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Development of an Improved Crack Propagation Model for Corrosion-Induced Cover Cracking in RC Structures

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Abstract. During the last two decades, reinforced concrete (RC) has been extensively used in most of the world as one of the common construction material due to its advantages and durability. However, RC structures exposed to marine environments are subjected to chloride attack. Chlorides from seawater penetrate into RC structures are not only causing severe corrosion problems but also affect the durability and serviceability of such structures. This paper investigates the influence of transverse reinforcement and spacing of reinforcing bars on concrete cover cracking of two-way RC slab specimens using accelerated corrosion tests. The experimental program involved the testing of four RC slab specimens and was generally designed to observe the crack width and the time of crack to propagate. An improved model for predicting the timing of crack propagation based on the experimental data was then developed.

1. Introduction

Reinforced concrete structures are normally exposed to environmental variability during their intended service life. An important phenomenon that should be considered for RC structures located adjacent to seawater is chloride-induced reinforcement corrosion [1]. Penetration of chloride is the main cause of corrosion in reinforced concrete structures located adjacent to seawater. Steel bars are naturally protected against corrosion by passivation of steel surface due to the high alkalinity of the concrete. The corrosion begins when a sufficient amount of chlorides penetrate into a concrete cover and destroy the inhibitive property by permeating the passivating layer of steel surface and this will increase the risk of corrosion.

Corrosion-induced cover cracking is an important measure for evaluating the service life of RC structures. The deterioration due to chloride-induced cover cracking leads to structural failure and reduces the service life of RC structure [2-5]. For these reasons chloride-induced cover cracking becomes a significant concern to asset owners. Structures suffering from chloride-induced cover cracking require a high frequency of site investigation, repair, maintenance and rehabilitation work as it demands large expenditure from asset owners.

Numerous studies have been conducted using non-destructive methods to study the corrosion process; however, it is impossible to accurately evaluate the corrosion process along the reinforcing bars in-situ with the concrete cover. Hence, an experimental work based on natural corrosion processes was carried out to study the empirical link between the occurrence and widths of cracks and the amount of corrosion [2]. The finding from the study supported that generally, the corrosion pattern accelerated by



imposing direct electrical current is closer to a general corrosion like the natural corrosion during the second stage of propagation. Therefore, the use of accelerated corrosion test in the laboratory has become the most common technique to speed up the corrosion-induced damage in reinforced concrete structures [3-5].

2. Research Significance

Several attempts have been made to study corrosion-induced cracking by using accelerated corrosion tests [3, 4]. However, results from these studies were not very encouraging due to limitations which have been highlighted in the study by Mullard and Stewart [3]. These limitations include the unrealistic geometry of specimens as well as limited investigation of variables such as concrete cover, bar diameter and concrete strength. The occurrence of the confinement effect on crack propagation was observed when cracks over the reinforcing bars located at the edge of specimens have a higher propagation rate than the cracks located at the internal positions and this is particularly significant for columns and other structural elements which have many edges. The Mullard and Stewart [3] study was based on experimental data for one-way RC slab specimens and did not include any transverse reinforcement in the RC slab specimens. The limitations present in these previous works provide an opportunity for pursuing research in this area by developing more realistic models for corrosion-induced damage. The first series of accelerated corrosion test, ACT (1) studied by Sabtu and Stewart [5] was successfully demonstrated that the presence of transverse reinforcement and spacing of reinforcing bars have a significant effect on the rate of crack propagation. Therefore, the second series of the accelerated corrosion test, ACT (2) was conducted to further investigate the cracking behaviour of chloride-induced cracking included crack patterns, crack width, time to first cracking, T_{1st} (the time taken by the crack to achieve 0.05 mm) and T_{ser} (the time taken by the crack to achieve a certain crack width) on the two-way RC slab specimens. Therefore, ACT (2) proposes an improved empirical model for predicting the time of crack propagation in the presence of transverse of reinforcement and spacing of reinforcing bars.

3. Experimental design for Accelerated corrosion tests

3.1. RC Slab Specimens.

The accelerated corrosion test (2) was conducted on four RC slab specimens made with the concrete compressive strength of 30 MPa and 50 MPa. The specimens used a ready mix concrete and the mixtures were prepared by the nominated company. The four specimens had an identical size of 850 mm × 850 mm × 250 mm thick. The specimens were moist-cured for 28 days to achieve the desired compressive strength. The process of inducing the corrosion along the length of the reinforcing bars is by adding the calcium chloride ($CaCl_2$) by weight of cement to the concrete mixture to simulate the corrosion process along the length of the reinforcing bars. There are ten reinforcing bars in each RC slab specimen. Five of the reinforcing bars are the main reinforcing bars and the remaining five reinforcing bars are transverse reinforcing bars. Figure 1 and Figure 2 show the arrangement of the reinforcing bars for two-way slab specimens and the experimental set-up for two-way RC slab specimens respectively. In this study, measurement of crack width was taken on the main reinforcing bars only to measure the crack width in the presence of transverse reinforcement. The crack initiation and propagation process, which is from zero crack width to crack width of 1.00 mm, was monitored using a microscope and crack width measurement card.

3.2. Crack observations of ACT (2).

The duration of the ACT (2) is 2784 hours which is approximately four months. The crack began randomly over the reinforcing bar and measurements of crack were taken at the specific location when the cracks achieved 0.05 mm.

3.3. Measured corrosion rate ACT (2).

The Gravimetric weight loss method as specified in ASTM G1-90 (1990) was performed after the completion of the accelerated corrosion tests to accurately determine the amount of corrosion at the

end of the testing. This is due to the actual corrosion rate in the accelerated corrosion test can vary from the theoretical applied current density. Previous experimental works based on the accelerated corrosion tests found that the measured corrosion rates were differed from the applied corrosion rate [3-6]. The time to cracking was corrected by multiplying the experimental time by the ratio of experimental corrosion rate/100, where $100 \mu\text{A}/\text{cm}^2$ is the applied corrosion rate. The applied corrosion rate, $100 \mu\text{A}/\text{cm}^2$ was chosen in order to be consistent with previous research works [3-5].

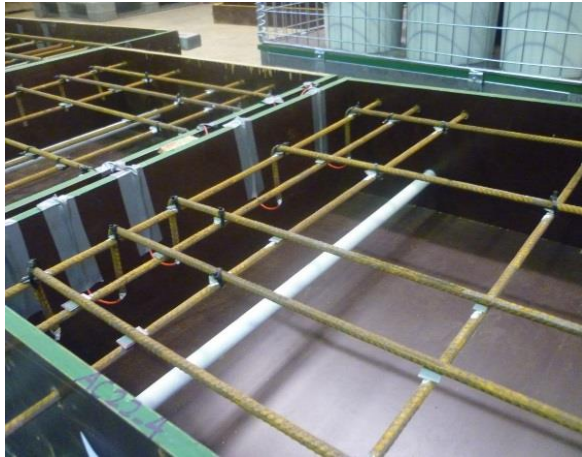


Figure 1. Arrangement of reinforcing bars for two-way RC slab specimens.

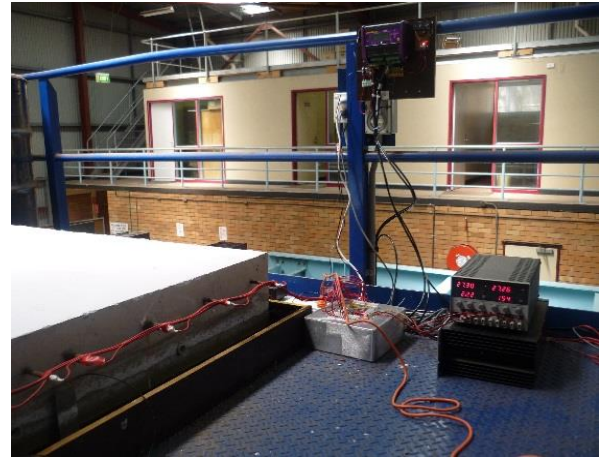


Figure 2. Experimental set-up for two-way RC slab specimens.

3.4. Crack initiation phase (T_{1st}).

The ACT (2) specimens took a longer time to achieve the first crack when compared to other studies eg., Andrade et al. (1993), Mangat and Elgarf (1999), Cabrera and Ghoddussi (1992), El-Maaddway et al. (2007) and Mullard and Stewart (2011). The ACT (2) specimens consider more variables, such as spacing of the main bars and spacing of transverse bars; therefore more factors contribute to the slower cracking process. All of the ACT (2) specimens are two-way RC slab specimens and the presence of the transverse bars will prolong the time for the crack to reach the concrete surface.

3.5. Crack propagation phase (T_{ser}).

The chosen magnitude of the current density allowed the specimens to achieve the desired crack widths within the specific time frame of approximately four months. By applying an electrical current to reinforcing bars through a current regulator, a constant value of current was supplied to each reinforcing bar. Cracks were observed through a microscope with a graduated scale of 0.02 mm increments. Based on the first observation, immediately after the visible cracks appeared, the cracks were found to begin at the external bar and were followed by the internal bars. The cracks were also found to be less in the intersection area between the main and transverse bars. With more intersection of reinforcing bars, this can reduce the size of crack and can even slower or prevent crack propagation.

3.6. Data observation.

Data points were plotted and appear to follow a straight line. Most of the data points are taken manually using a microscope with an accuracy of 0.02 mm and a crack width measurement card. The complexity of the two-way RC slab specimens with additional variables included in this test, such as spacing of the main bar, the spacing of the transverse bar, concrete cover, diameter bar and tensile strength, were found to contribute to the variation of the data. However, it would be reasonable to conclude that there is a linear relationship between crack width and time; as time increases, the crack width increases.

3.7. Calculating the rate of crack propagation, r_{crack} for internal bars.

In this study, r_{crack} was calculated based on the slope of the line of best fit for each individual reinforcing bar. r_{crack} was calculated by using the Least square method.

3.8. Effect of transverse reinforcement on concrete cover cracking.

By conducting the ACT tests on two-way RC slab specimens, the effect of confinement on RC structures is able to be studied in detail. It was found that the confinement effect on two-way RC slab specimens is due to two factors. As the confinement effect can reduce the rate of crack, the first factor that contributes to the slower cracking is the existence of reinforcing bars on either side. This condition happened to the internal bars. The second factor that can reduce the rate of crack, is the presence of transverse bars on top of the main bars that act as a confinement to the main bars. Figure 3 supports the confinement effect by comparing the one-way and the two-way RC slab specimens and clearly, the two-way RC slab specimens appears to have significantly reduced rates of crack propagation when compared to one-way RC slab specimens.

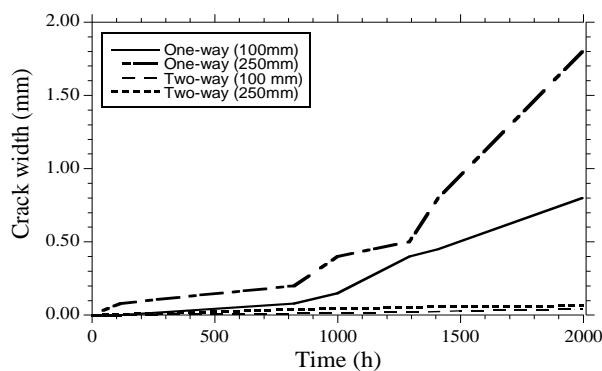


Figure 3. Comparison of one-way (ACT (1)) and two-way (ACT (2)) RC slab specimens [5].

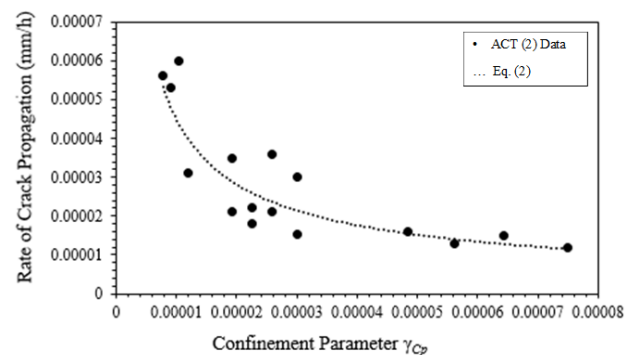


Figure 4. Crack propagation as a function of concrete confinement parameter γ_{cp} .

3.9. Effect of reinforcement spacing on concrete cover cracking.

Reinforcement spacing or distance between bars was observed to have an important effect on the cracking process. From observation made throughout the experimental work, the crack propagation is higher when the spacing is larger and the crack propagation is lower when the spacing is smaller. By increasing the spacing or by using the larger spacing, in this case 250 mm, the bond between concrete and steel bar is decreasing and the rate of crack propagation will increase. However, by decreasing the spacing or by using smaller spacing, in this case, 100 mm spacing, the bond between concrete and the steel bar is adequate and stronger hence, reducing the rate of crack propagation.

4. Crack propagation model based on two-way RC slab specimens

A predictive model for crack propagation developed by Mullard and Stewart [3] incorporates cover, diameter bar and concrete tensile strength. The model was found to be robust, having reasonable agreement between experimental and predicted time to crack propagation, however the study was based on the one-way RC slab specimens which excludes the presence of transverse and spacing of reinforcing bars. Therefore, the current study improved the Mullard and Stewart [3] model by proposing a new normalised parameter, “concrete confinement parameter” which incorporates spacing of main and transverse reinforcing bar. Concrete confinement parameter (γ_{cp}) defined as

$$\lambda_{cp} = \frac{C}{Df_t} \times \frac{1}{S_M S_{TR}} \quad (1)$$

where C is the concrete cover in mm, D is the reinforcing bar diameter in mm, and f_t is the concrete tensile strength in MPa, S_M is the spacing of the reinforcing bar in mm and S_{TR} is the spacing of

transverse reinforcing bar in mm. Figure 4 shows the influence of the concrete confinement parameter on crack propagation rate in mm/h. Data from each reinforcing bar were plotted independently, therefore, all the data points represent a single bar. The line of best fit for all the data points from internal bars is

$$r_{crack} = 2.0e^{-8\gamma_{cp}^{-0.674}} \quad 1 \times 10^{-5} \leq \gamma_{cp} \leq 8 \times 10^{-5} \quad (2)$$

where r_{crack} is the crack propagation rate in mm/h and γ_{cp} is the concrete confinement parameter. The crack propagation rate was found to decrease as the concrete confinement parameter is increased. The findings of the current study are consistent with other research which found that the concrete confinement such as transverse reinforcement, stirrups or other type of orthogonal reinforcement could reduce the rate of crack propagation.

5. Conclusions

This paper presented data obtained from the accelerated corrosion test conducted on two-way RC slab specimens. Clearly, the presence of transverse reinforcing bar reduces corrosion-induced cover cracking by a significant extent. The two-way RC slab specimens appear to have significantly reduced rates of crack propagation when compared to one-way RC slab. The data of the two-way RC slab specimens was used to develop an improved empirical crack propagation model is not only considered the effect of concrete cover, concrete compressive strength and bar diameter, the new model also included the influence of transverse reinforcement and spacing of reinforcing bars which then refers as the ‘concrete confinement parameter’.

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7. References

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