment of corroded reinforced structures.

The main objective of this experimental test is to investigate the influence of stirrup confinement, bar diameter, concrete strength and corrosion rate on the cover crack-width propagation. All specimens are also a part of the bond spitting test of corroded RC members. However, only the cracking behaviors are presented in this paper.

2. EXPERIMENTAL DESIGN FOR CORROSION TESTING

2.1 Specimens and Materials

Six rectangular beams of 220x400 mm cross-sections were produced. On each specimen, only the main bars located at bottom side of beam, which had 400 mm of exposed length, were designed to experience corrosion (Fig.1). The un-corroded part of main bar near the exposed length, i.e. near slit and support, was insulated by vinyl tape as un-corroded part and un-bonded zone. The stirrups at corrosion part were also covered by vinyl tape to protect the stirrup gages during concrete placing and accelerated corrosion testing. The specimens were cured for 28 days, before accelerated corrosion testing was applied.

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Two concrete strengths were selected having specified compressive concrete strengths of 28 days of 24 and 48 N/mm^2 conforming to Japan concrete code [1]. D19 and D22 were used as main bars. The bars were preheated high strength steel. The average yield strength, tensile strength and elastic modulus were 1053, 1128 and 1.87 × 10^5 N/mm^2 for D19 and 980, 1031 and 1.85 × 10^5 N/mm^2 for D22, respectively. For stirrups, high strength steel bar were also used having average yield strength, tensile strength and elastic modulus were 1414, 1490, and 2.0 × 10^5 N/mm^2, respectively. A summary of the test variables is shown in Table 1.

Table 1 Specimen's Test Variables

Spec No.	w/c	Actual σ_B N/mm^2	Main Bar	Stirrups
1	0.74	22	4D19	No (p_w=0%)
2			4D19	U6.4@200 (p_w=0.15%)
3			4D19	U6.4@100 (p_w=0.3%)
4			4D19	2-U6.4@200 (p_w=0.3%)
5			3D22	U6.4@100 (p_w=0.3%)
6	0.46	49	4D19	U6.4@100 (p_w=0.3%)

2.2 Accelerated Corrosion Test

To generate corrosion with reasonable time period, an accelerated corrosion through the electrochemical process was performed. The typical accelerated corrosion set up for all specimens is described in Fig.2. During accelerated corrosion process the specimens were placed on top of two supports and below the specimen it was put the tank containing 3% of NaCl solution. The solution penetrated to the concrete through the water sponge. Thus, the corrosion attack took place from one direction. The main bars were corroded up to approximately 6% of corrosion loss where cover crack width estimated larger than serviceability limit (e.g. ACI's crack width limit of 0.3-0.5mm). Furthermore, a constant 10 Volt from the power supply was charged and the current flowed on each bar was monitored and recorded using data logger.

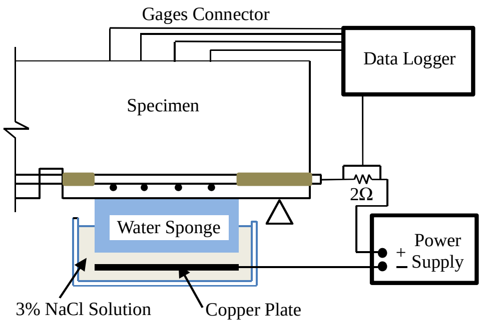

Fig. 2 Overview of accelerated corrosion setup

Fig. 3 Digital microscope measurement

2.3 Measurements of Crack Propagation

The crack initiation, the first visible crack on the concrete surface, and the crack propagation were frequently investigated by daily visual observations using digital microscope (see Fig.3). This digital microscope is not only for identifying the crack location, but also for measuring the cover crack width with the resolution of 0.01mm. After crack appeared on the cover, then the crack at certain locations were marked and the crack width were regularly measured to monitor crack width increment.

2.4 Measurements of Stirrups Strain

To measure strain development on stirrups due to corrosion expansion products, three gages were

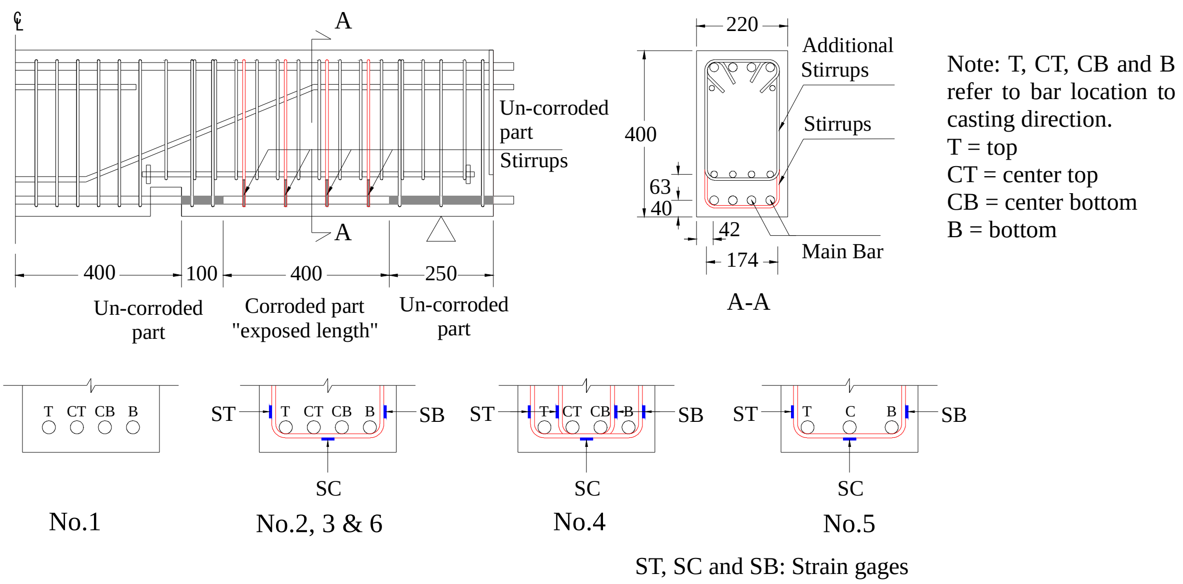

Fig. 1 Typical specimens and gages location

installed at each stirrup located at the middle of bottom leg and at the side leg of stirrups located at 50 mm from bottom stirrups as shown in Fig.1. The strain was recorded by a data logger in 60 minutes increments.

3. RESULTS FROM CORROSION TESTING

3.1 Corrosion Rate

To accurately determine the corrosion rate of reinforcing bar, at the completion of testing, the reinforcing bars were removed from their concrete beams and the corrosion rust was chemically cleaned by 10% diammonium hydrogen citrate solution, and then mechanically removed using a steel wire brush. The cleaning procedure of the rust and the measurement of weight loss are according to JCI-SC [3]. A summary of corrosion rate for each bar is shown in Table 2.

Table 2 shows that the corrosion rates of each bar at one beam are different, although the output of current of each bar is relatively similar. Higher corrosion rate is mostly obtained from the edge bar particularly bar located at top in casting (T).This trend was observed for all specimens. This can be attributed to the following: (a) crack due to corrosion mostly occur at edge of beam closed to edge bar, thus it allows the water and oxygen to penetrate easily to the bars; and (b) the bar located at top of concrete casting tends to have higher porosity than the bottom bar due to settlement of fresh concrete. The variation of corrosion rate of each bars are large in compared with the estimated corrosion rate by Faraday's law (predicted). However, if the average measured corrosion rate in a specimen compared with estimated corrosion rate by Faraday's law, the different between the two methods is approximately 10%.

Table 2 Corrosion Rate in Weight loss (%)

Spec. No.	Bar Location						$i_{corr\ (predicted)}$ mA.hr/cm^2
	T	CT	CB	B	Average		
1	10.6	4.7	3.8	5.6	6.2	(222)	210
2	8.9	4.9	4.4	4.9	5.8	(207)	210
3	8.2	4.4	5.4	6.3	6.1	(218)	210
4	7.4	4.5	4.6	5.2	5.4	(195)	210
5	7.4	3.9		6.3	5.8	(243)	262
6	6.6	4.0	6.0	6.1	5.7	(205)	210

Note: number in the parenthesis shows the equivalent of accumulative current density estimated by Faraday's Law in mA.hr/cm^2

3.2 Cover Crack Width Propagation

The crack initiation was visually observed within a few days after accelerated corrosion being started for all specimens. The crack appeared in various locations mostly located at bottom side of beams and near the edge of beams. This conforms to the corrosion rate distribution of each bar. The cracks then propagated and became a continuous longitudinal crack over the exposed length approximately parallel to reinforcing bar. Only specimen No.6, which has higher concrete strength, has a side cover cracking and a bottom cover cracking which perpendicular to the reinforcing bar

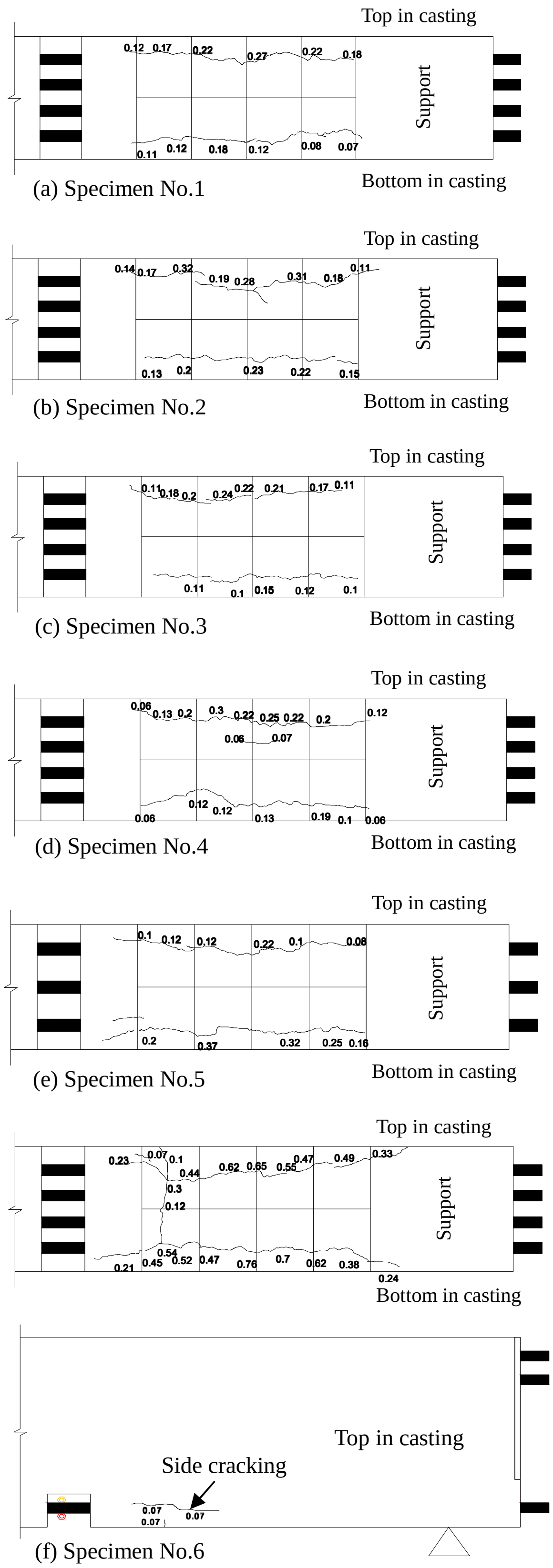

Fig.4 Cover Cracking Pattern

direction after longitudinal crack width of approximately 0.4 mm. The time to crack initiation of Specimen No. 6 also occurred more slowly than most of specimens due to the higher tensile strength. However, once crack initiate, the increase in crack width is faster than other specimens due to its lower porosity as described later. The cracking patterns of all specimens when corrosion rates approximately 6% are shown in Fig. 4. From the figure, the measured crack width in the middle of exposed length is larger than the edge of exposed length or near support.

Fig.5 presents the observed maximum crack width propagation of each specimen. Fig. 5 shows that it took lower corrosion rate to propagate to the same level of crack width for specimen No.6 which having higher concrete strength. This trend can be attributed to the lower porosity of high concrete strength prevents the corrosion product to penetrate or diffused within the concrete and so that it produces higher expansive pressure to surrounding concrete inducing higher crack width. However, it should be noted that the use of high concrete strength delays the corrosion initiation time

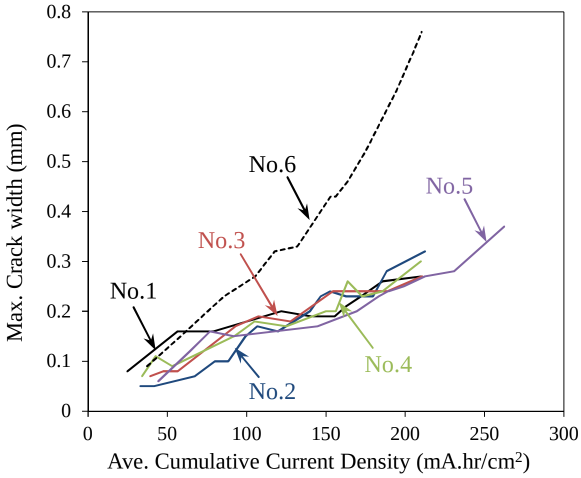

Fig.5 Crack propagation in accumulative current density domain

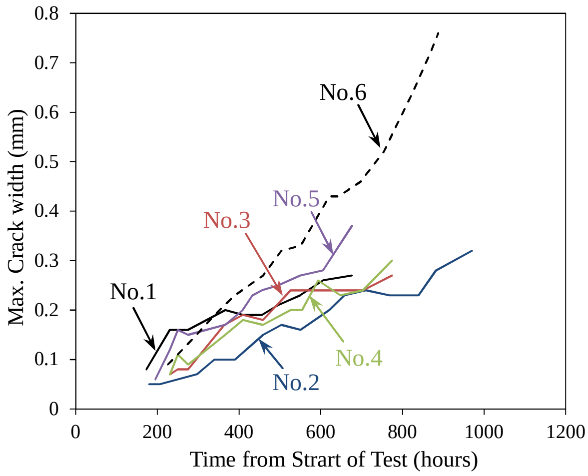

Fig.6 Crack propagation in time domain

due to the lower porosity of concrete, although evidently, higher concrete strength has faster crack propagation.

From Fig. 5 and Fig. 6, it shows that the crack propagation is also influence by the presence of stirrups. The higher stirrups ratio also increases the crack propagation rate due to the confinement to the concrete. However, for non-stirrup specimen or specimen No.1, the crack propagation rate is faster than specimen with stirrups at low corrosion rate, but then the crack propagate more slowly for high corrosion rate indicated by the slope become less stiffer. In general, the influence of stirrups is insignificant because the width of surface (cover) crack caused by corrosion cannot be controlled by stirrup.

3.3 Localized Corrosion

The localized corrosions (pitting corrosion) were observed on the bar surfaces. The sign of localized corrosion significantly occur at bottom of bar which face the bottom concrete cover. The appearance of localized corrosion could be attributed to the direction of current flow only came from the bottom of beams which results in uneven distribution of corrosion process. This clearly can be seen after removing the bar from the concrete that most of corrosion concentrates at bottom view of bar (see Fig. 7). The used of chloride ion as electrolyte is also known can promote pitting corrosion on reinforcement (Vu [8]).

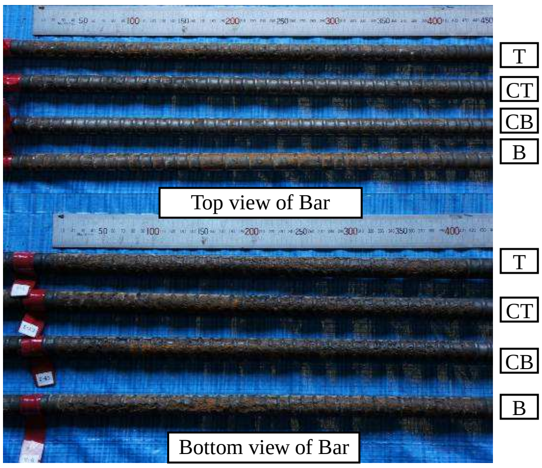

Fig.7 Localized corrosion (Specimen No.1)

3.4 Measured Stirrups Strain

Corrosion-induced strains, as measured in the stirrups are shown in Fig.8. The results clearly show that corrosion in a higher concrete strength caused the rate of stirrups strain to increase. This increasing rate is closely related with the increasing rate of crack propagation. This means that the speed of crack propagation rate can also be monitored from the strain rate of stirrups.

When the stirrup strains are compared between the bottom leg and the side leg of stirrups, the strain is not uniformly occurred. The bottom leg tends to have higher tensile strain than side leg. This can be due to

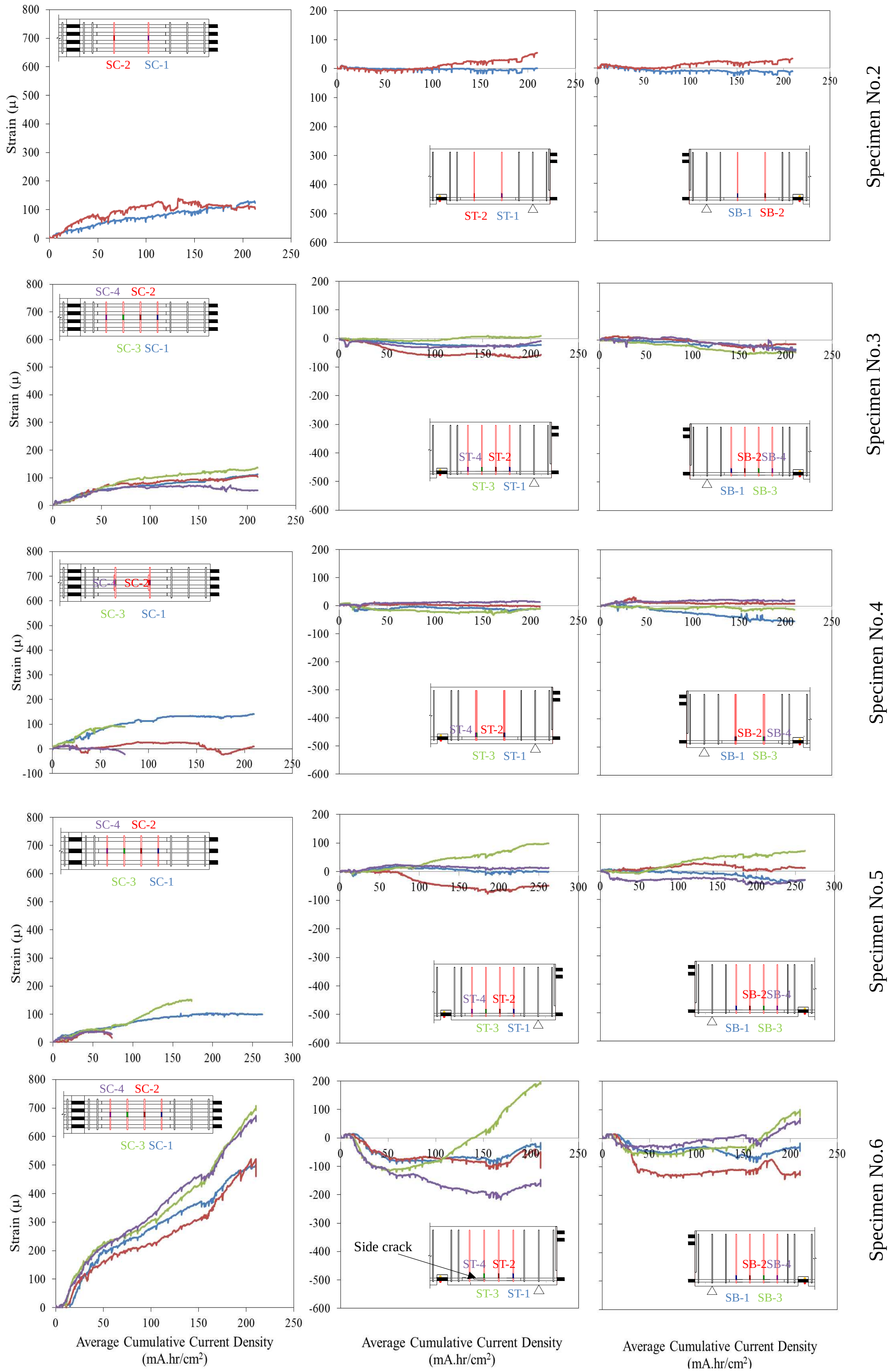

Fig.8 Corrosion-induced stirrup strains

the majority of cracks are propagated at bottom side of beams which most cracking lines cross the bottom leg of stirrups. The similar behavior is also showed for side leg stirrup when the crack propagated at side of beams as shown in Fig. 8 for specimen No.6.

Assuming a complete bond between concrete and stirrup, the strain should be approximately about 0.4mm/174mm = 2300μ for normal strength and 1.4mm/174mm = 8000μ for high strength. The stirrup strain rate from tests for both concrete strengths is not so much because the bond between steel bar and concrete is not perfect due to vinyl taping.

Moreover, for lower concrete strength, the strain rate tends to be constant after approximately 100mA.hr/cm^2 of corrosion rate. Meanwhile, the strain rate is still increase with an increasing of corrosion rate for higher concrete strength. This indicates a high dissipation capacity of corrosion products to dissipate into the pore structure of concrete or into initial crack (e.g. caused by shrinkage and temperature) or previous corrosion crack for lower concrete strength.

4. CONCLUSIONS

This paper presents the experimental results of corrosion-induced crack width propagation and corrosion-induced stirrup strain from accelerated corrosion testing of RC beam specimens. The following conclusions can be made.

(1) The corrosion rate among bars on a beam is not uniformly distributed. This behavior can be caused by some parameters such as bar location, supply of water and oxygen, and direction of chloride diffusion.

(2) The influence of concrete strength is significantly governs the crack-width propagation rate and stirrup strain rate. However, the influence of stirrups confinement is insignificant.

(3) The rate of stirrup strain is closely related to the rate of crack propagation. This means that the rate of crack propagation can also be monitored from the strain rate of stirrups. Conversely, the corrosion rate and strain of stirrups can be predicted from the crack propagation.

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