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Prediction of the Residual Flexural Capacities of Deteriorated and Retrofitted Reinforced Concrete Members with Different Corrosion Conditions

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Abstract: The structural performance of reinforced concrete (RC) members are adversely affected by reinforcement corrosion. Generally, corrosion is intensified and further corrosion occurs once corrosion appears on the concrete surface and it reduces the service life of RC structures. Several RC beams were cast and test specimens were subjected to the 'electrochemical corrosion technique' to corrode the embedded reinforcement bars of the specimens. A copper bar was connected to a negative terminal (cathode) and embedded reinforcement bars of the specimens were connected to a positive terminal (anode). Specimens were tested under static load after they were corroded for different corrosion conditions. Results of the study reveal that the flexural capacity of corroded test samples was linearly reduced as the severity of the corrosion condition increased. Xypex layer was applied on the corroded samples as an easily applicable retrofitting method. Specimens were tested under static load to obtain the ultimate load values. Results were compared with the ultimate load values of non-retrofitted beams to evaluate the efficiency of the retrofitting method. Observations indicate a considerable amount of percentage flexural capacity increment for the corroded retrofitted samples compared to the similarly corroded non-retrofitted samples.

Keywords: Corrosion, Chloride ion, Flexural capacity, Reinforced concrete, Retrofitting

1. Introduction

Physical infrastructure in a large part of the world has been constructed using reinforced concrete because of its cost-effectiveness. Reinforced Concrete (RC) has reasonable fire resistance and weather resistance ability while it possesses a long service life with low maintenance cost. Steel and concrete of RC deteriorate with time and highly affects RC performance. Durable collaboration between steel and concrete is crucial for safe and serviceable functioning. Codes for RC structures have been improved by many countries to prevent such corrosion problems in new concrete structures that are exposed to de-icing salts or other aggressive environments. To ensure a sufficient service life of a structure, minimum clear cover to the rebar and maximum water/ cement ratio should be decided depending on the environmental conditions. But, under extremely aggressive environments, additional protection measures are required to ensure sufficiently long service life. The surface of the corroding steel serves as a mixed electrode that is a composite of anodes and cathodes electrically connected through the body of steel itself, upon which coupled anodic and cathodic reactions take place, where pore water in the concrete functions as an aqueous medium. Generally, the physical and chemical nature of concrete protects the steel bars of RC members. But concrete members contact with some substances from the environment such as chloride ions from seawater, de-icing salts, carbon dioxide from the atmosphere when utilized for a long time. Then, it can cause corrosion of steel bars that results in the reduction or complete loss of the protection. Corrosion products can crack the concrete and subsequently remove the concrete cover of the steel bars. Loss of steel cross-section reduces flexural, shear and torsional capacities of RC structures.

Corrosion monitoring of RC structures is quite challenging. Galvanic monitoring probe, High-frequency UV method, Acoustic emission technique, Ground-penetrating radar methods, etc., are currently used as corrosion monitoring methods.

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These methods are expensive, time-consuming, and require experimental setups and mathematical calculations to define a corrosion level. Identification of corrosion level based on easily measurable parameters is vital in RC structures on site. Then, remaining flexural and energy absorption capacities could be calculated using directly identified corrosion levels. An easily applicable retrofitting method is important to enhance the residual flexural capacities to use corroded RC structures more safely.

2. Literature Review

Corrosion occurrence period in RC structures shows wide distribution since it depends on the level of routine maintenance, environmental conditions, cover depth and concrete quality. Corrosion affects durability and load-bearing capacity of structural elements [1-3]. Ultimate limit state load carrying capacity reduces due to loss of cross-section of reinforcement bars and cracking of concrete cover [4]. Researchers have developed analytical models to evaluate the effect of corrosion level, span to depth ratio, and the corroded length of the steel bar for the calculation of flexural strength of structural members. The models reveal the loss of strength capacity of beams with severe corrosion conditions due to the loss of reinforcement area [5]. A model was developed for the prediction of the flexural strength of corroded RC beams. The model was validated using experimental flexural strength details found in the literature. Corrosion levels of both tensile bars and stirrups have a significant effect on the flexural strength of corroded RC beams [6].

Excessive deflection or reduction of ultimate load-carrying capacities of existing RC structures can adversely affect both serviceability and ultimate limit requirements. Structures which were previously thought to have performed well will be unsatisfactory with current provisions in the revisions of loading manuals and structural design guidelines. Repair of deteriorated RC structures to achieve desirable serviceability and ultimate limit requirements of the existing codes and strengthening of existing concrete structures to carry higher permissible loads, seem to be a more attractive alternative to demolishing and rebuilding [7]. Adding material around existing concrete members is a well-known conventional rehabilitation method to cater to the reduced strength of deteriorated concrete structures. Advanced materials were used by many researchers in the field of structural engineering to study the behavior of the strength aspect. Plain cement concrete was introduced with steel members as innovation which gives quite satisfactory results. Section enlargement and plate bonding methods are used as a retrofitting technique for RC members to improve their performance. The use of externally bonded steel plates to retrofit existing structural members is widespread in the construction industry as the application of steel plates causes minimal effect on the cross-section size. Furthermore, it is quick and easy to handle at the site without causing disruptions. Corrosion of steel, undesirable shear failures, and handling difficulties due to heavyweights are prominent disadvantages of this method [8, 9]. It causes to increase the cross-section of the member, results in comparatively too long construction time, and adds self-weight and susceptibility to corrosion [10]. New techniques and materials are still searching to retrofit deteriorated concrete structures although many findings are available in the literature to enhance the strength capacities. Researchers investigated the applicability of Fiber Reinforced Polymers (FRPs) as an external reinforcement to upgrade the structural performance of concrete members. Limitations of conventional repairing methods can be overcome by using FRP composites. Deteriorated RC structures over a long time can be effectively repaired and strengthened using FRP. Compared to the conventional strengthening techniques, the application of FRP produces economic benefits [11]. FRP offers lightweight, cost-effective, and durable retrofitting while it has a high strength to weight and stiffness to weight ratios [12, 13]. FRP as retrofitting material improves the structural performance of RC members such as walls, beams, slabs and columns [14].

Although different rehabilitation techniques are available in the literature, it is salient to find an easily applicable retrofitting method for existing structural members while ceasing the corrosion process of affected structures. In this paper, we mainly focused on implementing laboratory experiments to predict the remaining strength capacities of corroded RC beams subjected to chloride attack under static loads. Furthermore, an efficient retrofitting technique was investigated for corroded RC beams to upgrade their strength capacities.

3. Methodology

3.1 Sample Preparation

Three corrosion levels (minor, moderate, severe) were selected as variables for 13 test specimens (120mm×200mm×1500mm) with two control samples to conduct the study. Flexural capacities of RC beams in three different series were obtained from a lower to a higher level of corrosion. Reinforcement arrangement of the samples is shown in Figure 1.

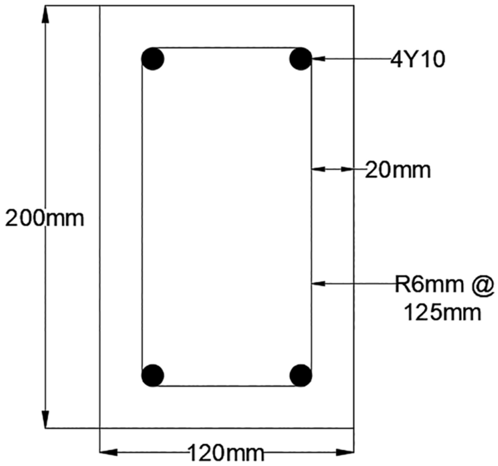

Figure 1 - Reinforcement Arrangement

In the longitudinal direction, 10 mm yield steel bars were used and 6mm mild steel was used as shear links with 125 mm spacing. Figure 2 shows the reinforcement and formwork of test specimens.

Figure 2 – Reinforcement and Formwork of Test Specimens

For the sample preparation, Grade 25 (25 MPa) concrete with a slump of 150 mm-175 mm was used while keeping a 20 mm clear cover to reinforcement bars. Table 1 gives the specimen identification codes.

Table 1 - Test Specimen Identification Codes

Test specimen	Description
C	Control sample
SB	Severely corroded-bending test
MB	Moderately corroded-bending test
LB	Minor corroded-bending test
RSB	Retrofitted-severely corroded-bending test
RLB	Retrofitted-minor corroded-bending test

3.2 Accelerated Corrosion by Impressed Current Technique

To accelerate the corrosion, electrochemical corrosion was used. A copper bar was connected to a negative terminal (cathode) and embedded reinforcement bars of the specimens were connected to a positive terminal (anode). Consequently, reinforcement of the specimens became the anode. To provide electrical contact between the anode and the cathode, samples were immersed in NaCl solution. A schematic diagram of the acceleration corrosion method is shown in Figure 3.

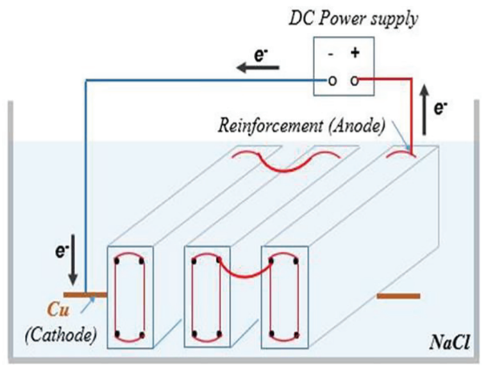

Figure 3 - Schematic Diagram of Acceleration Corrosion Method

Adding chlorides to concrete mixtures was avoided to simulate natural corrosion on the accelerated corrosion technique. After 28-day curing period, samples were immersed in a tank containing NaCl solution. Samples were connected in series to a direct current supply. Figure 4 shows the specimen configuration in the NaCl pond.

Figure 4 - Specimen Subjected to Accelerated Corrosion in NaCl Pond

3.3 Corrosion Rate Monitoring

The rate of mass loss of steel bars (Faraday's law) and minimum thickness ratios (μ) [15] were used to determine the level of corrosion. Mass loss of steel bars can be calculated using Faraday's law.

$$m = AQ/zF \qquad \dots (1)$$

where
m = Mass of the steel consumed (grams)
Q = Charge in coulombs
F = 96,500 coulombs
z = Ionic charge (2 for $Fe \rightarrow Fe2{+}{+}2e{-}$)
A = Atomic weight of the metal (56 g for Fe)

Corroded reinforced test specimens were taken out from the NaCl tank to determine the minimum thickness ratio of reinforcement bars.

Figure 5 shows the corroded test specimen.

Figure 5 - Corroded Test Specimen

Minimum thickness ratios were used to determine the level of corrosion, as follows:

$\mu > 0.75$	Minor corrosion
$0.75 \geq \mu \geq 0.5$	Moderate corrosion
$\mu < 0.5$	Severe corrosion

where; $\mu = t_{min}/t_o$
t_o = initial thickness
t_{min} = minimum thickness of the corroded section

In RC structures, steel bars are used as reinforcements considering the diameter of the steel for strength calculations. Hence the diameter ratio can be defined as follows;

$\mu = \frac{dmin}{do}$

d_o = initial diameter
d_{min} = minimum diameter of the corroded section

Samples were crushed to determine diameter ratios of corroded steel bars after observing different crack widths on test samples. Also, steel bars were properly brushed to remove the rust before determining the minimum diameter of corroded re-bars. Figure 6 shows a corroded reinforcement bar.

Figure 6 - Corroded Reinforcement Bar Extracted from Specimen

3.4 Retrofitting of Corroded Specimens

Xypex was used as retrofitting material. The Xypex crystalline technology has developed based on a thorough understanding of concrete's chemical and physical makeup. Furthermore, the chemical treatment was facilitated by Xypex filling the capillaries to prevent the penetration of water and other liquids from any direction. The application procedure is listed below.

1) Surface preparation
   A wire brush was used to remove laitance, dirt, film, or other foreign matter on the concrete surface.
2) Wetting concrete
   Generally, Xypex requires a saturated substrate and a damp surface. The concrete surface was thoroughly saturated with clean water before its application to aid proper curing of the treatment as well as to ensure the development of crystalline formation inside the pores of the concrete.
3) Mixing and applying the Xypex slurry
   The creamy consistency nature of Xypex was achieved by mixing the proportion of 5 parts Xypex powder to 2 parts water. Xypex slurry was applied using a brush throughout the corroded samples. Figure 7 shows the application of Xypex for test specimens.

Figure 7 - Application of Xypex as Retrofitting Material

4) Curing
   A mist fog spray of clean water was applied three times daily on consecutive four days, for curing the Xypex treatment. Curing was carefully set to the point where Xypex was not damaged by a fine spray of water.

3.5 Determination of Flexural Capacities

Corroded RC samples (for three different corrosion levels, minor, moderate, severe) were tested to determine bending capacities. Control (non-corroded) and corroded specimens were tested as a simply supported beam to determine the ultimate load-carrying capacity. A schematic diagram of the loading arrangement is given in Figure 8.

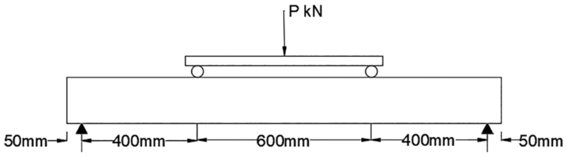

Figure 8 – Loading Arrangement of the Test

Two linear variable displacement transducers (LVDTs) were used to determine deflection at the center and close to the supporting points. The experimental setup is shown in Figure 9. Corroded and corroded-retrofitted RC samples (for three different corrosion levels, minor, moderate, severe) were tested to determine bending capacities. All the specimens were monotonically loaded to failure in four-point bending with a beam span of 1.5 m and a rate of loading at 0.04 mm/sec.

Figure 9 - Experimental Setup for a Flexural Capacity Test

4. Results and Discussion

4.1 Determination of Remaining Strength Capacities

Nine RC beams were cast to study the static behavior of corroded RC members. According to the above-mentioned study, the load-deflection behavior of control specimens and corroded specimens was graphed as shown in Figure 10.

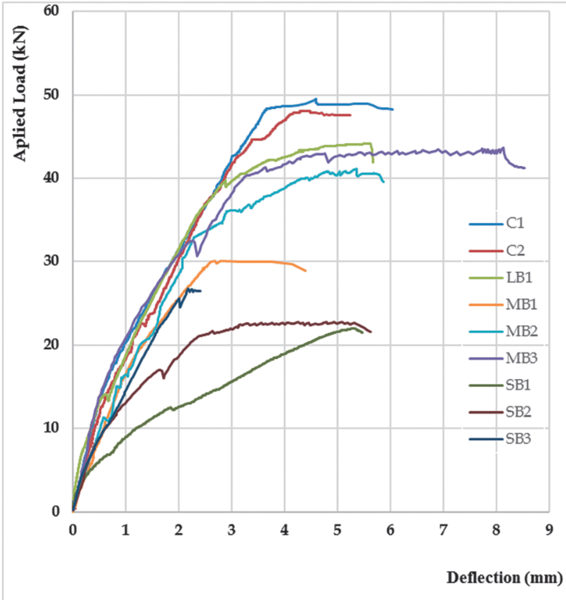

Figure 10 - Load vs. Deflection Curves for Control and Corroded Samples

It was observed that the control (non-corroded) beam has the highest ultimate load-bearing capacity and also strength reduced linearly with the severity of corrosion level. At the minor corrosion stage, according to results, the ultimate flexural strength of the corroded element deteriorates very slowly. When the corrosion level reaches a severe state, considerable deterioration takes place due to the significant reduction in re-bar diameter. The ultimate load-bearing capacity of each beam and percentage reduction of ultimate flexural strength with corresponding minimum diameter ratios are given in Table 2.

Table 2 - Percentage Loss of Ultimate Flexural Strength with Minimum Diameter Ratio

Test specimen	Minimum diameter ratio d_{min}/d_o	Ultimate flexural capacity (kNm)	Percentage loss of ultimate flexural strength
Control Sample (avg)	1.00	9.76	0.0
SB1	0.22	4.40	54.9
SB2	0.26	4.55	53.3
SB3	0.42	6.00	38.5
MB1	0.51	5.35	45.2
MB2	0.71	8.14	16.6
MB3	0.74	8.62	11.6
LB1	0.9	8.83	9.5

4.2 Determination of Remaining Strength Capacities of Retrofitted Samples

Four RC beams were cast to study the static behavior of corroded-retrofitted RC structures. According to the above-mentioned study, the load-deflection behavior of control specimens and corroded-retrofitted specimens were graphed as shown in Figure 11.

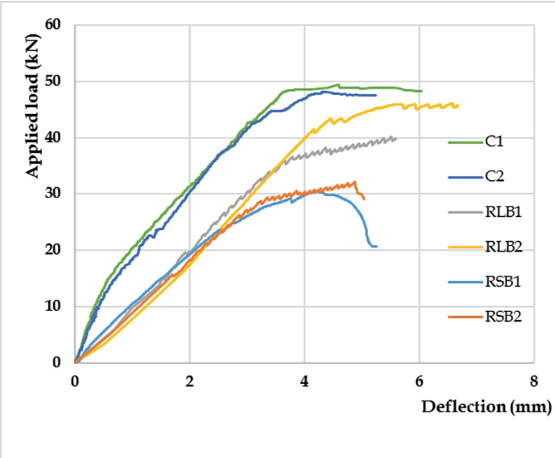

Figure 11 - Load vs. Deflection Curves for Control and Corroded-Retrofitted Specimens

The ultimate flexural capacity of each beam and percentage reduction of ultimate flexural strength with corresponding minimum diameter ratios are given in Table 3.

Table 3 - Percentage Loss of Ultimate Flexural Strength of Retrofitted-Corroded Samples with Minimum Diameter Ratio

Test specimen	Minimum diameter ratio d_{min}/d_o	Ultimate flexural capacity (kNm)	Percentage loss of ultimate flexural capacity
RSB1	0.34	6.08	37.7
RSB2	0.40	6.43	34.1
RLB1	0.76	8.04	17.6
RLB2	0.85	9.22	5.5

4.3 Relationship of Percentage Strength Reduction with Minimum Thickness Ratio

Table 2 and Table 3 indicate percentage strength reduction values for non-retrofitted and retrofitted samples, respectively. The graph of percentage reduction of ultimate flexural strength vs. minimum diameter ratio for retrofitted and non-retrofitted samples is shown in Figure 12.

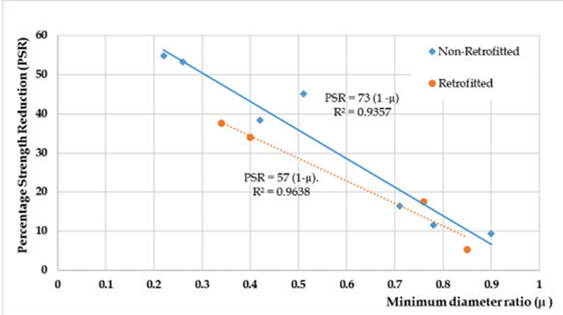

Figure 12 - Relationship of Percentage Strength Reduction vs. Minimum Diameter Ratio (µ) for Retrofitted and Non-Retrofitted Samples

The percentage reduction of flexural capacity due to corrosion can be defined using the following equation.

Percentage Strength Reduction = $73\times(1-\mu)$ …(2)

The linear reduction of ultimate flexural capacity for corroded non-retrofitted specimens with the severity of corrosion can be identified. It is noticed that there is a linear relationship between the ultimate percentage flexural strength reduction value with minimum diameter ratio of retrofitted-corroded samples. The percentage reduction of flexural capacity of retrofitted-corroded samples can be obtained using the following equation.

Percentage Strength Reduction = $57\times(1-\mu)$ ...(3)

There is a considerable amount of percentage strength increment for the retrofitted-corroded beams compared to the similarly corroded non-retrofitted beams.

4.4 Relationship of Crack Width with Minimum Thickness Ratio

Even though a relationship between the percentage strength reduction and µ is obtained, it is practically very difficult or sometimes impossible to find μ. As far as maintenance of the structure is considered, developing a method to identify μ is important. Therefore, with regular monitoring, a relationship between the crack width and µ was obtained as shown in Table 4.

Table 4 - Minimum Diameter Ratio (µ) Values for Corresponding Crack Width

Crack width(mm)	Minimum diameter ratio (µ)
0.2	0.32
0.15	0.4
0.1	0.68
0	1

Figure 13 shows the graphical relationship between the minimum diameter ratio (μ) and crack width (w_{cr}).

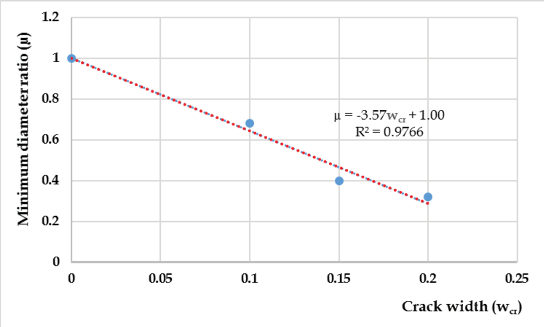

Figure 13 - Relationship between Minimum Diameter Ratio (μ) and Crack Width (w_{cr})

The following equation can be used to determine the minimum diameter ratio of corroded rebar.

$$\mu = -3.57(w_{cr}) + 1.00 \quad \ldots(4)$$

4.5 Discussion

With a comprehensive investigation of the crack width of structural members, practitioners can determine the minimum diameter ratio of the embedded reinforcement using Eq. 4. This would be beneficial for the engineers in the industry since the crack width is an easily measurable parameter at the site level. Once we determine the minimum diameter ratio, percentage strength reduction can be calculated using Eq. 2.

Engineers can decide whether the structural member is required to be retrofitted or not based on the residual strength capacities of the member. As a retrofitting material, Xypex can cease the corrosion process and reduce the percentage strength reduction as shown in Eq. 3. The construction industry can use this easily applicable retrofitting method according to the upgrade demand of the structural member.

5. Conclusions

Results imply that the flexural strength capacity is linearly reduced with the increase of the severity of the corrosion conditions. Further, reduction in cross-section of reinforcement and cracks along the reinforcement are the main causes for strength reduction of RC members. Especially when the corrosion level is increased, the beam failure mode is changed from ductile mode to brittle mode. The maximum flexural capacity reduction is 18% for minor corroded samples where moderately corroded samples have values between 18-37%. Severely corroded samples indicate more than 37% flexural capacity reduction.

During the study, the effectiveness of the retrofitting method was thoroughly observed when it was subjected to a static load. There is a percentage strength increase for the retrofitted sample compared to the non-retrofitted sample. Further, in the static loading case, the percentage of strength increment is small when μ approaches a higher value. The maximum flexural capacity reduction is 14% for minor corroded-retrofitted samples whilst severely corroded-retrofitted samples have more than 29%. According to the values of minor and severe corroded samples, it is revealed that 4% and 12% flexural capacity increments can be obtained by using Xypex as retrofitting material. It implies that the retrofitting method is effective for higher corrosion levels or was having low μ values.

Also, the relationship between crack width (w_{cr}) and minimum diameter ratio (μ) is linear according to the test results. Generally crack width of concrete structures is an easily measurable parameter in practical situations. The minimum diameter ratio of a reinforcement bar can be determined using the visually observed crack width of a RC member. Furthermore, once maintenance engineers found the μ value, they would be able to find the percentage strength reduction. Eventually, this retrofitting method can be used to enhance remaining strength capacities.

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