Concrete Corrosion Cracking and Transverse Bar Strain Behavior in a Reinforced Concrete Column under Simulated Marine Conditions

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Abstract: This study performed accelerated corrosion tests on reinforced concrete (RC) specimens reinforced with transverse steel bars to evaluate the concrete cracking and rebar strain behaviors caused by rebar corrosion. Seven RC specimens were created with variable compressive strengths, rebar diameters, and concrete cover thicknesses. To mimic in-situ conditions, the accelerated corrosion tests applied a current to the longitudinal bar and transverse bar for different periods of time to create an unbalanced chloride ion distribution. These tests evaluated the amount of rebar corrosion, corrosion cracking properties, and transverse bar strain behavior. The corrosion rate of the transverse bar was faster than that of the longitudinal bar, and cracking first occurred in the concrete around the transverse bar in the specimens with low concrete compressive strength and thin concrete cover. Corrosion cracking and rebar strain were greatly affected by the behavior of the corrosion products that resulted from the pore volume and cracking properties of the cement paste.

Keywords: reinforced concrete; corrosion crack; transverse bar; marine conditions

1. Introduction

Rebar corrosion from chloride attack is a major cause of reduced performance in reinforced concrete (RC) structures [1,2]. When chloride ions from the sea permeate and spread through concrete cover and reach the embedded rebar, the protective oxide film (passive film) on the rebar surface is destroyed and corrosion begins. Rebar corrosion not only causes section loss but also creates corrosion by-products that expand to two–six times the volume of the steel [3]. These corrosion by-products lead to expansion pressures around the rebar, which cause tensile stresses in the rebar’s circumferential direction. If the tensile stress exceeds the concrete’s tensile strength, radial corrosion cracking occurs, centering on the corroded rebar [4]. If corrosion cracking within the member propagates to the surface, the risk of spalling increases because the integrity of the concrete cover is reduced. Furthermore, when the corrosion cracking affects transverse bar, the tensile strain increases and the yield strength is reduced [5,6].

To evaluate the effects of rebar corrosion on the stability of RC structures, it is necessary to quantitatively assess the amount of rebar corrosion. One simple and practical method for doing this is to estimate the amount of corrosion in the internal rebar based on the width of corrosion cracks that can be seen from the surface. According to the previous study [7], the results of accelerated corrosion
tests were similar to those of non-accelerated corrosion tests. Therefore, to find the relationship between concrete surface corrosion crack width and the amount of rebar corrosion, several studies have employed accelerated corrosion tests based on electrochemical methods. Andrade et al. [8] conducted accelerated corrosion tests using RC specimens (150 × 150 × 380 mm) embedded with a 16-mm diameter rebar. Vu et al. [9] performed accelerated corrosion tests on RC specimens (250 × 700 × 1000 mm) that simulated a bridge deck, reporting that internal rebar corrosion increased when the cover thickness increased because the occurrence of surface corrosion cracking was delayed. Toongoenthong et al. [10] performed a two-dimensional crack analysis and examined the behavior of corrosion by-products in concrete rebar. These authors report that when concrete cover is thin, few corrosion by-products permeate into the corrosion cracks and cracking occurs at the surface relatively early. Toongoenthong et al. [10] also pointed out that when concrete cover is thick, cracks occur at the surface more slowly, and it is necessary to consider the creep process caused by the intrusion of corrosion products into crack surfaces (i.e., a buffer effect). Aryanto and Shinohara [5] performed accelerated corrosion tests on RC beam specimens with different compressive strengths. It was assumed that differences in corrosion cracking behavior are caused by differences in pore structure, and corrosion cracking behavior, similar to their test results, was recreated through a plane stress analysis in which the expansion rate of the corrosion products was varied (i.e., an expansion rate of 2.0 for Fc24 and 2.5–3.0 for Fc48).

In most studies, a single bar is placed in a concrete specimen [8] or RC specimens without transverse bars being used [9–11]. That is, most existing studies are limited by the fact that they do not consider representative beam and column member reinforcement placement and, as such, are unable to consider the process of chloride ion permeation in a realistic way because the rebar diameter and cover thickness are small. Therefore, this study sought to better replicate RC columns by creating seven specimens (600 × 600 mm cross-section) with D25–D38 longitudinal bars and three transverse bars and with varying compressive strengths, longitudinal bar diameters, and concrete cover thicknesses. Accelerated corrosion tests were performed to examine the concrete surface corrosion cracking and transverse bar strain behavior according to the amount of rebar corrosion. The accelerated corrosion tests were designed to mimic a chloride distribution similar to a RC member that exposed in the marine environment. This was done by controlling the current passing through the longitudinal bar and transverse bar and accounting for the differences in chloride ion permeation as a function of cover thickness.

2. Materials and Methods

2.1. Concrete Mixes

The concrete mixture used in this study is shown in Table 1. Type II ordinary Portland cement, a fine aggregate of less than 5 mm (river sand), and coarse aggregate with a maximum size of 20 mm were used. Three different water:cement ratios were used: 0.64, 0.44, and 0.34. To determine the mechanical properties of the concrete, cylindrical specimens with a diameter of 100 mm and a height of 200 mm were used. The specimens were cured underwater for 28 days in a water tank at a temperature of 20 ± 2 °C. A D25, D32, and D38 rebar were used for the longitudinal bars and D16 was used for the transverse bars. Table 2 shows the mechanical properties of the concrete and rebar used in this study.

| $f_{ck}$ (MPa) | W/C (%) | Slump (mm) | Air (%) | S/a (%) | Water (kg/m$^3$) | Unit Weight (kg/m$^3$) |
|----------------|---------|------------|---------|---------|------------------|-----------------------|
| 20             | 63.4    | 180 ± 30   | 4 ± 2   | 49.7    | 184              | 290                   |
| 40             | 43.7    | 180 ± 30   | 4 ± 2   | 47.1    | 170              | 389                   |
| 60             | 34.1    | 170        | 170     | 47.4    | 170              | 499                   |

Table 1. Concrete mixture proportions.

$\ f_{ck}$: design strength of concrete, C: cement, S: fine aggregate, G: coarse aggregate, a: S + G.
Table 2. Mechanical properties of the materials.

| Mechanical Properties       | Concrete (MPa) | Steel Bar (MPa) |
|-----------------------------|---------------|-----------------|
| Comp. strength              | F20           | D16             |
| Tensile strength            | F40           | D25             |
| Yield strength              | F60           | D32             |
| Young’s modulus (MPa)       | D16           | D38             |

| Comp. strength (MPa) | 22.3 | 44.7 | 59.0 | -    | -    | -    |
| Tensile strength (MPa) | 2.83 | 3.96 | 4.06 | 493  | 553  | 611  | 641  |
| Yield strength (MPa)    | -    | 340  | 380  | 439  | 447  |
| Young’s modulus (MPa)   | 24.1  | 29.7 | 36.4 | 182  | 191  | 189  | 191  |

Tensile strength was obtained from a split test.

2.2. Experimental Design

Table 3 shows the experimental design. Seven standards were designed based on compressive strength, longitudinal bar diameter, and concrete cover thickness as follows: to examine the effect of cement paste pore structure on corrosion product expansion cracking behavior, three compressive strengths were used (20, 40, and 60 MPa); to examine the effect of longitudinal bar diameter and spacing on cracking and transverse bar strain behavior, three types of longitudinal bar were used (D25, D32, and D38), which were embedded with a rebar ratio of 20, 12, and 8, respectively; and to examine the effect of cover thickness on the dispersal of corrosion products, three different cover thicknesses were used (20, 40, and 60 mm) (Table 3).

Table 3. Experimental design.

| Specimen ID | f<sub>ck</sub> (MPa) | Longitudinal Bar | Transverse Bar | Cover Depth (mm) |
|-------------|----------------------|------------------|---------------|-----------------|
| F20-D32-C40 | 20                   | 12-D32           |               |                 |
| F40-D32-C40 | 40                   | 12-D32           |               |                 |
| F60-D32-C40 | 60                   | 12-D32           |               |                 |
| F40-D38-C40 | 40                   | 8-D38            |               | 40              |
| F40-D25-C40 | 40                   | 20-D25           |               |                 |
| F40-D32-C20 | 40                   | 12-D32           |               | 20              |
| F40-D32-C60 | 40                   | 12-D32           |               | 60              |

2.3. Specimens

Figure 1 shows the RC specimens that were used in the accelerated corrosion tests. All specimens were 600 × 600 × 300 mm and were reinforced so that the amount of transverse and longitudinal rebar was similar. To examine the transverse bar strain caused by corrosion cracking in the longitudinal bar, a total of 12 strain gauges were attached to the specimens, with three devices each attached in four directions to the central transverse bar of the specimens. The longitudinal rebar protruded 50 mm from the top of each specimen to allow the attachment of the lead wire required for the corrosion tests.

Figure 1. Reinforced concrete (RC) specimens and the arrangement of the reinforcing bars.
2.4. Experimental Design

Figure 2 shows the accelerated corrosion test method used in this study. The top and bottom surfaces of the RC specimens were coated with epoxy resin after being air-cured for 28 days. After the epoxy coating had hardened, the specimens were immersed in a 3% NaCl aqueous solution. After 24 h, a current was applied and the accelerated corrosion tests begun.

As corrosion cracking progresses in RC, the amount of rebar corrosion is proportional to the concentration of chloride ions [12]. In in-situ RC columns, there are differences in the concentrations of chloride ions and the amount of corrosion in individual rebar bars because the cover thickness varies between longitudinal and transverse bars. Therefore, different current application times were used for the longitudinal and transverse rebar to simulate such differences in chloride ion concentrations. To control the current application times independently, individual parallel lead wires were connected to each rebar, and a switch was installed on the lead wires at the longitudinal bar side. To determine the chloride ion concentrations in the cover layers of the longitudinal and transverse rebar, and the current application times, Equation (1) was employed, which uses the relationship between the concentration of chlorides on the concrete surface and the ion diffusion factor for concrete according to Fick's second law of diffusion [12]:

\[ C(x, t) = C_0 \left(1 - \text{erf} \left( \frac{x}{2 \sqrt{D_{ap} t}} \right) \right) \]  

where \( C(x,t) \) is the chloride ion concentration (kg/m³) for length \( x \) (cm) and time \( t \) (years), \( C_0 \) is the surface chloride ion concentration (kg/m³), \( D_{ap} \) is the apparent diffusion coefficient for chloride ions (cm²/year) where the water cement ratio (W/C) is used in Equation (2), and \( \text{erf}(s) \) is the error function (Equation (3)) [13].

\[ \log_{10} D = -3.9(W/C)^2 + 7.2(W/C) - 2.5 \]  

\[ \text{erf}(s) = \frac{2}{\sqrt{\pi}} \int_0^s e^{-\eta^2} d\eta \]  

No current was applied to the longitudinal bar for approximately 50% of the overall test time for the standard specimen (12-Fc48) and 25% of the time for specimen 12-Fc24, which had a large concrete ion diffusion coefficient. After corrosion cracking occurred in the test specimens, a current was applied continuously to the longitudinal bar.

For the hourly integrated current amount, 2 Ω resistors were connected to wires of each rebar and the voltage between these resistors was measured hourly using a data logger. The current applied to
each rebar was then calculated based on the voltage data, and the ampere-hours of the accelerated test period (approximately three months) were determined. The transverse bar strain was measured and logged hourly. In addition, a digital microscope with a resolution of 1/100 mm was used to measure the widths of surface cracks.

3. Results and Discussion

3.1. Weight Loss of Corroded Steel Bar

The rebar that was separated from the specimens after the accelerated corrosion tests was soaked in a 10% diammonium hydrogen citrate solution for 24 h. After this, the corrosion products were completely removed from the rebar with a wire brush, the weight of which was used to determine weight loss \( W_{\text{loss}} \) caused by corrosion (mg/cm\(^2\)). The measured weight losses were compared to losses calculated using Equation (4) \( W_{\text{cal}} \). The amount of longitudinal bar corrosion was compared between the corner and intermediate bar of each specimen, and the amount of transverse bar corrosion was shown as the average of three different bars.

\[
W_{\text{cal}} = \frac{M_{\text{Fe}}i_{\text{corr}}t}{nF}
\]

where \( M_{\text{Fe}} \) is the atomic mass of iron (55.8 g/mol), \( i_{\text{corr}} \) is the corrosion current density (mA/cm\(^2\)), \( t \) is the test period (s), \( n \) is the valence of iron \( (n = 2) \), and \( F \) is Faraday’s constant (96,485 \( \degree \)C/mol).

Figure 3 shows the difference in the amount of corrosion between the corner and intermediate bars. In all specimens, the corner bars corroded more than the intermediate bars, by an average of 1.5 times. This trend was also found by Aryanto and Shinohara [5]. This occurs because chloride ions permeate in one direction in the intermediate bars but two directions in the corner bars. Thus, there is a higher rebar surface area in contact with chloride ions in the corners. As such, in cases where corners are expected to be exposed and chloride ions flow in from two directions, the amount of corrosion can be broadly estimated as 1.5 times that of intermediate bars.

Figure 4 shows the relationship between the rebar corrosion, as calculated by Equation (4), and the measured data. Assuming a linear relationship, the proportional constant of the longitudinal bar ranged from 0.27 (intermediate bar) to 0.32 (corner bar) and the observed amount of corrosion is less than half of the calculated amount. However, the proportional constant of the transverse bar was 1.5 and the calculated amounts were higher than the observed amounts. This is likely due to the fact that macro cells were formed between the transverse and longitudinal bars. Indeed, many studies [14–18] are currently being performed on macro cells. In cases where the distribution of chloride ions in a RC member is uneven, rebar anode reactions are dominant in areas of high concentrations. This leads to cathode reactions in the other rebar portions and the formation of macro cell circuits. As noted in Section 2.2, different currents were applied to the longitudinal and transverse bars to simulate the uneven internal distributions of chloride ions that occur in RC members exposed in the marine environment. As such, the chloride ion concentrations in the transverse bars with a thin concrete cover were relatively high, and anode reactions were activated. Because of this, the rate of corrosion accelerated and the measured amount of corrosion was higher than the calculated amounts based on the hourly integrated current.
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Figure 3. Comparison of weight losses between corner and intermediate bars.

Figure 4. Comparison of calculated and experimentally determined rebar weight loss.

Given the differences between the calculated and observed amounts of rebar corrosion, the calibrated corrosion amounts, which were calculated using the final cumulative amounts of current and the measured amounts of corrosion, were used as the amounts of rebar corrosion during the accelerated corrosion tests.

3.2. Corrosion-Induced Concrete Cracking

Table 4 shows the amount of transverse and longitudinal bar corrosion when the first corrosion cracking was observed at the surface of the specimens. Three transverse bars were embedded within the specimens, although all cracks occurred in the bars that were placed at the top or bottom of the
specimens. In the case of the longitudinal bars, cracking was observed only around the corner bars. As such, the cracking in association with the transverse bars is divided into ‘top’ and ‘bottom’ in Table 4.

Table 4. Corrosion rate and crack width at the time of the first cracking.

| Specimen ID | Corrosion Rate (mg/cm²) | Transverse Bar (Crack Location) |
|-------------|-------------------------|---------------------------------|
| Longitudinal Bar | | |
| F20-D32-C40       | 17                      | 14 (top)                        |
| F40-D32-C40       | 46                      | 38 (bottom)                     |
| F60-D32-C40       | 23                      | 28 (bottom)                     |
| F40-D38-C40       | 17                      | 61 (top)                        |
| F40-D25-C40       | 33                      | 49 (bottom)                     |
| F40-D32-C20       | 18                      | 18 (top)                        |
| F40-D32-C60       | 23                      | 75 (top)                        |

Corrosion cracking at the surface of the D32-Fc24-C40 and D32-Fc48-C20 specimens was first observed three days after the tests began. These specimens had the lowest compressive strength and thinnest concrete cover, respectively. In all specimens except D32-Fc48-C60, which had the thickest concrete cover, cracks occurred in the transverse bar before they occurred in the longitudinal bar. Corrosion cracking occurred first in the transverse bar (top) of D32-Fc24-C40, which was likely due to the bleeding that occurred in association with a large number of pores that formed in the hardened cement due to its high W/C ratio. According to Soylev [19], the pores expand due to bleeding during the mixing of concrete with a high water/cement ratio, and this causes the concrete density to vary according to the specimen’s height. Indeed, it was found that taller specimens tend to show evidence of accelerated rebar corrosion. On the other hand, when the compressive strength of concrete is high, the effect of bleeding is reduced. Therefore, corrosion cracking occurred in the lower transverse bars of specimen D32-Fc48-C40 and D32-Fc72-C40.

Figure 5 shows the amount of rebar corrosion at the point at which corrosion cracks reached the surface of RC specimens. This was lowest in D32-Fc24-C40 and highest in D32-Fc48-C40, and also tended to be higher in specimens with higher compressive strengths, although corrosion was less in D32-Fc72-C40 than D32-Fc48-C40 (Figure 5). Concrete with a high compressive strength has a correspondingly high tensile strength and, as such, its resistance to tensile cracking is enhanced. However, the density and volume of cement paste pores also tend to be lower in high-strength concrete [15] and, as such, the amount of corrosion product that is absorbed by pores is reduced and the corresponding expansion pressure in the surrounding concrete increases. Therefore, there is an increased possibility that corrosion cracks will form in high-strength concrete in response to a relatively low amount of corrosion. [4,10,20] Because of this, the amount of rebar corrosion at the point at which surface cracking occurred was lower in specimen D32-Fc72-C40 than in D32-Fc48-C40, despite the former having the highest compressive strength.

The amount of rebar corrosion at the point at which cracks reached the surfaces of specimens notably increased as the cover thickness increased. In Figure 6, the amount of rebar corrosion at the time of surface cracking increases by a factor of two when the cover thickness is increased by 20 mm. Zhao et al. [21] also found a linear relationship between concrete cover thickness and rebar corrosion expansion pressure, which is attributed to more strain energy being required to create cracks in concrete with a thicker cover.
products did not flow out. However, for specimens F20-D32-C40 and F40-D32-C20, which experienced relatively low amount of corrosion. Because of this, the amount of rebar corrosion at the concrete increases. Therefore, there is an expansion pressure in the surrounding concrete increases. Therefore, there is an expansion pressure, which is attributed to more strain energy being required to create cracks in concrete with a thicker cover.

Corrosion cracking occurred first in the transverse bar (top) of D32-Fc24-C40, which was likely due to chloride ion permeation and, therefore, the hourly integrated current amount is reduced. Additionally, corrosion cracking occurred on their surfaces and a significant amount of rust flowed out through these cracks.

Figure 5 shows the amount of rebar corrosion at the point at which corrosion cracks reached the surfaces of specimens. These specimens had the lowest compressive strength and the thinnest concrete cover, respectively. In all specimens except D32-Fc48-C60, which had the thickest concrete cover, cracks occurred in the transverse bar before they occurred in the longitudinal bar. Corrosion cracking occurred in the lower transverse bars of accelerated rebar corrosion. On the other hand, when the compressive strength of concrete is high, the effect of bleeding is reduced. Therefore, corrosion cracking occurred in the lower transverse bars of specimen D32-Fc48-C40 and D32-Fc72-C40.

Figure 6 shows the state of the specimen surfaces according to concrete compressive strength and cover thickness after approximately one month of accelerated corrosion testing. The same amount of voltage (10 V) was applied to all specimens, but the current was varied for each specimen and each rebar. As such, Table 5 shows the average corrosion amounts for the longitudinal and transverse bars that were calibrated using the integrated current amount.

The amount of longitudinal and transverse bar corrosion tended to be lower when compressive strength was higher and when the cover was thicker. This likely reflects improved resistance to chloride ion permeation and, therefore, the hourly integrated current amount is reduced. Additionally, efflorescence, which is an indicator of concrete deterioration, was observed on the surfaces of specimens F60-D32-C40 and F40-D32-C60, both of which showed little corrosion and from which corrosion products did not flow out. However, for specimens F20-D32-C40 and F40-D32-C20, which experienced large amounts of (calibrated) corrosion, corrosion cracking occurred on their surfaces and a significant amount of rust flowed out through these cracks.

3.3. Development of Corrosion-Induced Concrete Cracking

Figure 7 shows the state of the specimen surfaces according to concrete compressive strength and cover thickness after approximately one month of accelerated corrosion testing. The same amount of voltage (10 V) was applied to all specimens, but the current was varied for each specimen and each rebar. As such, Table 5 shows the average corrosion amounts for the longitudinal and transverse bars that were calibrated using the integrated current amount.

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Figure 7. Surface condition of RC specimens after 30 days of accelerated corrosion testing.

Table 5. Average calibrated corrosion amount for steel bar after 30 days of accelerated corrosion testing.

| Specimen ID (30 Days Passed) | Average Calibrated Corrosion Amount (mg/cm²) |
|------------------------------|---------------------------------------------|
| F20-D32-C40                  | Longitudinal Bar: 45, Transverse Bar: 150   |
| F40-D32-C40                  | 21, 61                                       |
| F60-D32-C40                  | 12, 39                                       |
| F40-D32-C20                  | 33, 170                                      |
| F40-D32-C60                  | 8, 29                                        |

Figure 8 shows the surface cracks and the permeation of corrosion products after the accelerated corrosion tests were completed. Vertical cracks formed that were divided into concrete cover cracks and core cracks according to the position of the rebar (Figure 8a). Most corrosion products were observed in the vertically formed crack surfaces. After the concrete cover and rebar were separated, a diamond cutter was used on the core-side of the concrete to view the bottom of the section (Figure 8b). It was found that no cracks had formed due to rebar corrosion or corrosion by-product permeation in the core-side of the specimens. This indicates that the by-products from the corrosion of the longitudinal and transverse bars in the central portions of the specimens (where cracking did not occur) did not permeate toward the core but flowed out toward the surface through the cracks that formed in the upper and lower transverse bars.

Figure 8. (a) Representative internal crack surfaces (b) corrosion product migration and (c) surface condition of the longitudinal bar after accelerated corrosion testing.
Figure 8c shows a comparison of corrosion occurring on the inward- and outward-facing sides of the longitudinal bar (D38) of F40-D38-C40, with the other specimens showing similar patterns. Corrosion by-products can be seen on the outward-facing side (i.e., the side of the rebar facing the concrete cover) but not on the inward-facing side (i.e., the side of the rebar facing the specimen core). Therefore, in an environment where rebar corrosion progresses relatively rapidly, such as in the ocean, the effect of rebar corrosion on the core material of RC members may be relatively small. However, reductions in shear capacity may represent a risk due to increases in the transverse bar strain or member flexural strength associated with concrete cover peeling or a reduction in the rebar cross-section.

Figure 9 shows the crack shape and maximum width for each specimen after the accelerated corrosion tests were completed. With the exception of specimen F20-D32-C60, in which corrosion cracking only occurred in association with the longitudinal bar, crack widths were greatest around the transverse bar placed at the top and bottom of the specimens. In comparison, there were few cracks around the longitudinal and transverse bar placed in the middle of the specimens. As previously noted, this was likely the result of corrosion by-products being concentrated on the surface of cracks, as corrosion products were able to flow out of the cracks formed by the corrosion of the transverse bars placed at the top and bottom of the specimens [4,20]. Longitudinal bar corrosion cracking also occurred at the corner bars in all specimens. This was likely due to the weight reduction ratio of the corner bars being 1.5 times higher than that of the intermediate bar, as observed from the rebar corrosion amounts.

3.4. Crack Widths According to the Corrosion of Transverse Bar

The longitudinal bar corroded less than the transverse bar, although some of the corrosion by-products flowed out towards the concrete surface through the transverse bar corrosion cracks that formed during the early stages of the test. Because of this, the influence of longitudinal bar corrosion on the growth of corrosion cracks was relatively small. Figure 10 shows the relationship between the amount of corrosion and crack width at the transverse bar, which is where the largest surface cracks were observed. Because the widths of transverse bar corrosion cracks were influenced by the products that occurred at the longitudinal bar, larger crack widths may be recorded than would be the case in tests employing unidirectional rebar. The crack width in all specimens showed a tendency to increase with 20–70 mg/cm² of corrosion, which is the range at which corrosion cracking occurs. However, at crack widths of >0.2 mm, the ratio of crack width increase tended to be lower because an increased amount of corrosion product could flow out through these cracks.

Figure 9. Crack patterns at the final stages of corrosion testing.
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Figure 10. Comparisons of corrosion crack behaviors over transverse bars.

The effects of concrete compressive strength are shown by comparing specimens F20-D32-C40, F40-D32-C40, and F60-D32-C40. In specimen D32-Fc24-C40, which had the lowest compressive strength, the changes in crack width were limited up to 200 mg/cm² of corrosion. This was likely due to a higher density of pores in the cement paste due to the higher water:cement ratio, into which rebar corrosion by-products diffused and were accommodated. In contrast, as seen in specimens D32-Fc48-C40 and D32-Fc72-C40, the cement paste of higher-strength concrete will have fewer pores and, as such, rebar corrosion by-products become concentrated at the crack surfaces. As a result, crack width rapidly increased in the higher strength concrete, even when the amount of corrosion was relatively low.

In the comparison between specimens with different concrete cover thicknesses (F40-D32-C20, F40-D32-C40, and F40-D32-C60), specimen D32-Fc48-C20, which had a thin cover, showed an increase in crack width at a smaller amount of corrosion. However, after cracking had occurred, corrosion by-products could easily flow out via the cracks in the concrete cover. Therefore, at 50 mg/cm² of corrosion, the increase in crack width was lower than in specimen D32-Fc48-C40, which has a thicker cover. In the specimen with the thickest cover (D32-Fc48-C60), the fracturing energy required to create surface cracks would have been higher, meaning that more corrosion was required to initiate cracking (100 mg/cm²), after which crack width increased rapidly (Figure 5). According to the previous study [22], it was investigated that the cover depth had a greater effect on the durability of RC than the crack width.

For the specimens with different longitudinal bar diameters and numbers (F40-D25-C40, F40-D32-C40, and F40-D38-C40), the relationship between rebar corrosion and crack width was less distinct. This is unsurprising considering that these specimens had the same compressive strength (Fc48), cover thickness (40 mm), and transverse bar diameter (D16), and their longitudinal bar reinforcement ratios were similar. As such, the reinforcement ratio is considered to have a greater effect on the relationship between the amount of transverse bar corrosion and crack width than differences in the longitudinal bar diameter.

3.5. Strain Behavior of Transverse Bar Resulting from the Corrosion of Longitudinal Bar

Figure 11 shows the relationship between transverse bar strain (shown as the maximum strain in each specimen) and the amount of longitudinal bar corrosion. According to previous studies [5], internal cracking can be estimated by evaluating the strain behavior of horizontal rebar, as crack width and transverse bar strain are strongly correlated. A comparison of the specimens with different compressive strengths (F20-D32-C40, F40-D32-C40, and F60-D32-C40) showed that the maximum
strain of the transverse bar tended to be higher in higher strength concrete. This was again likely a result of corrosion by-products becoming concentrated at the crack surfaces due to the relative scarcity of pores and the formation of dense micro-structures in the cement paste associated with a lower water/cement ratio. In specimen F60-D32-C40, the transverse bar strain was more than 400 \( \mu \text{m} \), which approaches 25% of the rebar yield stain. However, as the corrosion by-products could flow out through the cracks in the concrete cover, the strain did not exceed 400 \( \mu \text{m} \) by much. In contrast to our findings, strain values above 800 \( \mu \text{m} \) have been recorded in experiments where transverse bar corrosion cracking did not occur. This can be explained by the fact that, unlike in our experiments, corrosion products could not flow out through the transverse bar corrosion cracks.

![Figure 11. Relationship between the calibrated corrosion amount and transverse bar strain.](image)

For the specimens with different longitudinal bar diameters (F40-D25-C40, F40-D32-C40, and F40-D38-C40), the largest longitudinal bar diameter was associated with higher transverse bar strain values with a relatively low amount of corrosion (<10 mg/cm\(^2\)). This might reflect the occurrence of greater ring tension at similar expansion pressures due to the higher longitudinal bar diameter, which would lead to cracking even with a relatively low amount of corrosion. However, when the amount of corrosion increased, the transverse bar strain values tended to converge at approximately 300 \( \mu \text{m} \).

In the specimens with different concrete cover thicknesses (F40-D32-C20, F40-D32-C40, and F40-D32-C60), corrosion cracking occurred later in those with thicker covers. However, there is a high possibility of increased damage to concrete around a longitudinal bar in these cases as the transverse bar strain increases rapidly. Therefore, caution must be taken when evaluating durability, even when a thick concrete cover is used.

4. Conclusions

The aim of this study is to investigate the concrete corrosion cracking and transverse bar strain behavior in a reinforced concrete column under simulated marine conditions. Based on the results, the following conclusions can be drawn:

1. This study performed accelerated corrosion tests on RC column specimens with transverse and longitudinal rebar and under marine-like conditions. The specimens were set-up so that current flowed through the longitudinal and transverse bar independently, and the current application time was controlled to create an environment with an uneven chloride ion distribution representative of in-situ RC columns.
(2) The rebar was removed from the RC column specimens after the accelerated corrosion tests and the rebar weights were measured. The extent of longitudinal bar corrosion varied according to the direction of chloride ions permeation, and the corner rebar corroded 1.5 times more than the centrally embedded rebar. Macro cells also formed due to the uneven chloride distribution, and more transverse bar corrosion occurred than longitudinal bar corrosion.

(3) Cracks occurred first in the concrete around the transverse bar in the RC specimens with a low concrete compressive strength and thin cover. It was confirmed that concrete corrosion cracking and rebar strain are greatly affected by the behavior of rebar corrosion by-products and their interaction with pores in the cement paste.

(4) In RC column specimens with high-diameter longitudinal rebars or thick concrete cover, the inability of corrosion products to flow out resulted in a sharp increase in transverse bar strain, even with relatively low amounts of corrosion. Therefore, it is necessary to be cautious of reduced durability resulting from the accumulation of chlorides in RC columns that have rebar with large longitudinal bar diameters or thick concrete covers.

(5) The weight reduction of rebar after the accelerated corrosion experiments was determined and a calibrated corrosion amount was calculated, assuming that this was proportional to the ampere-hours. However, under field conditions, rebar corrosion may vary due to environmental conditions, including chloride ion concentrations, oxygen supply, and humidity. Therefore, further experiments are needed to examine the progression of rebar corrosion and to evaluate the effect of rebar corrosion on concrete cover cracking behavior.

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