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Article

External Strengthening of Corrosion-Defected Beam–Column Members Using a CFRP Sheet

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Abstract: The efficiency of external strengthening using CFRP (Carbon Fiber Reinforced Polymer) sheets to rehabilitate corrosion-defected RC (Reinforced Concrete) beam–column members is experimentally studied. ALL specimens were tested under a combined axial force and transverse load until failure. The axial forces were applied with two levels either 25% or 50% of the ultimate design load of control specimen. The accelerated corrosion process was used to get steel reinforcement corrosion inside the concrete at three levels, 0% and approximately 5% and 20%, according to Faraday's law. External strengthening with a CFRP sheet was used in this study to overcome the effect of deterioration in the mechanical properties of the corroded steel bars. A significant deterioration in the load carrying capacity, stiffness, and serviceability was recorded for corrosion-defected specimens. The increase of the axial force was recorded as a positive effect on the ultimate strength, stiffness, and serviceability of the testing specimens. This effect was clearly evident for the defected specimens, with an increasing corrosion level, by decreasing the adverse effects of corrosion. The external strengthening with a CFRP sheet restored the load-carrying capacity, stiffness, and serviceability to an undamaged state.

Keywords: carbon fiber reinforced polymers; strengthening; corrosion-defected; beam–column

1. Introduction

Structural rehabilitation has now become an important technique that needs to be improved and enhanced to show efficiency with defected structural members. The most common reason that causes premature material deterioration is that the structure is exposed to a harsh service environment, and then reinforcement corrosion takes place. Concrete is alkaline in nature, with a porous solution that naturally passivizes embedded reinforcing bars; here, protective oxide films from the high alkaline environment will be produced. Corrosion can take place when the passive film is removed or locally damaged. Carbonation-induced and chloride-induced damage are the most common environmental impacts that cause failure in the Reinforced Concrete (RC) members. There are several major defects caused by corrosion, such as an early failure of corroded steel reinforcements due to a lowering of the ductility and area of the cross section of the reinforcement bars, thereby increasing the volume of the bars from corrosion products, which then causes a steel bar–concrete bonding problem to appear [1].

Using new materials instead of steel (for corrosion resistance), such as fiber reinforced polymers (FRP), has become a rapidly increasing area of study, to construct and rehabilitate concrete structures with new techniques. FRPs, which are composite materials used for rehabilitations, are non-corrosive, light-weight, materials with a high tensile strength. FRP materials are used in several shapes, such as sheets, laminates and bars, using the Near Surface Mounted NSM technique for the rehabilitation of defects in concrete.

Due to the improvement of modern science and technology, a radical change in structural construction has been observed. The structural constructions of the 1800s are architecturally simple and have fewer floors compared to those built in this century. In the 1900s, a slightly more complex architectural parameter was introduced, and the structures became comparatively taller. At present, this has become a challenge for structural and Geotechnical engineers to meet design needs, considering the variation in shapes, vertical irregularities, safety against natural calamities like wind and earthquakes, and economical facts. As the height of Reinforced Concrete (RC) structures has increased, these structures have become prone to severe effects from earthquakes and wind [2]. For these reasons, many researchers have shown great interest in studying high rise RC structures, and the effect of wind and earthquakes on their structural members. Structural elements used in a building with many stories and with large structures, such as flexural members, will be under combined transverse and axial loading. Reinforced concrete structural members that are subjected to combined axial compression force and transverse load at the same time are called "beam–column" members, and they are mostly used in frame type structures. In this case, these beam–column members are often subjected to lateral loads from wind and earthquakes, in addition to transverse loads.

Many researchers have shown the effects of corrosion on the mechanical properties of steel reinforcement, in addition to its effects on the behavior and flexural strength of RC beams. Al-musallam [3] showed the effect of steel reinforcement corrosion on the mechanical properties of steel bars. He found that the ductility of corroded bars was decreased when corrosion levels increased and steel bars with more than a 12.6% corrosion level indicated a brittle behavior. Mangat and Elgarf [4] tested 111 RC beams to examine their flexural capacities after being exposed to different levels of reinforcement corrosion by an accelerated corrosion process. They mentioned that the deterioration in the bond strength of the steel–concrete interface was the main cause of decreasing flexural strength. Ballim and Reid [5] experimentally studied the influence of corrosion reinforcement on the serviceability state of the deflection of RC beams. They measured the mid-span deflection of specimens when subjected to 34% and 23% of the designed ultimate load and a period of 30 days of simultaneous accelerated corrosion. Results showed that a 6% reduction of the mass of steel leads to an 40%–70% increase of deflection compared with the control beam. Goitseone M. et al. [6] carried out a test on 9 RC beams subjected to four-point loading and corroded using an impressed current to deform the tensile steel bars, alongside a 5% NaCl solution with constant wetting cycles and two different drying cycles. They showed that the ultimate moment capacity of beams was reduced linearly to the level of corrosion, so for every 1% corrosion level, there was a 0.7% reduction in the ultimate capacity. Gu XL. et al. [7] constructed twelve beams where three beams were corroded by the natural corrosion process and others by an artificial corrosion process. They noted that the load carrying capacity and stiffness of beams decreases with an increase in the corrosion degree. Wenjun Z. et al. [8] experimentally investigated the behavior of corroded RC beams under a real chloride environment condition.

The long-term corrosion process was used to represent a real structural condition, so the specimens were stored in a chloride environment for twenty-six years. The test results showed that a lower ductility failure of corroded bars was recorded, and the ultimate elongation was reduced by more than 50% compared to the non-corroded steel bars. The mode of failure changed more for the corroded beams than for the non-corroded one from shear to flexural failure due to the larger effect of corrosion on flexural capacity than shear capacity. Torres-Acosta et al. [9] found that structural stiffness was reduced linearly with an increase in the level of corrosion. Yafei M. et al. [10] investigated the effect of corrosion on the steel–concrete interface bond behavior. They mentioned that when the corrosion loss is less than 2.4% so the corrosive influence on bond strength can be ignored, and the bond behavior is more sensitive between the smooth bar and concrete than deformed bar to corrosion. Lijum H. et al. [11] experimentally studied the behavior of the reinforced concrete ultrahigh toughness cementitious composite (RC/UHTCC) beam. They indicated that corrosion clearly affected the load carrying capacity, deformation, ductility, and flexural crack patterns of the defected specimens.

On the other hand, there are several studies of defected/rehabilitated RC beams using composite materials. Bonacci and Maalej [12] conducted an experimental program to get a realistic assessment of the potential of using FRP materials in the repair and strengthening of RC flexural members exposed to a corrosive effect. External strengthening with a Carbon Fiber Reinforced Polymer (CFRP) sheet was used to rehabilitate the deterioration of RC beams. They found that using composite materials for a CFRP sheet to strengthen corroded RC beams is an efficient technique that can maintain the structural integrity and enhance the behavior of the damaged beams. The study of Al-Saidy et al. [13] consisted of an experimental program from ten damaged/repaired reinforced concrete beams. Carbon fiber reinforced polymer (CFRP) sheets were used for the external strengthening of the corroded beams. Results showed that a strengthening technique via CFRP sheets for corroded RC beams was capable of maintaining the load carrying capacity. In this way, the strength of the beams that were damaged due to corrosion was restored to the control state when they were strengthened with CFRP sheets. Deterioration of the beams showed a lower stiffness and strength than the undamaged control beams. Almassri et al. [14] investigated NSM (CFRP) rods as a repair technique for the rehabilitation of defects in the RC beam members of buildings and as a way of restoring the mechanical performance of corrosion-damaged beams. The test results showed that the NSM technique was able to increase the ultimate load capacity of corroded beams and slightly increase stiffness. Furthermore, sufficient ductility could be restored. Rami H. Haddad [15] experimentally investigated the effectiveness of using segmented or continuous U-warp CFRP sheets to retrofit RC beams with corrosion damage. An acceleration corrosion process of dry/wet cycles was used to accelerate the corroded main tension bars. The test results showed a significant reduction of about 13% in the load carrying capacity under a corrosion level of 8% (the average weight loss) compared with the non-corroded control beams. The flexural performance of the corroded beams was tested as the load capacity, and the stiffness was increased by using the CFRP sheet. Huifeng Z. et al. [16] carried out a test on eight RC beams subjected to an accelerated corrosion process and then rehabilitated the beams with CFRP sheets. These beam specimens were divided into two groups—one that was strengthened with CFRP sheets and one that was un-strengthened. The test results showed that the flexural bearing capacity of the RC beams decreased as the corrosion level of the tensile bars increased. The specimens strengthened with composite material CFRP sheets showed a positive effect on the load-carrying capacity and the flexural behavior. Maaddawy T. [17] a total of 16 square of corrosion-damaged and eccentrically loaded reinforced concrete (RC) columns were tested to show the effect of CFRP to upgrade these members. An accelerated corrosion test along 30 days was used for damaged specimens to get corrosion level of about 4.25% (mass loss). The scheme of CFRP and the eccentricity-to-section height ratio were the main test parameters. The strength was up to 40% higher than that of the undamaged control columns when the damaged specimens fully wrapped with CFRP. Partial CFRP-wrapping was 8% less effective than full CFRP-wrapping at a nominal e/h of 0.3. At higher e/h values, the confinement level had a negligible effect on the columns' strength. Hadi et al. [18–22] they conducted several studies on the analysis of eccentrically-loaded FRP confined concrete. They found that an application of multiple layers of composite material increases the stiffness of the external confinement and enhances the efficiency of the confining system. Also, they found an improvement of ductility was more obvious than the gains in strength [18,20]. Carbon fibers (CFRP) embedded in a polymeric matrix provided the highest amount of confinement compared to other types of fibers or steel reinforcement [19–22].

Many researchers have studied the effects of corrosion on the behavior and the ultimate strength of RC beams in addition to the studies on the rehabilitation techniques used for this purpose, but no study was found on the structural behavior and ultimate strength of defected/rehabilitated RC beam–column members exposed to a bending moment and axial force. Therefore, the present study concentrated on the experimental investigation of load carrying capacity, serviceability limit state in terms of deflection and crack width, stiffness, and crack patterns of defected and defected/rehabilitated RC beam–column members by using a CFRP sheet. In addition, the study shows the effects of increasing axial force on the structural behavior and ultimate strength of defected and defected/rehabilitated specimens.

2. Experimental Program

2.1. Specimen Details

The experimental work was conducted in the structural laboratory of the civil engineering department of Al-Qadisiyah University. Ten RC beam–column members with a dimension of $160 \times 200 \times 1500$ mm^3 were tested under constant axial force and a four-point transverse load up to failure. The reinforcement details of the beam–column members are shown in Figure 1. Two deformed bars with 10 mm diameters and two other bars with 8 mm diameters were used for longitudinal tension and compression reinforcement, respectively. For stirrups, a 6 mm diameter was used at a spacing of 50 mm, except the middle third span of the member, where the spacing used was 100 mm. The clear concrete cover was 20 mm on all sides of the specimen.

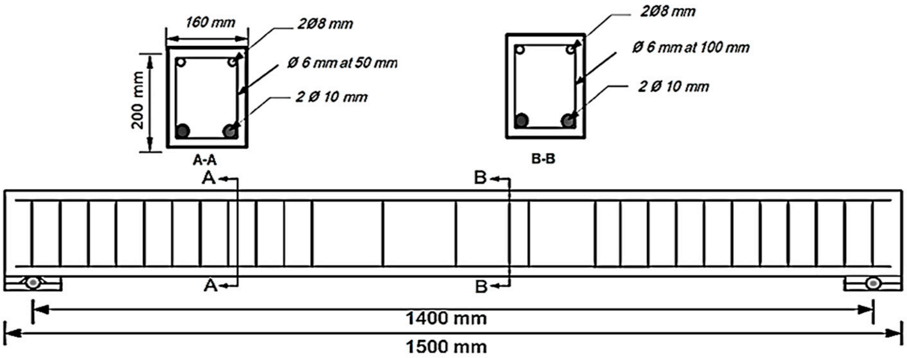


Figure 1. Concrete geometry and reinforcement details of tested specimen.

The experimental study consisted of two test groups, as illustrated in Table 1. Group (A) included control non-corroded specimen, corrosion-defected specimens under low or high corrosion levels of 5% or 20%, respectively, and defected/rehabilitated specimens with the CFRP sheet. These specimens were tested under an axial force of 15 kN in addition to the transverse applied load. Group (B) included the same set of specimens but with an axial force of 30 kN.

Table 1. Designation and details of tested members.

Groups	* Symbol of Specimens	Degree of Corrosion (%)	Rehabilitation Technique	Axial Force (kN)
A	$BC.C_0.R_N.A_{15}$	0	Non	15
	$BC.C_5.R_N.A_{15}$	5	Non	15
	$BC.C_{20}.R_N.A_{15}$	20	Non	15
	$BC.C_5.R_{CFRP\ sh}.A_{15}$	5	CFRP Sheet	15
	$BC.C_{20}.R_{CFRP\ sh}.A_{15}$	20	CFRP Sheet	15
B	$BC.C_0.R_N.A_{30}$	0	Non	30
	$BC.C_5.R_N.A_{30}$	5	Non	30
	$BC.C_{20}.R_N.A_{30}$	20	Non	30
	$BC.C_5.R_{CFRP\ sh}.A_{30}$	5	CFRP Sheet	30
	$BC.C_{20}.R_{CFRP\ sh}.A_{30}$	20	CFRP Sheet	30

* Where: BC stands for beam–column, Ca stands for degree of corrosion (5% or 20%), Rb stands for rehabilitation technique (CFRP sh.: Carbon Fiber Reinforced Polymer sheet). Ac stands for Axial Force (either 15 kN or 30 kN).

2.2. Material Properties

The properties of the main tension bars were recorded as follows: 587 MPa as yield strength, 678 MPa as rupture strength, and 19.4% as elongation. The reinforcement bars' elastic modulus was assumed to be 2×10^5 MPa. A mechanical concrete mixture machine was used to produce normal strength concrete for RC beam–column members, and all these members were cast at the same time and had the same concrete quality. The calculated concrete compressive strength was 35 MPa based on cubic tests. The repair materials used in this study were from Sika productions as Sika Wrap Hex 230C (Sika Iraq, Baghdad, Iraq) and Sikadur 330 (Sika Iraq, Baghdad, Iraq). The first one was a unidirectional carbon fiber fabric used with Sikadur 330 as external strengthening for RC members with high tensile strength, corrosion resistance, and modulus of elasticity. The second one consisted of two parts, was solvent free, and used thixotropic epoxy based impregnating resin/adhesive; it was used as an impregnation resin for Sika Wrap fabric.

2.3. Accelerated Corrosion Process

An electrochemical process was used in this study to accelerate the corrosion of steel reinforcement embedded inside the concrete. The corrosion was limited to the critical flexural zone with a length, a width, and height of 400 mm, 160 mm, and 40 mm, respectively. This limited region of the member was submerged in a plastic container with 5% concentrate of sodium chloride solution. Power supplies with adjustable voltage and a direct current (DC) of 700 mA were used for this process. The reinforcement cage was connected to the positive side and the stainless steel plate was connected to the negative side of the DC power supply. The desired degrees of corrosion were 5%, and 20% of the deformed bars, which could occur in a period of 8 and 32 days, respectively according to Faraday's law. The theoretical mass of rust produced per unit of surface area could be determined based on Faraday's law, as illustrated in Equation (1):

$$M_{th} = \frac{W\, I_{app.} T}{F}. \tag{1}$$

The actual mass of rust per unit of surface area was determined by a gravimetric test in accordance with (American Society for Testing and Materials) ASTM G1 [23], as illustrated in Equation (2):

$$M_{ac} = \frac{W_i - W_f}{\pi DL}. \tag{2}$$

The degree of induced corrosion is also expressed in terms of the percentage mass loss (ρ) calculated, as shown in Equation (3):

$$\rho = \frac{W_i - W_f}{W_i} \times 100. \tag{3}$$

The equivalent corrosion current density ($I_{corrosion}$: $I_{corr.}$) could be determined by equating Equations (1) and (2), assuming that the theoretical mass and the actual mass of rust was equal (i.e., $I_{app.} = I_{corr.}$ ($_{app.\ =\ applied}$)), as

$$I_{app.} = I_{corr.} = \frac{\rho \times w_i \times F}{100 \times \pi \times D \times L \times W \times T} \tag{4}$$

where $I_{app.}$ represents an applied electrical current (Amp/cm^2), ρ is the degree of corrosion (%), w_i is the initial mass of corroded bars (g), F is Faraday's constant (F = 96,500 Amp × Sec), D is the original diameter of corroded bars (cm), L is the length of corroded bars in the corrosion region (cm), W is the equivalent weight of reinforcing steel, which represents the atomic weight of the iron element (Fe) to its equivalent weight (W = 27.925 g).

Equation (4) represents the simplified Faraday's law formula that was used for calculating the time required to get the t desired degrees of corrosion. Figure 2 shows the experimental setup of the accelerated corrosion process.

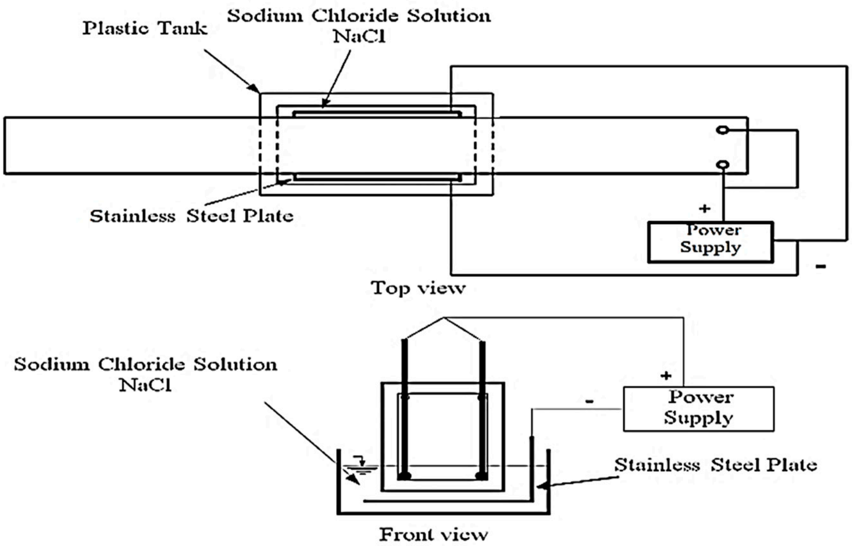


Figure 2. Details setup of the accelerated process.

2.4. External Strengthening with the CFRP Sheet

The rehabilitation technique used in this study was an external strengthening with a CFRP sheet to overcome the effect of deterioration in the mechanical properties of corroded steel bars. A new external strengthening technique was used by wrapping the damaged region and extending it to undamaged regions using CFRP sheets with overall dimensions of 65 × 160 × 1200 mm^3, and without repairing the concrete defects, as shown in Figure 3. SikaWrap Hex 230C was used for this purpose, it is a unidirectional carbon fiber fabric used with sikadur 330 epoxy to form a carbon fiber reinforced polymer (CFRP). Firstly, the substrate surface of the concrete was cleaned of dust, then the impregnation resin sikadur 330 was applied. After this, we carefully placed the fabric on the resin with gloved hands and smoothed out any irregularities or air pockets using a plastic laminating roller. We then allowed the resin to squeeze out between the rovings of the fabric. Finally, we applied a coat of Sikadur 330 to the exposed surface.

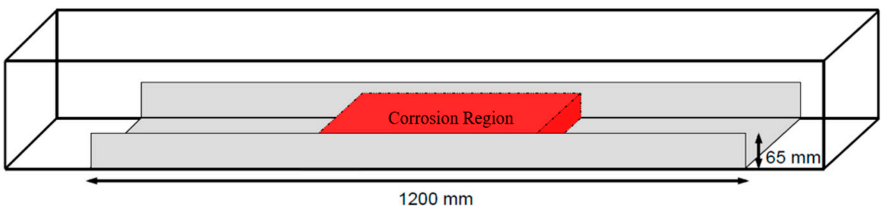


Figure 3. Details setup of CFRP Sheet external strengthening.

2.5. Test Setup

A flexural test was performed for each beam–column member supported over a span of 1400 mm and under constant axial force in addition to the four-point transverse load up to failure. After the accelerated corrosion process and the patch repair technique, all specimens were painted with a white color to observe the crack development and marking. A steel frame with a hydraulic jack of 60 ton capacity was used in this study. A necessary modification to this frame was made by strengthening the lower horizontal part of the frame and fixing a new supporting frame with a new hydraulic system and new hydraulic cylinder (700 bar, 500 kN maximum force) capacity, for axial force, as shown in Figure 4. During each load step, the corresponding central vertical deflection, crack patterns, and flexural crack width were recorded, as well as the ultimate capacity.

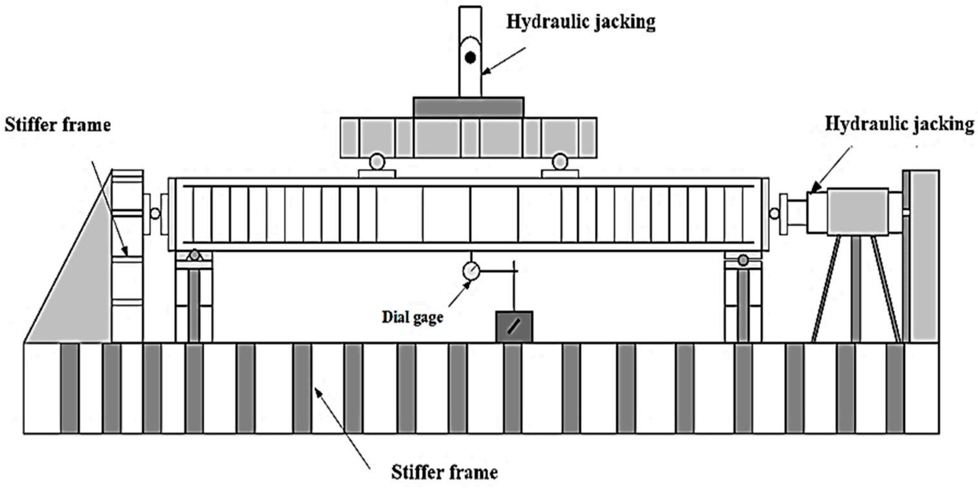


Figure 4. Sketch of modified testing machine.

3. Experimental Results and Discussion

3.1. Actual Degree of Corrosion

Low level (5%) and high level (20%) corrosion degrees were considered in this study. To calculate the actual degree of corrosion, we followed the steps of the ASTM G1. After testing all beam–column members, the corroded reinforcement bars were cut and extracted from the limited region of corrosion. Then, they were cleaned and re-weighted without any rust. The actual corrosion degree was calculated based on Equation (5):

$$C_D = \frac{W_i - W_f}{W_i} \times 100 \quad (5)$$

where W_i is the initial mass of the non-corroded bars (g) and W_f is the mass of the corroded bars after cleaning the rust (g). The exact masses of the original and the corroded (after cleaning) steel bars with the same lengths were measured. Then, the degrees of corrosion were calculated from Equation (5), as illustrated in Table 2, and were found to be 5.5% and 20.7% at 8 days and 32 days, respectively. This level of corrosion was close to the predicted corrosion from Faraday's law.

Table 2. Desired and actual degree of corrosion of corroded steel bars.

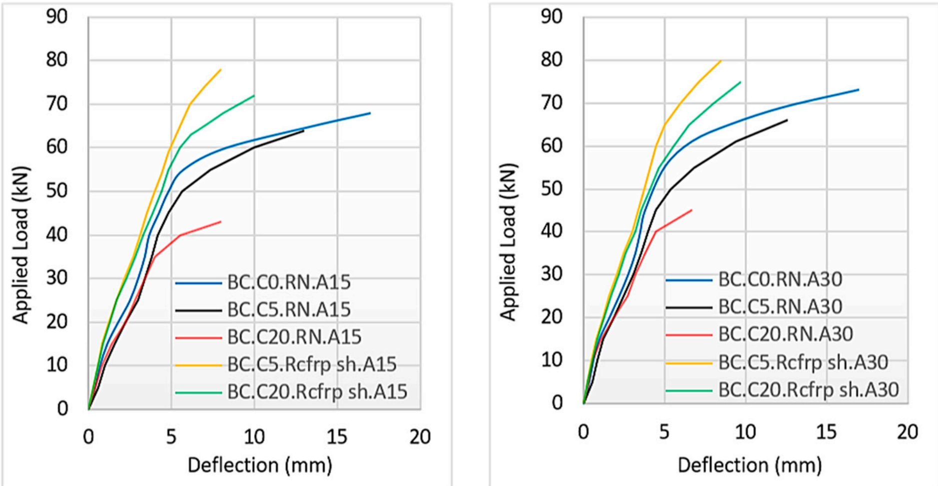
Initial Mass of Non-Corroded Bar W_i, (g)	Final Mass of Corroded Bar W_f, (g)	Desired Degree of Corrosion (%)	Actual Degree of Corrosion C_D, (%)
270	255	5	5.5
270	214	20	20.7

3.2. Load-Deflection Response and Cracking Pattern

The experimental study was performed under constant axial compressive force and transverse four-points load up to failure. The experimental results recorded in this study were the ultimate transverse load up to the peak load and service mid-span deflection for the tested specimens in addition to the allowable limit of service deflection according to the American concrete institute (ACI) code. These results are illustrated in Table 3. A comparison of the load-deflection response for each group is given in Figure 5.

Table 3. Ultimate load capacity, service deflection, and allowable deflection according to American concrete institute: ACI for tested specimens.

Groups	Symbol of Specimens	Degree of Corrosion C_D (%)	Ultimate Load P_U, kN	Mid-Span Service Deflection, mm	Allowable Deflection ACI-318 [24], mm
A	$BC.C_0.R_N.A_{15}$	0	68	3.6	3.9
	$BC.C_5.R_N.A_{15}$	5	64	4	3.9
	$BC.C_{20}.R_N.A_{15}$	20	43	5.1	3.9
	$BC.C_5.R_{CFRP\ sh}.A_{15}$	5	78	3.1	3.9
	$BC.C_{20}.R_{CFRP\ sh}.A_{15}$	20	72	3.3	3.9
B	$BC.C_0.R_N.A_{30}$	0	73	3.5	3.9
	$BC.C_5.R_N.A_{30}$	5	70	3.91	3.9
	$BC.C_{20}.R_N.A_{30}$	20	48	4.5	3.9
	$BC.C_5.R_{CFRP\ sh}.A_{30}$	5	80	3	3.9
	$BC.C_{20}.R_{CFRP\ sh}.A_{30}$	20	75	3.2	3.9



(**a**) (**b**)

Figure 5. Comparison of load deflection response for each group. (**a**) Group A; (**b**) Group B.

3.2.1. Specimens in Group A

Five specimens ($BC.C_0.R_N.A_{15}$, $BC.C_5.R_N.A_{15}$, $BC.C_{20}.R_N.A_{15}$, $BC.C_5.R_{CFRP\ Sh}.A_{15}$, and $BC.C_{20}.R_{CFRP\ Sh}.A_{15}$, as shown in Figure 6 were tested under a constant axial force of 15 kN, and we gradually applied a transverse load up to failure. Horizontal corrosion cracks appeared before testing due to internal pressure from the corrosion product. First, flexural cracks appeared in the middle third span of the tension face and started to propagate and widen. Then, inclined flexural shear cracks were shown. A flexural yielding followed by a concrete crushing failure occurred for the control and low corrosion specimens. A premature rupture of the corroded bars or a sudden rupture of the CFRP sheet were shown for high corrosion or strengthening specimens, respectively. A significant reduction in the ultimate flexural strength and serviceability was recorded with an increased level of corrosion degree in addition to a lower stiffness in all stages of load-deflection response. An improvement in defected/rehabilitated specimens was noticed in the behavior and increase in the ultimate strength by 22% for low corrosion level and 67% for high corrosion level with respect to corresponding defected specimens. Serviceability in terms of mid-span deflection was restored to the allowable limit of the American concrete institute (ACI) code.

Figure 6. Cracks pattern at failure for specimens in group A.

3.2.2. Specimens in Group B

Further, five specimens (illustrated in Figure 7) were tested under a constant axial force of 30 kN, and we gradually applied transverse loading up to failure. The crack patterns were similar to those of the previous group with more propagation of the flexural crack. A flexural yielding followed by concrete crushing failure occurred for the control and low corrosion specimens, a premature rupture of corroded steel bars occurred for high corrosion specimens, and a sudden rupture of CFRP sheet failure for strengthening specimens were modes of failure. An improvement was noticed in the behavior and increased in ultimate strength by 14% for the low corrosion level and 56% for the high corrosion level with corresponding defected specimens. Also, the serviceability in term of mid-span deflection was restored to the allowable limit of the ACI code. Compared with the specimens in Group A, the increase of the axial force was recorded to be a positive effect on the ultimate strength, as well as the service deflection and stiffness. This effect was evident in the corrosion-defected specimens by decreasing the adverse effect of corrosion.

Figure 7. Cracking patterns at failure for specimens in group B.

3.3. Maximum Crack Width

3.3.1. Specimens in Group A

During testing, the maximum crack width was recorded for flexural cracks in critical sections (maximum moment and corrosion region), as illustrated in Figure 8.

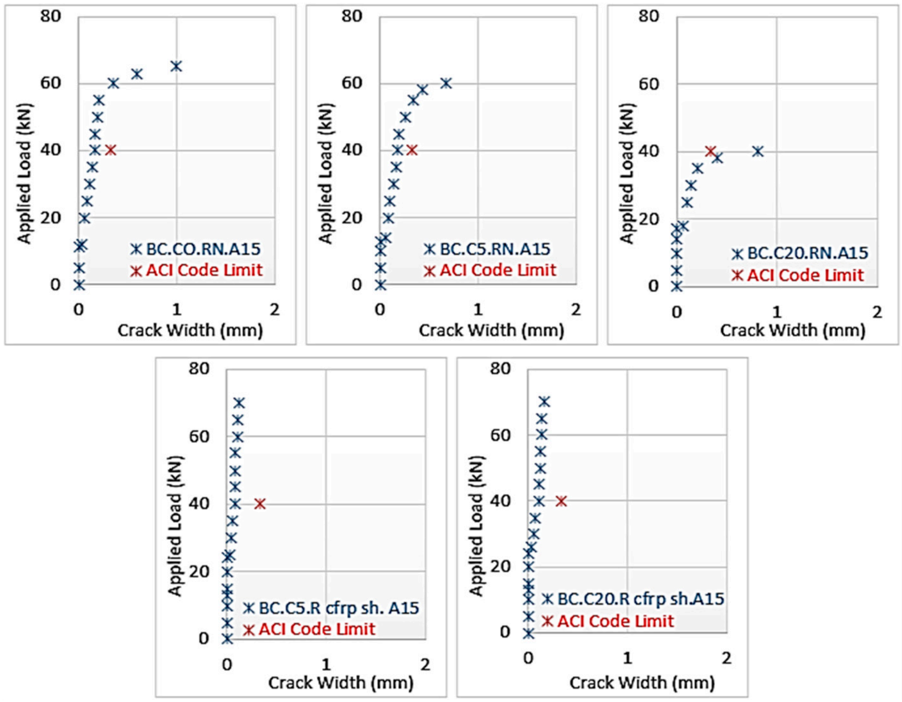


Figure 8. Maximum crack width for specimens in group A.

As shown in Figure 8, there are two effects on the maximum flexural crack width. The first effect was the corrosion effect, so one can notice that the maximum crack width at the same service load level increased by about (12.5% and 400%) when the corrosion level increased from 5% to 20% respectively, as compared with the non-corroded control specimens. That effect occurs because of the reduction of the cross-section area of corroded steel bars, which reduces its ductility. The maximum crack width for the specimen with a high corrosion level exceeded the allowable limit of the ACI code. Using the CFRP sheet to repair the defected specimens showed a significant decrease in the maximum crack width, which then restored the allowable limit.

3.3.2. Specimens in Group B

Moreover, the maximum crack width was recorded for the flexural crack in the critical section, as illustrated in Figure 9. The results of the maximum crack width in this group showed an effect of corrosion that was similar to those in group A, the maximum crack width at the same service load level increased by about 8% and 120% when the corrosion level increased from 5% to 20%, respectively, and compared with non-corroded control specimen. Also, the effect of increasing the axial force was shown by decreasing the maximum flexural crack width at the same load level, which is due to the reverse effect of the compression stress of the axial force.

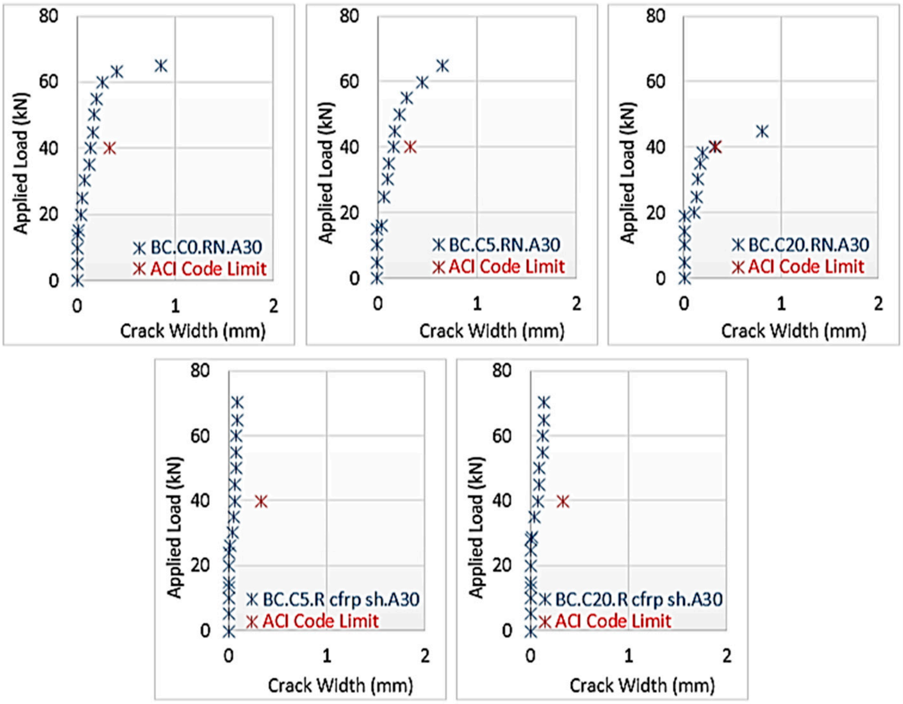


Figure 9. Maximum crack width for specimens in group B.

4. Conclusions

The main conclusions obtained from experimental results are as follows.

- After a period eight days and thirty-two days of accelerated corrosion, real corrosion degrees of 5.5% and 20.7%, respectively, were evidenced. Thus, the predicted corrosion level of Faraday's law was suitable to find the corrosion period in the reinforced concrete under accelerated corrosion.
- Significant deterioration in the ultimate strength, stiffness and serviceability were recorded due to the reduction in the mechanical properties of corroded steel bars, such as reducing the tensile strength, bond strength, and ductility.
- Compared with the control specimens, there were significant reductions 6%, and 4% in the ultimate flexural capacities for low corrosion levels and reductions of 37%, and 34% for high corrosion levels under axial forces of 15 kN and 30 kN, respectively.
- A significant deterioration in serviceability limited the state in terms of mid span deflection and a maximum crack width, which exceeded the allowable limit of the ACI code, was recorded.
- When applying external strengthening with CFRP sheet technique on the defected specimens, the problem of corrosion reinforcement could be overcome with different levels of efficiency, which might then enable the restoration of the structural integrity.
- By using a CFRP sheet for specimens with a low or high-corrosion degree, a complete restoration of load-carrying capacity, and even an improvement over the undamaged state, was recorded.
- The serviceability limit state of the defected/rehabilitated specimens in term of deflection and maximum crack width was restored to the allowable limit of the ACI code.
- The increase of the axial force for the defected specimens was shown to reduce the adverse effects of corrosion in regard to the ultimate strength, stiffness, and serviceability of RC beam–column members.

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