



Compressive Performance of Corroded Reinforced Concrete Columns

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KEY WORDS

Columns, corrosion, mass loss reinforcing steel, ultimate axial strain, ultimate axial strength.

ABSTRACT

Corrosion of reinforcement has been identified as the deterioration mechanism of reinforced concrete structures, which seriously affects the safety and integrity of structures. The corrosion of the embedded reinforcing steel in concrete is a major problem facing civil engineers today, which initiates 80% of the reinforced concrete structures deterioration. This paper reveals the outcomes of an experimental investigation on the mechanical performance (residual strength) of circular steel reinforced columns which have been damaged by corrosion of the steel rebar. Small scale circular reinforced concrete columns with a diameter of 100 mm and 300 mm in height were adopted. Different rates of steel reinforcement mass loss (corrosion damage) ranged between 10%, 20% to 30 % were created in the columns by using a galvanostatic accelerated corrosion method combined with wetting-drying cycles. The uniaxial compression test was implemented for damaged columns up to failure. Based on the experimental outcomes, it was revealed that the corrosion damage had substantially reduced the performance of columns. The decrement of the load capacity of corroded columns ranged between 19% to 40% and for corrosion level ranged from 10% to 30%, respectively. The decrement of the final deformation of corroded columns ranged between 15% to 30% and for corrosion level ranged from 10% to 30%, respectively. Likewise, the failure mode and relationship between the stress and strain for corroded columns had been adversely affected by corrosion.

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1. INTRODUCTION

Amongst all concrete durability problems, steel reinforcement corrosion has been recognized as the main source of the concrete structures deterioration. The increase of mass loss of corroded steel reinforcement is principally owing to two autonomous reasons. The first reason is the carbonation of the concrete cover and, therefore, the alkalinity of the concrete is lost. The second reason is the existence of ions of chloride in adequate quantities at the surface of steel reinforcement [1]– [3]. Reinforced concrete columns, like concrete piles, columns in highways bridges and marine structures, are valuable structural elements which are basically susceptible for corrosion of embedded steel due to exposing the moisture and harsh environment, leads to extreme reductions in the load carrying capacity and structural integrity of the columnar supportive elements. Besides to the anodic dissolving for steel bars, corrosion creates tensile strain in concrete surrounding region because of the corrosion products holds a larger volume than the original steel. The corrosion of steel bars has several adverse impacts: loss the cross section and the ductility of steel reinforcement bars, cracking and spalling in the cover of concrete, weakening the bond between the concrete and reinforcement steel. The serviceability and ultimate capacity of structure member is undesirably affected [4].

Many experimental researches reported on the performance of corroded reinforced members, especially the columns. Rodriguez et al. [5] implemented experimental investigation on reinforced concrete columns. The reinforced columns cross section was (200×200 mm) and the height (2000 mm). The reinforced concrete columns were prepared, corroded, and tested under compression. Corrosion was revealed to decrease the ultimate load carrying capacity and final axial strain in the affected columns relative to non-corroded columns. The reduction in the ultimate strength ranged from about 25% to 40% and for corrosion level ranged from 10% to 30%, respectively. Revathy et al. [6] studied experimentally the performance of the corroded reinforced columns. Columns of small size of reinforced concrete were prepared and synthetically corroded at corrosion level (loss of steel mass) ranged from 10% to 25%. The results showed that the ultimate strength, the ductility, and final strain of reinforced concrete columns decreases as the corrosion level increases. The decrease in strength and strain of corroded columns was mainly coming from the effect of corrosion on the section area of steel reinforcement. Xia et al. [7] studied the behavior of the corroded reinforced concrete columns. The concrete columns were fabricated, corroded by combined accelerated method (electrochemical process and wetting-drying cycles), and tested under compressive load. The obtained outcomes illustrate that the crack width of the corroded columns increases as the level of corrosion increases. Both the ultimate strength and stiffness of the reinforced columns were decreased as the level of corrosion damage increase. Likewise, Altoubat et al. [8] present a research to laboratory to simulate the effect of the corrosion on the reinforced concrete circular columns. Small scale reinforced concrete columns were fabricated, corroded and tested under uniaxial compression. The obtained outcomes exhibited that the corrosion of the reinforcement steel adversely affects the concrete column's performance. While, limited of locally experimental investigations have been executed on the performance of corroded reinforced concrete beams [9]– [11].

Despite the fact that the corrosion of the reinforcing steel in concrete is the main source of the deterioration of concrete structures, a limited number of local studies that focused on the effect of corrosion process on the performance of concrete structures, especially concrete columns. Thus, the main goal of this work is to assess experimentally the influence of selected corrosion level on the mechanical performance of circular reinforced concrete columns. Also, using the galvanostatic accelerated corrosion method combined with wetting-drying cycles were employed to simulate the corrosion process for columns.

2. EXPERIMENTAL WORK

A total of eight small scaling reinforced concrete columns with cylindrical shape (height 300 mm and diameter 100 mm) were exposed to different level of corrosion damage.

1. Preparation of the reinforced concrete columns

This subdivision summarizes the characteristics of reinforced concrete ingredients and the columns fabrications process were adopted in the current study. The mix ingredients involved are cement, fine and coarse aggregate, admixture, water and steel reinforcing bars. Steel reinforcement bars for fabrication of the reinforced concrete columns were deformed bars with 6 mm for

longitudinal reinforcement and 4 mm plain rounded bars for transverse reinforcement (spiral loops, obeying the qualifications of ASTM A-1064-15 [12]. High sulfate resistance cement manufactured by Karbala cement plant commercially known (Al-Jesr) was employed in the production of the concrete and conforms to cement type (V) requirements according to ASTM C-150-15 [13]. AL-Ekhaider naturally acquiring sand was used as a fine aggregate with 4.75mm maximum size, compatible to natural sand requirements according to ASTM C-33-13 [14]. Black crushed gravel of 9.5 mm maximum size from Al-Nebaai quarry was utilized as a coarse aggregate in the concrete production compatible to ASTM C-33-13 [14]. A third generation chemical admixture based on modified polycarboxylates copolymers, which is known commercially as Sika ViscoCrete, one of Sika products, was used as a high range water-reducing admixture. Sika ViscoCrete is deliberated and complies with ASTM C494-15 [15].

To accomplish the object of the current study, the concrete mix was designed in conformance with ACI 211-91 [16], to achieve a specified 40 MPa concrete compressive strength based on a 28 days, 100 cube. In consonance with the mix design, the adopted mix proportion of the concrete was (1cement :1.75 fine aggregate :3.5 coarse aggregate) by weight and, a ratio of water to cement equal to 0.38. In other words, the ingredients content for one cubic meter of concrete was 420, 750, and 1100 kg respectively, moreover, the water content was 160 liters. Numerous trial mixes were implemented to achieve appropriate workability. A high workability of the fresh concrete was acquired by 1.5 % dosage of superplasticizer by weight of cement. The workability was represented as slump of concrete, and the adopted slump was 120 ± 5 mm which was in agreement with ASTM C-143-12 [17]. Mixing process is essential to acquire the desirable homogeneity and workability of concrete mixture. The mixing procedure was implemented according to ASTM C-192-15 [18], utilizing 0.03 m³ capacity tilting concrete mixer.

Reinforced concrete cylinders simulated as short reinforced concrete columns with 100 mm diameter and 300 mm height were prepared and 28 days water cured to realize the object of the study. The concrete columns were reinforced with two types of steel reinforcement, six deformed steel bars of diameter 6 mm for longitudinal reinforcement. The tie reinforcement comprises of spiral stirrup made up from plain rounded steel bars of diameter 4 mm at 55 mm pitch distance. A concrete cover about 12.5 mm was maintained between the end of the spiral stirrup and the surface of the concrete. Figure (1) displays the details of reinforced circular concrete columns. Four series of reinforced concrete columns were cast, cured, exposed to saline solution for three days (then to 500 $\mu\text{A}/\text{cm}^2$ external electrical current with 1 wetting and 3 drying cycles method) and tested under uniaxial compression loads.

II. Accelerated corrosion regime

The manner of steel corrosion naturally is very slow, demanding more than ten years from origin to extreme structural destruction. For instance, Zhang et al [19]– [21] who permitted the laboratory specimens to rust naturally, needed to wait more than four years for starting steel corrosion and an extra two years for occurring the first crack, they only acquired extreme structural damage after 20 years. These intervals are not frequently provided in laboratory tests. Researchers, reasonably, require and proceed to use several techniques to accelerate the steel corrosion in an attempt to reduce the required testing time. Several accelerated corrosion methods, but most comprises one or a combining of succeeding principles [22]– [24]:

- 1- Impressing an electrical current throughout the embedded steel reinforcement (glavanostatic method).

- 2- Exposure the samples to high humidity circumstance (by spraying, ponding, and wetting-drying cycles).

- 3- Providing the chlorides to samples (direct adding to mixing water or via immersion the samples in the chloride solution).

Numerous studies have been stated in the literature on accelerated corrosion of reinforced concrete specimens via impressed current technique (also known as galvanostatic method) combined with saline solution [9]– [11], [25], [26]. Afterward of water curing for 28 days, the reinforced concrete circular columns were immersed in a solution of NaCl (salt concentration of salt of 3.5%) for 3 days for eliminating the passivity of steel reinforcing bars, at that time the columns were encircled by a mesh of stainless steel. The gap between stainless steel net and the concrete reinforced

columns and was occupied by sponge material. A constant electrical current was provided between the anode (steel reinforcing bars in the circular concrete columns) and the outside cathode (stainless steel mesh), by a D.C. power device. The employed current was $500 \mu\text{A}/\text{cm}^2$. The 1-day wetting- 3-days drying cycles of the NaCl solution (concentration of 3.5%) were joined with impressed current throughout the corrosion process. In the drying periods, the impressed current was switched off. The concrete columns were taken away and subjected to room air for drying periods. The preparations of the system of acceleration corrosion procedure was designated by Radhi et. al [27], [28]. The reinforced columns under corrosion process were observed once for each day. The columns were allocated into four groups based on the required level of steel corrosion (0 % corrosion, 10% corrosion, 20 % corrosion, and 30% corrosion). The level of corrosion indicates to the percentage of loss mass of steel reinforcement in affected columns. The required time for exposing the accelerating steel process for each group was theoretically calculated by Faraday's law, ((Many former researchers have effectually employed the Faraday's law to theoretically calculation of steel mass loss or estimation the essential time for attaining a definite level of corrosion in the reinforced concrete samples (Equation .1) [29] – [33]). The accelerated corrosion process was accomplished for all columns at about 120 days.

$$t = (\Delta m F Z) / (M i) \quad (1)$$

Where: (t) is the required time for corrosion in seconds. (F) is the Faraday's law constant 96500 A/s. (Δm) is steel mass loss caused by the accelerated corrosion regime, (M) is the steel molar mass which is about 56 g, (i) is the current impressed accelerated corrosion regime in Am. (Z) is the ionic charge in iron equal to 2.

III. Uniaxial Compressive Strength Test

All reinforced concrete columns were tested under uniaxial compression load, prior to compressive testing all reinforced concrete columns were capped at upper end with a thin high strength concrete. As well as, all unconfined reinforced concrete columns were confined at both end by steel rings. To measure the load capacity and stress-strain performance for the concrete columns, automatic computerized compression MCC control machine of 2000 kN capacity was utilized at displacement level of 0.25 mm per minute. The compression instrument was incorporated with three centrifugal linear variable differential transducers (LVDTs) were located at mid height of concrete samples. Figure (2) displays the arrangements of the testing process, an automatic information acquirement system was utilizing for recording the axial loads and corresponding displacements.

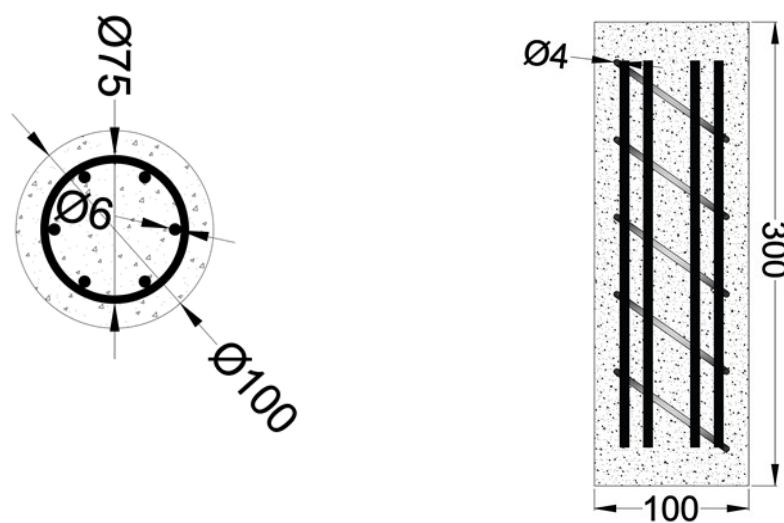


Figure 1: Column schematic, rebars details and section (all dimensions are in mm).



Figure 2: The column specimen under compression load.

IV. Tables

All tables should be numbered according to their appearance in the text. Refer to tables as Table 1 and Tables 1 and 2 in the paper text. The data are black and white but sometimes include color.

3. RESULTS AND DISCUSSION

Ultimate loads and final axial displacement for each column were recorded throughout the testing and the outcomes are illustrated in Table (1).

TABLE I: The results of concrete columns in the current study.

Column No.	Series	Corrosion level %	Ultimate Loads (kN)		Axial displacement (μm)	
			Individual	Average	Individual	Average
1	I	Without	419	408	195	178
2		Corrosion	397		161	
3	II	10%	342	331	173	150
4		Corrosion	320		127	
5	III	20%	323	290	157	142
6		Corrosion	257		127	
7	IV	30%	267	244	134	125
8		Corrosion	221		116	

I. Load Carrying Capacity

Reinforced concrete column specimens were tested under uniaxial compression after artificially subjected to accelerated corrosion regime at different duration (the complete duration is about four months). The required level of corrosion damage (mass loss) were (10%, 20%, and 30 %), then compared with non-corroded columns. Pattern of the corrosion cracks were observed after accomplish of the accelerated corrosion process. Utmost of the corroded reinforced concrete circular columns had surface cracks at least sides of column equivalent to the main reinforcing steel bar was identified. The corrosion cracks increased in the width and numbers as the level of the corrosion increased by reason of higher corrosion expansion effect for severe level of corrosion (30 %). The crack widths based on the corrosion level varied from about 0.7 mm to 2.9 mm.

The influence of steel corrosion on load capacity of the corroded reinforced concrete columns associated with the unaffected columns is very clear, as displayed in Figure (3). The tested reinforced concrete columns exhibited a decline in the ultimate load carrying capacity with increasing the level of the steel reinforcement corrosion. The percent of the reduction in the ultimate load capacity for the columns with corrosion damage level 10%, 20%, and 30% was about 19%, 20 %, and 40%, correspondingly. This reduction in the load capacity can be attributed to adverse influence of the corrosion process on the steel bars section, the damage of concrete section, and the drop of the bond between the steel bars and the concrete. This trend of performance in the corroded reinforced concrete columns is to some extent similar trending that stated by other researchers [4], [6].

II. Final Displacement

The influence of steel corrosion on the final axial displacement of the corroded reinforced concrete columns related with the non-corroded columns is very clear, as demonstrated in Figure (4). The tested reinforced concrete columns revealed a decrease in the final displacement with increasing level of the steel reinforcement corrosion. The percent of the reduction in the final displacement for the columns with corrosion damage level of 10%, 20%, and 30% was about 15%, 21%, and 30%, correspondingly. This reduction in the final displacement can be attributed to adverse influence of the corrosion process on ductility and energy absorption of the corroded columns. This tendency of performance in the corroded reinforced concrete columns is to some extent comparable trending that identified by other researchers [6], [7].

III. Stress Strain Performance

Stress strain curves were plotted for non-corroded and corroded reinforced concrete columns, and are presented in Figure (5) to indicate the effect of the steel corrosion on the mechanical performance of the reinforced concrete column. The relationship between the axial stress and axial strain was considerably affected by corrosion owing to loss in the strength capacity of corroded reinforced concrete columns. In the ultimate condition, the stress strain response of corroded columns decreased as the corrosion degree of the corroded columns increased. The ultimate strength of corroded columns was reduced with rise in level of corrosion destruction. The ultimate strength of column was 50.95, 43.68, 38.21, and 32.36 MPa for 0%, 10%, 20%, and 30% level of corrosion correspondingly. The final axial strain was reduced with growing the amount of corrosion level. The final strain percent of column was 0.118 %, 0.101%, 0.095%, and 0.083% for 0%, 10%, 20%, and 30% level of corrosion correspondingly. Moreover, this tendency of decreasing the slope of the curve with rising amount of corrosion destruction level designate to steady decrease in the stiffness and ductility of the corroded columns. This proposal about stress strain performance of the corroded reinforced concrete columns was supported by other researchers [25], [34].

IV. Mode of Failure

The failure mode presents an important information for assessment of the ultimate situations of different kinds of reinforced concrete [35], [36]. Figure (6) displays the failure mode for reinforced concrete columns at different corrosion level after testing. Dissimilarity in the mode of failure was identified between the corroded and non-corroded reinforced concrete columns. The shear failure mode was the typical failure mode for unaffected reinforced concrete columns. This kind of failure happened instantly afterward the stress attained its ultimate strength. This failure was attended by abrupt fracture with a high pitch sound. While, the failure mode of corrosion affected columns were gradually converted from former failure mode to splitting and debonding failure mode as the corrosion level of damaged columns increased, and it was clearly observed in the higher level of the corrosion. A regular reduction in the stress afterward the failure was perceived lower companying sound failure. This trend in the failure was a result of the existing cracks and loss of the bond between the concrete and steel reinforcement in corroded reinforced concrete columns.

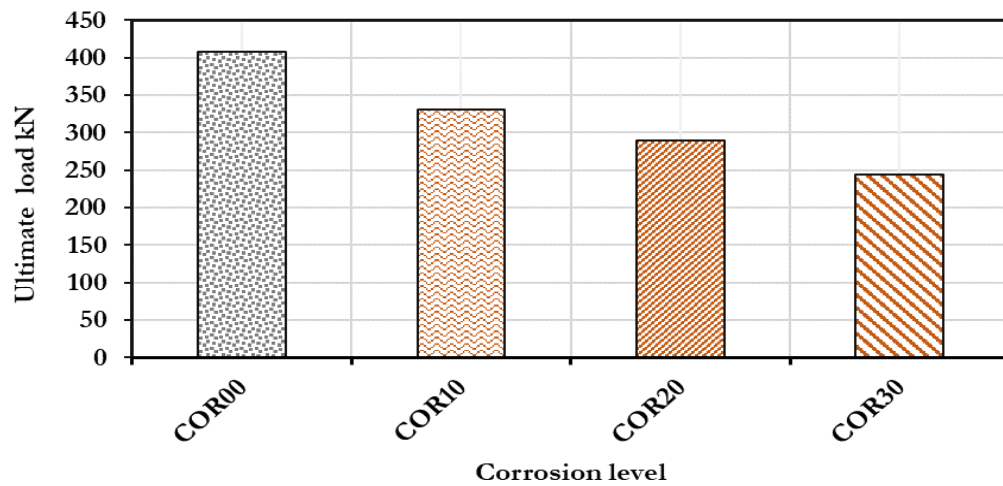


Figure 3: The effect of the corrosion on the load capacity of columns.

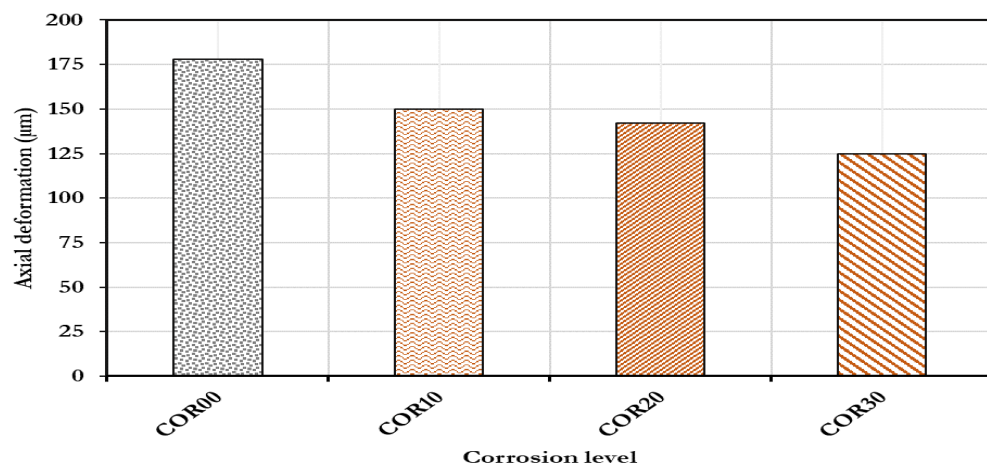


Figure 4: The effect of the corrosion on the final displacement of columns.

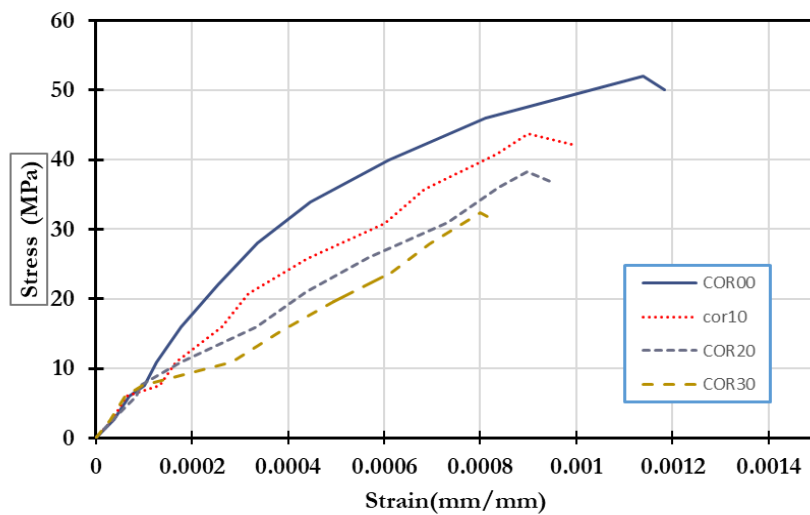


Figure 5: Stress strain curves of the corroded columns.



(a)



(b)



(c)



(d)

Figure 6: The mode of failure at different corrosion level. (a) without corrosion. (b) 10 % level. (c) 20 % level. (d) 30 % level

4. CONCLUSIONS

Depending upon the outcomes that attained from experimental investigation on the influence of the level of corrosion damage on performance of the circular reinforced concrete columns, the subsequent findings can be determined:

1-The clear corrosion damage in the reinforced concrete columns due to corrosion process only can be observed by pattern and width of the cracking.

2-The load carrying capacity of the corroded reinforced concrete columns reduces as the level of the corrosion increases. The reduction in the ultimate loads was about 19%, 29 % and 45% at level of corrosion damage of 10%,20%, and 30%, respectively.

3-The increasing in corrosion level damage lead to decrease in the final displacement. The decrement of the final displacement under compression test for corroded reinforced concrete columns was around 15%, 21 % and 30% at level of corrosion damage of 10%,20%, and 30%, one-to-one.

4-The slope of the stress and strain curves decreases as the corrosion level increase, that means reduction in the stiffness and ductility of corroded reinforced concrete columns.

5-The mode of failure of the concrete columns gradually transformed from shear failure mode to splitting and debonding mode as the corrosion level increase.

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