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- Technical Paper -

ANALYSIS OF EFFECTS OF NON-UNIFORM CORROSION ON CONCRETE CRACKS PROPAGATION

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ABSTRACT

Concrete cracks propagation due to non-uniform corrosion was examined experimentally and analytically. In the experiments, the single-rebar slab specimens with different cover thicknesses were corroded using an electric corrosion method and the internal crack pattern was investigated. In the analysis, the corrosion expansion model incorporated into Rigid Body Spring Method was applied to simulate the cracking behavior by assuming the corrosion distribution around the rebar. The effects of the corrosion distribution and side cover thickness were studied. As the result, the internal crack pattern is strongly related with the corrosion distribution. When the corrosion broadly distributes around the rebar, the internal crack pattern for small concrete cover may be the same as that for large cover, which consists of parallel cracks to the concrete surface. The concentrated corrosion may cause the inclined internal cracks even in large cover. They are different from the theoretical crack pattern.

Keywords: non-uniform corrosion, internal crack pattern, surface crack width, RBSM,

1. INTRODUCTION

Corrosion of reinforcing steel bars is a principle cause of deterioration of reinforced concrete (RC) structures. The concrete cracking due to corrosion may not result in a significant loss of the structural strength of concrete elements, whereas it raises a risk to human safety by concrete falling. Hence, there is a need for the understanding of the concrete cracking behavior caused by the rebar corrosion, especially the relation between surface cracking process and internal crack propagation, which is beneficial for an effective maintenance of corroded RC structures and the prevention of such kind of accidents.

Considering concrete with embedded rebars to be a thick-wall cylinder and assuming a perfectly uniform distribution of corrosion products around the rebars, Bažant [1] suggested that cracking caused by rebar corrosion may occur basically in two different modes, which are related with the cover thickness *C* and the rebar spacing *S* as shown in Fig.1. If spacing *S* of the rebars is larger than six times the rebar diameter *D* and/or the cover thickness *C* is relatively small, two cracks propagate diagonally from the rebar to the concrete surface at an angle of 45°; if the cover thickness is larger than (*S*-*D*)/2, the two cracks propagate separately to adjacent rebars and form a parallel crack to the concrete surface. In a similar way, based on the elastic theory that accounts for the stress concentration, Tsutsumi et al. [2] proposed a criterion about the effect of the concrete cover thickness to rebar diameter ratio on the internal crack pattern for the single rebar specimen, which is shown in Fig.2. The criterion is that if *k* value is less than 3, cracks propagate diagonally to the concrete surface; if *k* value is greater than 3, cracks develop in the shortest path to the concrete surface, i.e. a vertical crack in addition to two lateral cracks occur in the concrete cover.

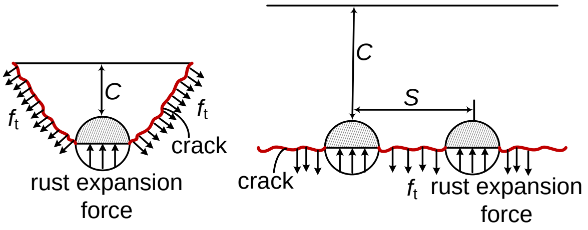
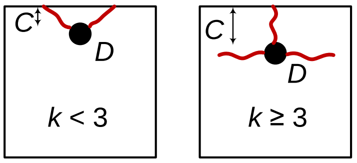


Fig.1 Bažant's cracking mode [1]



$$k = \frac{2C + D}{D}$$

Fig.2 Tsutsumi's criterion for crack pattern [2]

The inclined crack is considered to be more dangerous than the parallel crack, because it can not only provide a flow channel connecting to the surface, accelerating the corrosion process, but also incurs the cover spalling [1]. Therefore, the maintenance work should pay more attention to such kind of crack.

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Although the theoretical models described above are contributable to the prediction of the development of corrosion-induced cracks, they are based on the assumption of uniform corrosion around the rebar, which is different from the corrosion state resulted from chloride attack. In such situations, the corrosion occurs at the surface of the rebar facing the concrete cover, which may lead to non-uniform expansion pressure [3]. Yuan and Ji [4] observed the distribution of corrosion products around the rebars that were obtained by exposing the RC specimens to an artificial climate environment, and indicated that the corrosion products distribute on the half circumference of the rebar facing the concrete cover only. A few numerical studies [5, 6, 7] has been carried out to study the effect of non-uniform corrosion on concrete cracking behavior, which generally indicated that non-uniform corrosion causes faster appearance of cracks in concrete cover than uniform corrosion. In spite of these valuable results, there is still a lack of data concerned with the internal crack pattern, which is essential for the applicability of the theoretical models on the assessment of corrosion damage of RC structures exposed to marine environment.

In this study, the internal crack patterns of the single rebar specimens with two different cover thicknesses were experimentally examined using an electric corrosion method. Meantime, a corrosion expansion model incorporated into Rigid Body Spring Method (RBSM) is used to simulate cracks propagation by assuming the distribution of corrosion products around rebar. In the end, a discussion about the effects of the corrosion distribution and side cover thickness on the cracking behavior is presented.

2. EXPERIMENTAL WORK

2.1 Specimen

The former study [8] shows that the internal crack pattern is in a close relation with the geometry of the cross section of concrete specimens, such as the arrangement of reinforcements and the side and cover thickness. In order to remove these effects, a type of sing-rebar slab specimen with a dimension of 600mm×500mm×200mm was used as shown in Fig.3. The rebar embedded was 550mm long and 19mm in diameter. Two specimens with different cover thicknesses, 10mm and 30mm, were considered in the experiments. According to Tsutsumi's criterion [2], the *k* values are 2.05 and 4.16 respectively, and therefore the two different crack patterns as indicated in Fig.2 can be expected.

The two specimens were fabricated with early strength cement. Table 1 shows the mixture proportion. The maximum diameter of coarse aggregate was 20mm and the volume fraction of coarse aggregate to total aggregate was 0.6. The concrete elastic modulus, compressive strength and splitting tensile strength at 14 days were 31.95GPa, 39.92MPa and 2.97MPa, respectively.

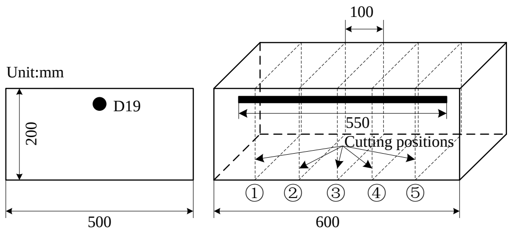

Fig.3 Specimen dimension

Table 1 Mixture proportions of concrete

W/C (%)	s/a (%)	Unit (kg/m^3)				
		Water	Cement	Sand	Aggregate	AE (liter/m^3)
56.5	44	166	294	779	990	1.18

2.2 Electric Corrosion Test

During the test, the corrosion process was accelerated using the impressed current method, which applied an external direct electric current to the embedded rebar. In order to simulate non-uniform corrosion, a 100mm wide water pool filled with 3% NaCl solution was set on the top surface of each specimen, which was right above the rebar. A copper plate as the cathode was placed in the water pool. The cracks in the concrete cover can allow a faster transport of chloride ions and thereby accelerate the corrosion process, which can cause a higher corrosion level in the upper part of the rebar facing the concrete cover than that in the lower part. A schematic of the electric corrosion method is shown in Fig.4.

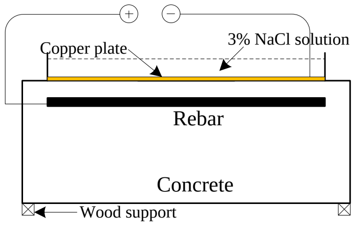

Fig.4 Electric corrosion method

The nominal current density applied in the test was 900μA/cm^2, which was greater than the maximum corrosion rate 100μA/cm^2 recorded in practical chloride-contaminated concrete [9]. Although the current density may affect the evolution rate of crack width [10, 11], there are no conclusive findings about its influence on the crack pattern. Hence, a large current density was used to allow a quick cracks generation as referred to in the other reported study [3]. The objective current flow was 159.77A*hr. After the corrosion tests, the specimens were cut at the positions as shown in Fig.3 with an interval of 100mm for the investigation of internal crack patterns and the measurements of the crack widths and lengths. In order to observe the corrosion state, the rebar samples were obtained afterwards and cleaned by immersing the rebar samples in 10% diammonium hydrogen citrate for 24h firstly and then using a wire brush. The corrosion degrees of these rebar samples were also obtained based on the measured weight loss.

2.3 Test Results

Fig.5 shows the measured corrosion degrees against the corresponding positions along the rebar, in which each data represents the corrosion degree of a rebar portion about 50mm long. As can be seen, for 30mm cover, the corrosion degrees at different positions appear to be close to 3%, while in the case of 10mm cover, a sharp increase of corrosion degree occurs from 250mm to 450mm. It is caused by the mutual effect between cracking and corrosion, i.e. cracks enable a faster transport of chloride and water, thereby accelerating corrosion and causing more cracks. The severe cracking condition corresponding to this area is shown in Fig.6 (see cracks marked in blue).

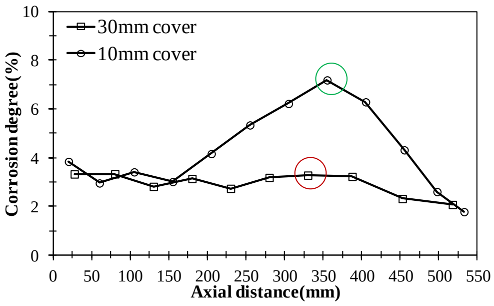

Fig.5 Measured corrosion degree

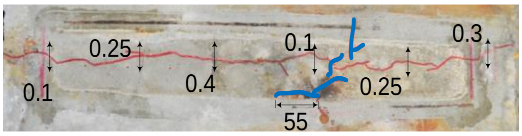

Fig.6 Surface cracking state (10mm cover)

Two rebar samples obtained from the positions as indicated in Fig.5 are selected for the demonstration of the typical corrosion state by using water pool, which is shown in Fig.7. It is obvious that the upper part is far more corroded than the lower part, which can be used as an approximation of natural non-uniform corrosion.

Fig.8 compares the internal crack patterns observed from each cut section between the test specimens. For 30mm cover, the internal crack patterns on different cut sections are nearly the same. One vertical crack connects the concrete surface to the rebar and two lateral cracks that are roughly parallel to the concrete surface propagate to the concrete sides, which form the same crack pattern as suggested by Tsutsumi [2]. For 10mm cover, the expected internal crack pattern that consists of two inclined cracks only appears on the section ④, while the other four sections all present a crack pattern similar to that of 30mm cover. Considering that the theoretical models are under a consideration of uniform corrosion, it seems that the cracking behavior of small concrete cover is sensitive to the corrosion state around rebar.

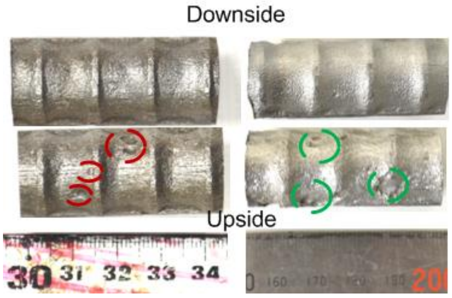

Fig.7 Corrosion state of rebar sample

The performed experiment shows that the application of the theoretical models on the prediction of internal crack pattern of chloride-affected RC structures is limited. In order to gain a better understanding about the influencing factors on internal crack pattern, a numerical analysis is carried out to investigate the effects of the corrosion distribution around rebar and side cover thickness.

3. ANALYTICAL MODEL

3.1 Three-dimensional RBSM

In this study, three-dimensional RBSM is applied [12]. The RBSM is a kind of discrete approaches, which represents a continuum material as an assemblage of rigid particle elements interconnected by zero-length springs along their boundaries as depicted in Fig.9. The elements are randomly generated with Voronoi Diagram. Each element has six freedom degrees at its nucleus. At the center point of the triangles formed by the center and vertices of the boundary between two elements, three springs, one normal and two shear springs are set, which are introduced with the nonlinear material models [13]. The material parameters were set in accordance with those obtained from the experiments. Cracks appear at the boundaries between adjacent rigid particles and the crack width can be automatically calculated as the relative displacement between their centers, which facilitate the simulation of crack pattern.

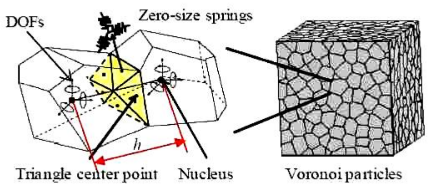

Fig.9 Voronoi particle definition of RBSM element

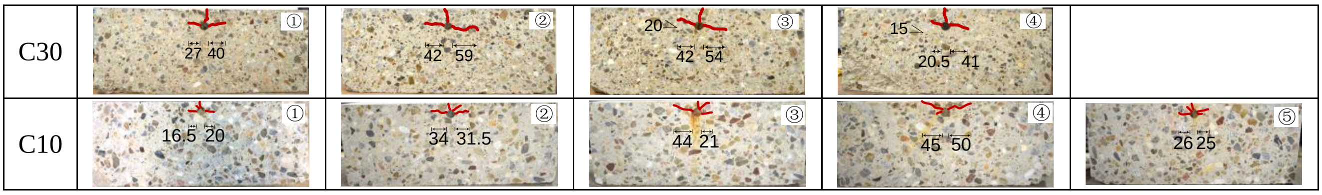

Fig.8 Internal crack patterns of test specimens

3.2 Corrosion Expansion Model

In the RBSM model, the expansion of corrosion products is modeled by internal expansion pressure. A three-phase material model including rebar, corrosion products and concrete is established. The corrosion products layer is modeled by an elastic material model and the thickness of the corrosion products layer is assumed to be constant in the simulation. The previous work [13] shows that a thickness of 1mm and an elastic modulus of 500MPa enable a reasonable simulation of cracking behavior in comparison with the test results, which were also employed in this work. Considering the nature of corrosion expansion, the internal expansion pressure is assumed to be only activated in the normal direction. Hence, the expansion stress is employed only to the normal springs on the boundary between the corrosion products and the rebar layer. The increment of expansion stress at each analysis step is determined:

$$\Delta\sigma_{cor} = E_r\left(\Delta\varepsilon - \Delta\varepsilon_0\right) = E_r\left(\frac{\Delta U_{cor}}{H} - \frac{\Delta U}{H}\right) \qquad (1)$$

where,

E_r : elastic modulus of corrosion products
$\Delta\varepsilon$: increment of total strain
$\Delta\varepsilon_0$: increment of initial strain by free expansion
ΔU_{cor} : increment of real increase of rebar radius
ΔU : free increase of rebar radius
H : thickness of corrosion product layer

The experiment showed that a rebar is more corroded at the part near cracked concrete than that surrounded by uncracked concrete. Considering the effect of cracks on the corrosion process, the non-uniform corrosion in the rebar circumferential direction is simulated with an assumption on the corrosion distribution as shown in Fig.10. Here the angle θ is used to represent the distribution of corrosion products around rebar. When a vertical crack near the rebar exceeds 0.1mm in width, the corrosion products is only distributed in the upper part facing the concrete cover (the shadow area). Correspondingly, the expansion stress is only applied in this part.

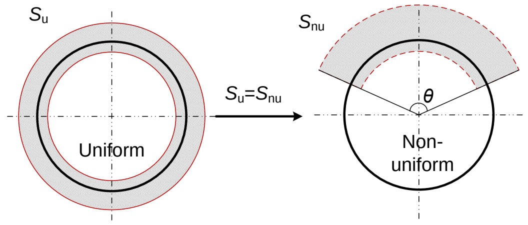

Fig.10 Non-uniform corrosion model

3.3 Model Verification

The corrosion expansion model is verified using the test results. The created RBSM model has the same dimension as the tested specimen as shown in Fig.11. The mesh sizes of the Voronoi particles near rebar are 5mm for 30mm cover and 2mm for 10mm cover, respectively, while the mesh size in the outer area is 30mm. Based on the observed corrosion state around the rebar as shown in Fig.7, θ is assumed to be 180° in the simulation. The concentrated corrosion in the rebar length direction that occurred in 10mm cover case was not considered in this study. Hence, the corrosion amounts along rebar stay the same.

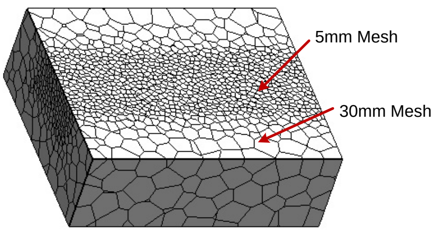

Fig.11 3D view of RBSM model

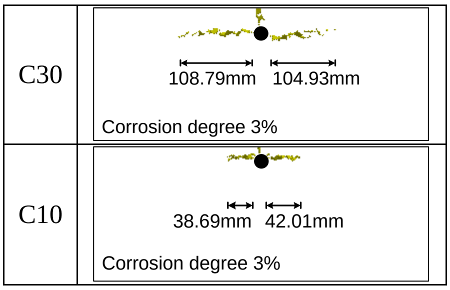

Fig.12 Simulated internal crack pattern

Fig.12 shows the simulated internal crack pattern under the corrosion degree of 3%, in which the crack width value is indicated by the color, i.e. the yellow and red ones represent the cracks with widths greater than 0.1 and 0.3mm separately. As can be seen, the crack patterns agree with those observed in the test, while the modeled lateral crack length is larger because the effect of corrosion products penetrating into the corrosion-induced cracks was not considered in the corrosion expansion model. Like the test results, the simulation also shows that the internal crack pattern for 10mm cover is similar to that for 30mm cover, suggesting that the internal cracks propagation may be affected by the corrosion distribution around rebar. Therefore, a parameter analysis using the verified numerical model was conducted to investigate the influence of corrosion distribution on the cracking behavior. Considering that a much more concentrated corrosion facing the concrete cover may occur in practical situations, the angle θ has been ranged from 360° to 45°, in which 360° represents a uniform corrosion process.

4. EFFECTS OF CORROSION DISTRIBUTION

Fig.13 shows a comparison of simulated internal crack patterns for different corrosion distributions when the corrosion degree reaches 2.5% and 5% respectively. It appears that under the same level of corrosion, non-uniform corrosion causes more cracking in the concrete cover than uniform corrosion (see the red cracks in the non-uniform corrosion cases). Both series with different cover thicknesses demonstrate that internal crack pattern has a strong relation with the corrosion distribution. For 30mm cover, as a decrease

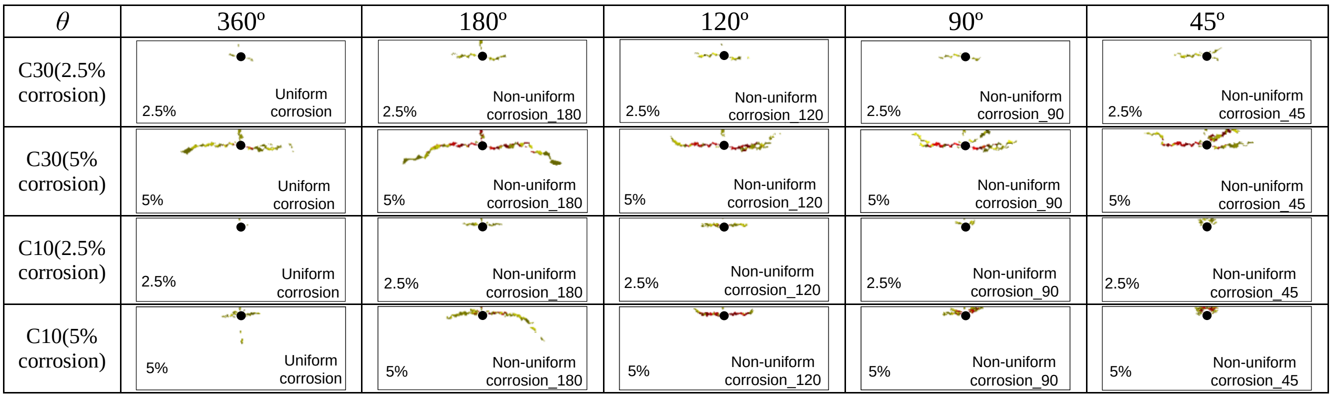

Fig.13 Comparison of internal crack patterns for different corrosion distributions (240.5mm side cover)

of the angle θ, i.e. the corrosion concentrates in a much smaller area of the rebar upper part facing the concrete cover, the lateral cracks firstly propagate in the direction parallel to the concrete surface and then develop diagonally to the surface rather than the concrete sides. When θ equals to 45°, the inclined crack even becomes the main crack with a larger width. For 10mm cover, the crack patterns are roughly the same as those of 30mm cover when the corrosion distributes in a broad area around the rebar ($\theta \geq 120°$). The predicted crack pattern by the theoretical models for small concrete cover only appears when the corrosion is highly concentrated ($\theta \leq 90°$). It suggests that the corrosion state around the rebar also has a significant influence on the internal crack pattern, while the theoretical models only indicate the relation between the internal crack pattern and the geometry of the cross section of concrete specimens.

Fig.14 presents the surface crack width development against the corrosion degree. It seems that when the corrosion area concentrates, the evolution rate of surface crack width is smaller even under the same corrosion degree. Chen and Leung indicated [7] that a large part of surface crack opening caused by rebar corrosion is resulted from rotation of the concrete cover. Considering the internal cracks propagation, when θ equals to 90°, the lateral cracks gradually propagate diagonally to the concrete surface instead of going the concrete sides, which limits the rotation of the concrete cover and leads to a smaller surface crack width. This situation should be noted when using the surface crack width to assess the corrosion-damage. Once the concentrated non-uniform corrosion occurs, the internal cracks propagation becomes dominant and the inclined crack that can accelerate the corrosion process and also induce cover spalling may occur in a concrete cover normally considered to be safe.

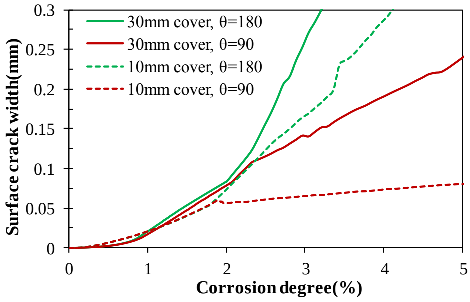

Fig.14 Surface crack evolution for different corrosion distributions (240.5mm side cover)

4. EFFECTS OF SIDE COVER THICKNESS

The side cover thickness affects the rotation of the concrete cover and thereby influences the evolution of surface crack width, which is an important on-site survey item. Hence, the effects of side cover thickness on the development of surface cracks and internal cracks are also investigated using the corrosion expansion model. In the simulation, the width of the specimen investigated in section 3 is changed to 200mm.

Fig.15 shows the simulated internal crack pattern with the assumption of corrosion distribution. When the corrosion distribution θ is assumed to be 90°, the simulation corresponds to the crack pattern observed by Kawamura [8] as shown in Fig.16. The test used the single rebar specimen with a similar section dimension of 150mm×150mm. When the side cover thickness is reduced, it still shows a similar trend about the effect of corrosion distribution on the internal crack pattern. The internal crack pattern for 10mm

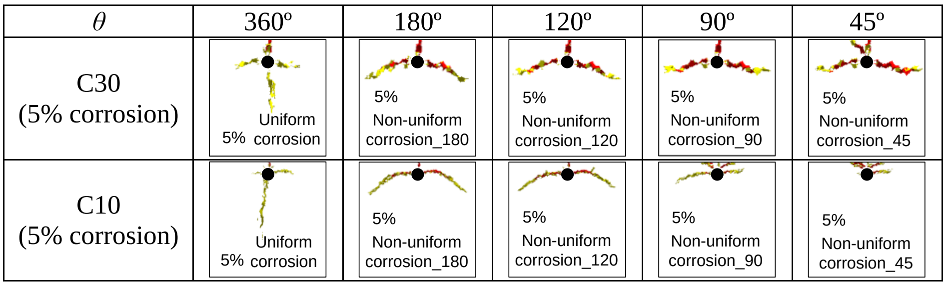

Fig.15 Comparison of internal crack patterns for different corrosion distributions (90.5mm side cover)

cover is the same as that for 30mm cover when the corrosion appears in a large area around the rebar ($\theta \geq 120°$). It implies that the corrosion distribution around the rebar may have a more influence on the internal cracks propagation than the concrete cover thickness, which is a main factor for the theoretical crack pattern as shown in Fig.2.

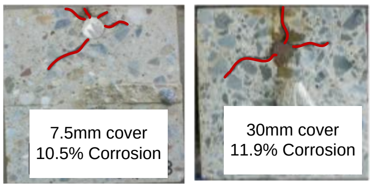

Fig.16 Observed internal crack pattern in test [8]

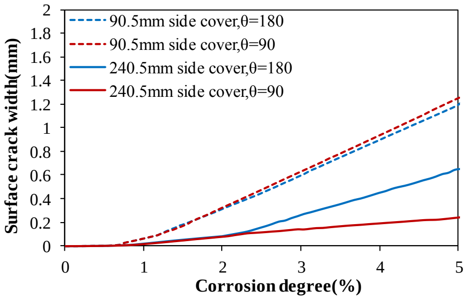

Fig.17 Surface crack evolution for different side cover thicknesses (30mm concrete cover)

Fig.17 compares the development of surface crack width between the cases with different side cover thicknesses. As can be seen, for a small side cover the corrosion distribution hardly affects the evolution rate of surface crack width, while for a large side cover the more concentrated corrosion causes a smaller surface crack width. It can be attributed to the changed internal crack pattern in the specimen with a large side cover, in which the lateral cracks may incline to the concrete surface. This result suggests that when the side-cover thickness or the spacing of rebars is large, highly concentrated non-uniform corrosion may lead to a great development of internal cracks without a discernible sign in the surface crack width.

5. CONCLUSIONS

Generally it can be concluded from the current study that:

(1) The corrosion expansion model combined with RBSM can simulate correctly the internal crack pattern using a reasonable assumption on the corrosion distribution around the rebar.

(2) The internal crack pattern is highly affected by the corrosion distribution. When the rebar is corroded broadly in the circumferential direction, the internal crack pattern for 10mm cover is the same as that for 30mm cover without the appearance of the inclined crack. When the corrosion concentrates significantly in the area facing the concrete cover, the internal cracks for 30mm cover may also incline to the concrete surface, if the side cover thickness is sufficiently large.

(3) It is difficult to estimate the corrosion extent based on the surface crack width alone. The simulated results show that for 30mm cover, non-uniform corrosion may cause the internal cracks gradually incline to the concrete surface and suppress the surface crack opening.

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