Effects of sustained loading and pre-existing cracks on corrosion behavior of reinforced concrete slabs

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Abstract

An experimental study was conducted to characterize the structural behavior of reinforced concrete (RC) slabs subjected to accelerated corrosion. Eighteen steel reinforced concrete slab specimens were cast for testing. Transverse cracks were formed in some of the test specimens by applying controlled amount of static loading. Sustained loading was maintained during the entire time of the corrosion process. Three different test conditions were induced: (i) specimens without pre-existing cracks and sustained loading, (ii) specimens with pre-existing cracks but no sustained loading, and (iii) specimens with pre-existing cracks and sustained loading. The crack pattern and crack widths were recorded for each specimen. The final mass loss and the ultimate load carrying capacity after achieving the desired corrosion level were also determined. The results highlight that un-corroded steel reinforced concrete slabs exhibit several bending-induced cracks transverse to the steel reinforcement with a ductile failure mode. Corroded specimens exhibit fewer but wider transverse cracks under bending loads and the failure mode is a brittle failure mode. Pre-cracked initial condition and sustained loading during the corrosion process have noticeable influence on the corrosion behavior of RC slabs. These conditions cause a larger reduction in ultimate load carrying capacity of such slabs compared to slabs subjected to corrosion when there are no cracks and the loading is not sustained in nature during the corrosion process. Ignoring this deleterious performance can lead to unsafe condition assessment.

1. Introduction

Corrosion of steel reinforcement embedded in concrete is a worldwide problem that affects numerous reinforced concrete (RC) structures. While corrosion has always been problematic since the beginning of mining and refinery of metals, corrosion in RC structures only gained research attention during the 1960s and 1970s, following widespread use of de-icing salts on highways within the United States and a construction boom in the Arabian Gulf. Since then, research has been undertaken worldwide to address corrosion issues. Theoretical models have also been developed and calibrated with experimental results to predict the behavior and service life of concrete structures with corroding steel bars [1-10]. Malumbela et al. [11-13] performed a critical review and experimental work with beam specimens and found that while in-service, RC structures normally corrode under sustained loading [14]. The majority of articles on corrosion have focused on structures that corroded in the absence of sustained loading [1-3, 5-8, 15-36]. Since 1999, some researchers have examined sustained loading effects [6, 17, 18, 22, 25, 30, 32, 37]; however, none of these studies focused on corrosion during the service life of the structural components of RC structures having pre-existing surface cracks.

Cracks in reinforced concrete elements are a common occurrence due to the low tensile strength of concrete. Cracking that occurs in reinforced concrete structures at service load (i.e., during the normal use of the structures) cannot generally be avoided. Among the studies published after 1999, only a study by Yoon (2000) [32] considered preloaded test specimens where cracks existed prior to accelerated corrosion testing, but the test program in this study did not use a sustained loading condition. Sustained service loads on structures, surface cracks, or a combination of both conditions can affect the rate of corrosion, the residual moment strength of corroded RC members, and the effectiveness of repairs. Experiments conducted and theoretical

models developed without the consideration of pre-existing cracks and sustained loading conditions do not capture the true behavior of in-service RC structural elements that are subjected to corrosion and can lead to unsafe and non-conservative condition assessment.

The primary objective of this study is to highlight that two important factors (i) pre-existing cracks and (ii) sustained loading need to be considered in corrosion performance evaluation and to determine the influence of these two factors on the mass loss of the reinforcement as well as the crack expansion ratio and the patterns of cracks on the surface of the concrete specimens. To address these factors, concrete slab specimens having steel reinforcing bars were prepared. These specimens were carefully loaded in static loading to introduce the first visible transverse crack and then unloaded. Each specimen with this prior transverse cracking was set up in a corrosion cell, and sustained loading was applied along with an external induced current over the entire duration to accelerate the corrosion process. The electrical current applied in the accelerated corrosion test was based on a desired theoretical mass loss design levels (10%) calculated from Faraday's law. The experimental results were used to compare the theoretical calculations of metal loss and the actual measured mass loss. The ultimate load carrying capacity of the corroded specimens with various experimental conditions (different wetting and drying cycles and sustained loading levels) were measured and compared. After bending test, the different failure modes of corroded and un-corroded specimens are also compared. The mechanisms regarding the effect of the transverse cracks were developed based on the observations of this experimental program to explain the different characteristics of the longitudinal crack expansion ratio of specimens corroded under different test conditions (i.e., with or without pre-cracking and sustained loading).

2. Motivation of experiment work related to corrosion of slab specimens

Few corrosion-related experimental studies [32, 33] on slab specimens are reported in the literature. The motivations for conducting accelerated corrosion experiments on slab specimens with and without pre-existing cracks and sustained loading is as follows:

- 1) Pre-cracked condition has not been considered by researchers in earlier studies for RC slab elements. Consequently, there is a need to study the effects of this condition.
- 2) Sustained loading (primarily from dead loads and permanent parts of live loads) exists during the service of continuous span structural slab bridge decks exposed to de-icing salts. Exposure of the deck slabs to these salts can be simulated in an accelerated corrosion test.
- 3) The wetting–drying cycle is an important experimental condition for accelerated corrosion tests employed to simulate bridges subjected to a corrosive environment due to the use of de-icing salt, since de-icing salt is not applied continuously during the winter season.
- 4) Structural slabs do not have shear reinforcement (stirrups) around the main tensile reinforcing bars and therefore behave differently from beams. The failure modes of corroded RC slabs need to be assessed and compared with those for un-corroded RC slabs.

3. Test setup

All specimens were cast using concrete (ASTM Type I Portland cement) with a cement content of 335 kg/m³ (564 lb/yd³), a coarse aggregate to fine aggregate ratio of 1.3, and a water-to-cement ratio (w/c) of 0.44. A total of 18 slab specimens with dimensions of 305 × 76 × 711 mm (12 × 3 × 28 in) were cast in four batches. For each batch of concrete, several cylinders that were 102 mm (4 in) in diameter and 204 mm (8 in) in length were also cast to determine the compressive strength of each batch of concrete. The reinforcement configuration of the test specimens is shown in Fig. 1. Each test specimen was loaded from the bottom upward at the mid-span and supported at the ends from the top. This loading configuration was designed

to cause tension on the top surface of the test specimens and compression at the bottom. The test specimens were placed in a curing room for 28 days approximately 24 hours after casting. The curing room maintained the required humidity and temperature during the entire curing period.

After curing, three un-corroded specimens were subjected to a three-point bending test to determine the ultimate load carrying capacity. The flexural strength is expressed in terms of the critical load when the specimen reached the failure point. The failure loads recorded from the structural load tests for three un-corroded specimens were 42 kN, 36 kN and 42 kN (9.45 kips, 8.19 kips and 9.43 kips) with the average of 40 kN (9.02 kips). Fig. 2 shows the test setup and the failure mode of an un-corroded specimen, with typical flexural cracks.

4. Specimen groups and their designation

Concrete cylinders were used to determine the compressive strength of the concrete used for making the test specimens. Test results for eighteen test slab specimens are reported in this paper. These specimens were cast in four batches on different days but with same mix proportions and target 28-day strength. The average compressive strength for each set of specimens was determined on the first day of the start of the corrosion test for the set. Therefore, the average compressive strength for different sets of specimens was different from batch to batch, despite the use of the same mixture proportions, same materials, and a similar casting procedure. The range of the average compressive strengths varied from a minimum of 38 Mpa (5484 psi) to a maximum of 58 Mpa (8266 psi). For the #4 (12.7 mm) Grade 60 reinforcing bars used in the test program, the specified yield strength was 414 Mpa (60 ksi).

The remaining 18 specimens of the program were divided into two sets (Set A and Set B), where each set is further divided into three different groups, representing the conditions of no pre-existing cracks and sustained loading (Group 1), specimens with pre-existing cracks (Group

2), and both pre-existing cracks and sustained loading (Group 3). For specimens in Set A, the theoretical corrosion level based on Faraday's law is 10% of steel mass loss, and the applied sustained loading level is 12% of the capacity of the corresponding un-corroded specimen. For specimens in Set B, the theoretical corrosion level based on Faraday's law is 10% of steel mass loss, and the applied sustained loading level is 60% of the capacity of the un-corroded specimens. A 12% sustained load level was selected as the lower load level based on a study by Malumbela et al. [37]. The higher load level of 60% was based on the consideration (e.g., ACI 318-14 [38]) that the total service load is likely to be about 60% of the factored load. The detailed description of the different specimen groups based on the pre-existing cracks and sustained loading conditions is shown in Table 1. In addition, specimens in Set A were subjected to two days of wetting and no drying time, while specimens in Set B were subjected to two days of wetting and one day of drying. The total duration of the experiments for specimens in Set A was 14 days (only wetting time) and the total duration for specimens in Set B was 21 days (14 days of wetting and 7 days of drying). The accelerated corrosion process only occurred during the wetting time, so the electrical current used in this program for the two sets to reach the theoretical corrosion level (10%) was exactly the same.

5. Procedure for introducing pre-cracked condition

A three-point loading configuration was used to induce bending moments with one load at the mid-span and two supports at the end of each specimen. The distance between the two end supports of the test specimens was 610 mm (24 in). Load was applied on a universal testing machine to introduce cracks in the test specimens. Among the theoretical equations for crack propagation, ACI 318R-95 [39] and Oh and Kang's [40] equations were reported to be better for predicting surface crack width, as compared to the experimental values of crack width [41, 42].

Therefore, these two equations were used in the test program to predict the approximate load that would be needed to produce the first crack in the test specimen without causing any damage to the test specimens prior to the initiation of the corrosion process. The expression of ACI 318R-95, and the expression of Oh and Kang are shown in Eqs (1) and (2), respectively.

$$ACI: \quad W_{max} = 0.011\beta f_s^3 \sqrt{d_c A_0} \quad (1)$$

$$Oh \text{ and } Kang: \quad W_{max} = \phi a_0 (\epsilon_s - 0.0002) \beta \quad (2)$$

where W_{max} is the maximum crack width; β is the ratio of the distance between neutral axis and extreme tension face to the distance between the neutral axis and the centroid of reinforcing steel; f_s is the stress in the tension reinforcement calculated on the basis of a cracked section; d_c is the distance measured from the centroid of tensile steel to the edge of the section on tension side; A_0 is the concrete area surrounding each reinforcing bar; ϕ is the diameter of tensile reinforcing bar; and a_0 is the coefficient that is a function of certain variable as defined in the reference; and $\epsilon_s = \frac{f_s}{E_s}$. A more detailed explanation of all items in these two equations can be found in ACI code [39] and Oh and Kang [40].

Typically, the minimum width of visible cracks under normal conditions is approximately 0.13 mm (0.005 in). If the point load is removed, the bending crack will usually close and the crack will not be visible. Table 2 shows the point load value when the first visible bending crack appeared on the tension surface of the test specimens. The theoretical value is approximately 13.3 kN (3000 lb), which was calculated based on the theoretical equations. The load applied to the slabs in the testing program to create the first crack was between 13.3 – 17.8 kN (3000 – 4000 lb), which means the pre-cracked load used in this testing program did not induce the tensile reinforcements to yield prior to corrosion testing.

6. Accelerated corrosion procedure

6.1. Theoretical determination of electrical current

Faraday's law was used to calculate the theoretical steel mass loss of the reinforcement embedded in each specimen when subjected to accelerated corrosion using impressed current.

The relation between the steel loss and current flow is as follows:

$$\Delta m = Mit/zF \quad (3)$$

where Δm is the mass of steel consumed in grams; M is the atomic weight of the metal (56 grams or 0.1232 lb for Fe); I is the current (amperes); t is time (seconds); z is the ionic charge (which is equal to 2); and F is Faraday's constant (96,500 amperes/seconds).

In this study, the total corrosion duration of 14 days (1,209,600 seconds) was used. The applied current value determined from Faraday's law that is required to reach the theoretical corrosion level in two weeks is shown in Table 3. As mentioned in Section 4, specimens of two sets in this program had the same wetting time (14 days), so the electrical current value used to induce accelerated corrosion was the same for all specimens. After reaching the desired level of corrosion, the specimens were subjected to a three-point bending test to determine the residual ultimate load carrying capacity.

6.2. Corrosion test setup

Fig. 3 shows the schematic representation of the accelerated corrosion cell. The DC power supply was used to generate electrical current to facilitate accelerated corrosion, where a stainless steel plate is submerged in the salt solution and connected to the cathode of the DC power supply and the reinforcement embedded in the concrete is connected to the anode of the DC power supply. The sustained loading was applied from the bottom of the test specimen. Photos of test specimens during the corrosion process with and without sustained loading are shown in Fig. 4a and Fig. 4b, respectively. The test slab is partially exposed to 5% NaCl solution

to allow for chloride ions to permeate the concrete cover and reach the reinforcement embedded in concrete. The sustained load was monitored by a load cell, while the crack widths on the surface of the specimen were measured using a micrometer.

7. Test results and discussion

7.1. Capacity and metal loss after accelerated corrosion

After the specimens were subjected to the accelerated corrosion within the specified corrosion period for different test conditions, each specimen was removed from the frame and was subjected to bending test to determine the residual ultimate load carrying capacity. For comparison purposes, the crack patterns and load–deflection curves for un-corroded specimens and corroded specimens at the collapse load are shown in Fig. 5a and Fig. 5b, respectively. By comparing the crack patterns, it was observed that the failure modes were different: the un-corroded slab specimen exhibited several flexural cracks at collapse load indicating ductile failure mode, while the corroded slab specimen only exhibited one wide crack running in the transverse direction indicating a brittle failure mode. Fig. 5b shows the load-deflection curves for the corroded specimens and un-corroded specimens. The corroded specimens were observed to suffer larger deflections at smaller loads than those for the corresponding un-corroded specimens.

The ultimate load carrying capacity for the corroded specimens of different groups in different sets is listed in Table 4. The ultimate load carrying capacity reduction values listed in Table 4 were calculated using the following equation:

$$\text{Ultimate loading carrying capacity reduction} = \left(1 - \frac{\text{Ultimate load of corroded specimens}}{\text{Ultimate load of un-corroded specimens}}\right) \times 100 \quad (4)$$

In order to evaluate the steel mass loss variation along the length of the rebar, the specimen surface that was exposed to the salt solution was divided into ten segments of 50.8 mm (2 in) in

length, as shown in Fig. 6a. The corroded reinforcement obtained by removing concrete indicated that the corrosion products were concentrated on the top surface of the bars (i.e., the surface closer to the slab face that was exposed to the salt solution). From the visual comparison of the corrosion concentration for specimens with different corrosion conditions, it was found that specimens corroded with pre-existing cracks and sustained loading exhibit larger amounts of the corrosion product.

After removal and cleaning of the corrosion products from corroded reinforcement using a specially formulated acid solution, the reinforcement were cut into small coupons that were 50.8 mm (2 in) in length, corresponding to the division of the specimen surface, as shown in Fig. 6b and Fig. 6c. The steel mass loss of reinforcement in the coupons (Fig. 6c) was determined by the following equation:

$$\text{Steel mass loss} = \left(1 - \frac{\text{residual weight of steel coupon}}{\text{original weight of steel coupon}}\right) \times 100 \quad (5)$$

The variation of steel mass loss along the reinforcement length is shown Fig. 7a and Fig. 7b for Set A and Set B, respectively. It can be observed from Fig. 7 that the general trend of steel mass loss along the direction of the reinforcement can be represented by a parabola with a maximum vertex close to the middle of the span of the specimens. However, the specimens corroded without pre-existing cracks and sustained loading do not show this type of variation. It was also observed that the steel mass loss extended to the full length of the reinforcement, even beyond the ends of the exposure region. As shown in Fig. 7, the level of steel mass loss and its variation along the longitudinal direction of the slab appears to relate to the specimen conditions. The specimens with pre-existing cracks subjected to sustained loading during the accelerated corrosion process exhibited more severe steel mass loss. For the specimens corroded without pre-existing cracks and sustained loading in Group 1, the mass loss along the longitudinal direction

of the reinforcement is quite uniform. Table 4 shows the larger mass loss by comparing the specimens in the same group in Set B (10% theoretical corrosion level and with two days of wetting and one day of drying) than the mass loss detected from Set A (10% theoretical corrosion level and without drying time). The most likely reason why slabs with longer drying cycles exhibit a larger mass loss of steel is that the longer drying cycles could have allowed for more natural corrosion to occur because of the extended time required to reach the desired time of electrolysis [43].

7.2. Observation of Corrosion cracks

One telltale sign of corrosion of reinforcement in concrete slabs/beams is the development of surface cracks [42]. A commonly accepted explanation is that a higher corrosion level induces a larger amount of corrosion products, which in turn causes a larger crack width as a result of volume expansion of the corrosion products. However, few researchers have paid attention to the crack patterns developed due to corrosion for slabs with pre-existing cracks and sustained loading maintained during the corrosion process. In this study, it was a significant determination that the development of both longitudinal cracks and transverse cracks for the specimens under these combined test conditions is far more severe than when these two conditions did not exist. Because the appearance of transverse cracks under the loading and corrosion conditions is random, only the maximum transverse crack widths of test specimens were monitored in this test program. The maximum transverse crack widths for specimens in Set A and Set B are shown in Fig. 8a and Fig. 8b, respectively. The specimens in Group 3 (specimens with both pre-existing cracks and sustained loading) exhibit wider transverse cracks than those in Group 2 (specimens with only pre-existing cracks). Clearly, the sustained loading in Group 3 contributed to the larger transverse crack widths.

The maximum longitudinal crack widths of all specimens were also measured and recorded. Based on a comparison of the crack widths observed in Set A (10% theoretical corrosion level without drying time) with those in Set B (10% theoretical corrosion level with two days of wetting and one day of drying), the following observations can be made:

- 1) A longer accelerated corrosion time leads to larger crack widths, which can be seen in Figs. 8 and 9 for both longitudinal and transverse cracks. The difference in wetting and drying cycles between Set A and Set B does not significantly affect the crack expansion for both longitudinal and transverse cracks when compared to the final crack widths shown in Fig. 8 and Fig. 9.
- 2) In Fig. 9a, it can be noticed that specimens in Group 3 (those with both pre-existing cracks and sustained loading) of Set A (10% theoretical corrosion level and without drying time) initially have the maximum longitudinal crack width. This could be attributed to the fact that the pre-existing cracks and sustained loading leads to the development of transverse cracks, which allow the chloride ions from the salt solution to penetrate into the concrete and reach the surface of reinforcements more rapidly. Therefore, the corrosion reaction occurs at an earlier stage in the specimens of Group 3 than that in the other two groups. A similar phenomenon of longitudinal crack width expansion was detected in the specimens in Set B, as shown in Fig. 9b. However, in the later stage, the longitudinal cracks of specimens in Group 1 grew faster than other two groups.
- 3) At the end of the experiment, the widest longitudinal cracks observed in specimens in Group 1 (specimens without both pre-existing cracks and sustained loading) were similar to or larger than those in the Groups 2 or 3. This trend changed at approximately 11 days (7.8% theoretical corrosion level) for Set A and at 18 days (8.6% theoretical corrosion level) for Set

B. This reversal of trend for the longitudinal crack width in the early stage of corrosion compared to later stages may be explained by the hypothesis that the transverse cracks appearing in Group 2 (specimens with only pre-existing cracks) and Group 3 (specimens with both pre-existing cracks and sustained loading) provided additional space for the corrosion products to fill and grow, thus releasing the stresses caused by the volume expansion of the corrosion products. Therefore, transverse cracking could reduce the increased rate of stresses caused by corrosion products.

- 4) Specimens in Group 2 (specimens with only pre-existing cracks) showed a similar crack width as the specimens in Group 3 (specimens with both pre-existing cracks and sustained loading). It appears that the net effect of sustained loading in creating transverse cracks on the longitudinal crack expansion is the combination of two contradictory mechanisms: accelerated corrosion rate due to faster ingress of chloride ions and reduced stresses due to the opening of transverse cracks.

7.3. Practical Recommendations from This Study

Several earlier studies on corrosion of steel reinforced concrete flexural members reported by others did not consider the combined effects of pre-existing cracks and sustained loading on corrosion damage occurring in such members. This study revealed that corrosion degradation is significantly more severe when pre-existing cracks and sustained loading are prevalent in a structure which is in service in a corrosive environment. In most reinforced concrete members, the self-weight is sustained in nature, and cracking is inevitable under its own self-weight. Therefore it is not conservative or safe to ignore the effects of pre-existing cracks and/or sustained loading when practical structures are evaluated for corrosion damage.

8. Conclusions

Based on the experimental results that were obtained in this study, the following conclusions were drawn:

1. Corroded RC slab specimens subjected to three-point bending loads have different failure modes than un-corroded specimens. The un-corroded specimens exhibit flexural failure with several bending-induced cracks transverse to the steel reinforcement which is a ductile mode of failure. However, corroded specimens exhibit fewer but wider transverse cracks under bending loads leading to a brittle failure mode.
2. Maximum mass loss of steel bars was found to be close to the middle of the span length of test specimens for specimens with pre-existing cracks.
3. Specimens with pre-existing cracks and sustained loading during the accelerated corrosion process exhibited the most severe level of corrosion-induced damage in terms of the amount of steel mass loss and the reduction in ultimate load carrying capacity.
4. In the experimental program, the pre-existing cracks and sustained loading conditions have been shown to exert an influence on both the crack width expansion rate and crack pattern. The pre-existing cracks combined with sustained loading were found to induce transverse cracks with greater widths. The development of transverse cracking was further shown to affect longitudinal crack development. At earlier stages of the corrosion, the transverse cracks allow a faster corrosion rate, resulting in a faster expansion rate in longitudinal corrosion cracks. At later stages of the corrosion, the large transverse cracks provide space and pathways for the corrosion products to fill, grow and/or escape, thus releasing the stresses, which in turn reduces the rate of longitudinal crack expansion. Therefore, the level of invisible corrosion of the steel embedded within reinforced concrete slabs cannot be

realistically assessed purely based on the measurements of crack widths or inspections of cracks on the surface.

5. The wetting and drying cycles incorporated in the corrosion process will have an effect on the steel mass loss, but they did not cause a large difference in the longitudinal and transverse crack widths in this study.

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Table 1 Details of test specimens

Set A		
Group Name	Specimen label	Description
Group 1	N-1	No pre-cracked or sustained loading applied during accelerated corrosion test
	N-2	
	N-3	
Group 2	P-1	Pre-cracked before applying accelerated corrosion current
	P-2	
	P-3	
Group 3	PS-1	Pre-cracked and sustained loading during corrosion process
	PS-2	
	PS-3	
Subject to wetting and no drying time		
Set B		
Group Name	Specimen label	Description
Group 1	N-1	No pre-cracked or sustained loading applied during accelerated corrosion test
	N-2	
	N-3	
Group 2	P-1	Pre-cracked before applying accelerated corrosion current
	P-2	
	P-3	
Group 3	PS-1	Pre-cracked and sustained loading during corrosion process
	PS-2	
	PS-3	
Subject to two days wetting and one day drying		

Note: N – No pre-cracked and sustained loading; P – Pre-cracked condition; PS – Pre-cracked and sustained loading condition

Table 2 First cracking load from tests and the theoretical cracking load

Specimen number	Set A	Set B	ACI	Oh and Kang [33]
P-1	15 <i>kN</i> (3,300 <i>lb</i>)	14 <i>kN</i> (3,100 <i>lb</i>)		
P-2	16 <i>kN</i> (3,500 <i>lb</i>)	14 <i>kN</i> (3,100 <i>lb</i>)		
P-3	14 <i>kN</i> (3,200 <i>lb</i>)	13 <i>kN</i> (3,000 <i>lb</i>)		
PS-1	15 <i>kN</i> (3,400 <i>lb</i>)	16 <i>kN</i> (3,500 <i>lb</i>)	14 <i>kN</i> (3,158 <i>lb</i>)	13 <i>kN</i> (3,039 <i>lb</i>)
PS-2	15 <i>kN</i> (3,500 <i>lb</i>)	13 <i>kN</i> (3,000 <i>lb</i>)		
PS-3	13 <i>kN</i> (3,000 <i>lb</i>)	16 <i>kN</i> (3,500 <i>lb</i>)		

Table 3 Accelerated current value for theoretical steel mass loss levels

Rebar number	Theoretical mass loss	Corrosion length	Original mass	Mass loss	Time (seconds)	Current value (amperes)
#4	10%	1,118 <i>mm</i> (44 <i>in</i>)	1,100 <i>grams</i> (2.45 <i>lb</i>)	111 <i>grams</i> (0.245 <i>lb</i>)	1,209,600	0.32

Note: The mass loss is represented by the percentage of the original steel weight.

Table 4 Mass loss and ultimate load carrying capacity for corroded specimens

Experiment Set	Experiment Group	Number of the specimens	Mass loss		Ultimate load carrying capacity reduction
			Average mass loss	Maximum mass loss	
Set A	Group 1	3	5.2%	6.1%	17%
Set B	Group 1	3	7.7%	8.8%	19%
Set A	Group 2	3	7.6%	11.2%	21%
Set B	Group 2	3	9.5%	14.8%	24%
Set A	Group 3	3	9.7%	12.6%	23%
Set B	Group 3	3	12.2%	17.6%	27%

Note: Moment capacity reduction is represented by the percentage of un-corroded specimens shown in Table 1.

Fig. 1 Reinforcement configuration within test slabs (mm)

(a) Test setup

(b) Typical test specimen after bending failure

Fig. 2 Flexural test for un-corroded slab specimen

Fig. 3 Accelerated corrosion test setup, the dimensions are in mm

(a) Corrosion setup for Group 1 and Group 2

(b) Corrosion setup for Group 3

Fig. 4 Accelerated corrosion test setup: (a) without pre-cracked and sustained loading; (b) with pre-cracked and sustained loading

(a) The side surface cracks comparison between un-corroded and corroded specimens

(b) Load-deflection graph for un-corroded and corroded specimens

Fig. 5 Crack pattern and load-deflection behavior for specimens without corrosion and after corrosion

(a) Division of the surface of the specimen exposed to the salt solution

(b) Corroded reinforcement

(c) Steel coupons after the removal of the corrosion products

Fig. 6 Steel coupons of corroded bars and division of the surface of the specimen

(a) Specimens of Set A

(b) Specimens of Set B

Note: Group 1: No pre-crack, and no sustained loading

Group 2: Pre-cracked, but no sustained loading

Group 3: Pre-cracked with sustained loading level 12% or 60% of the un-corroded specimen capacity

Set A: 10% theoretical corrosion level with Group 3 and 12% sustained loading

Set B: 10% theoretical corrosion level with Group 3 and 60% sustained loading

Fig. 7 Variation of mass loss of steel along the specimens within the tank

(a) Maximum transverse crack width for Set A

(b) Maximum Transverse crack width for Set B

Note: Group 1: No pre-crack, and no sustained loading

Group 2: Pre-cracked, but no sustained loading

Group 3: Pre-cracked with sustained loading level 12% or 60% of the un-corroded specimen capacity

Set A: 10% theoretical corrosion level with Group 3 and 12% sustained loading

Set B: 10% theoretical corrosion level with Group 3 and 60% sustained loading

Fig. 8 Transverse crack width results

(a) Maximum longitudinal crack width for Set A

(b) Maximum longitudinal crack width for Set B

Note: Group 1: No pre-crack, and no sustained loading

Group 2: Pre-cracked, but no sustained loading

Group 3: Pre-cracked with sustained loading level 12% or 60% of the un-corroded specimen capacity

Set A: 10% theoretical corrosion level with Group 3 and 12% sustained loading

Set B: 10% theoretical corrosion level with Group 3 and 60% sustained loading

Fig. 9 Longitudinal Crack width results