Effect of Rebar Corrosion Level on Behaviour of Reinforced of Corroded Columns

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Abstract. Corrosion of steel reinforcement has been specified as the impairment mechanism of reinforced concrete buildings, which severely affects the safety and integrity of buildings. The corrosion of the embedded reinforcing steel in concrete is a significant trouble facing civil engineers nowadays, which initiates 80% of the reinforced concrete buildings impairment. This paper detects the outcomes of an experimental investigation on the mechanical performance of five squared steel reinforced columns which have been damaged by corrosion of the steel rebar. Small scale square reinforced concrete columns with a rectangular cross-section of b×h=150mm×150mm and 500 mm in height were adopted. Various degrees of steel reinforcement mass loss (corrosion damage) ranged between 8%, to 15 % were formed in the columns by using an accelerated galvanostatic corrosion method. The uniaxial compression test was carrying out for harmed columns up to failure. Based on the experimental outcomes, the corrosion damage had substantially reduced the performance of columns. The deterioration of the load capacity of corroded columns was 13.4%,24.6%,22.5% and 45.34% at level of corrosion damage of 8% and 15% respectively for longitudinal bars only and for longitudinal and ties reinforcement. The reduction of the axial and lateral deformation of corroded columns ranged between 7.1% to 70.22% and for corrosion level ranged from 8% to 15%, respectively. Likewise, the failure mode for corroded columns had been adversely affected by corrosion.

Keywords: corrosion, rebar, modes of failure, concrete column, Accelerated corrosion

1. Introduction
corrosion of the embedded reinforcing steel reduced the service lifetime of a reinforced concrete structure. Such corrosion is due to aggressive agents which come from the ambient environment. Chloride is the most harmful aggressive agent contained either in deicing salts or in seawater. The passive film is locally damaged under chloride attack and steel starts to dissolve in these unprotected areas. Thereupon, the amount of corrosion products increases and depassivated areas grow. When these products are solid, their volume is higher than their original metal. As this volume gradually increases, a pressure is induced around the embedded steel, and the concrete cover expands up to possible cracking, spalling or delamination. [1], to describe the corrosion process of steel in concrete different conceptual models are proposed [2-4] According to Tuutti, Kyosti [2], steel corrosion in concrete under natural conditions includes two consecutive stages the first stage when aggressive agents enter concrete without depassivating steel “initiation” and “propagation”, when corrosion is
initiated, so that rust forms and expands around the steel and cracking or induces cover swelling. According to [3], three consecutive distinct stages are to be considered involving diffusion of aggressive agents, steel corrosion and deterioration of cover deterioration. The first stage is the same as the initiation stage described by [2]. The second stage corresponds to the development of corrosion products resulting in the first damage and the third stage (deterioration) starts when the damaged reinforced concrete structure needs to be rehabilitated. These models for steel corrosion in concrete were complemented in [4]. In fact, the process of reinforcement corrosion under outdoor environment is very slow; usually the first crack observed on the external concrete surface appears after numerous years. So laboratory studies need an acceleration of corrosion process to achieve a short test period. This can be accomplished by applying an electric current of constant magnitude [5–7] or a constant potential [8,9] to the embedded steel. In accelerated tests, ion migration chloride penetration is increased. Corrosion rate is growing by an electric field on steel surface. The results obtained have many applications. Accelerated corrosion tests are carried out by [5,9] to understand the effect of corrosion on bond strength of reinforced concrete. Cracking of the cover versus rebar corrosion is studied in [6,7].

Many experimental researches reported on the performance of corroded reinforced members, especially the columns. Rodriguez et al. [10] prepared experimental investigation on reinforced concrete columns. The reinforced columns height was (2000mm) and the cross section was (200×200 mm) The reinforced concrete columns were corroded and tested under axial compression. Corrosion was detected 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 for corrosion level ranged from 10% to 30% about 25% to 40%, respectively. Revathy et al. [11] studied the behavior of the corroded reinforced concrete columns experimentally. small size of reinforced concrete Columns were prepared and synthetically corroded at corrosion level (loss of steel mass) ranged from 10% to 25%. The results showed that the ductility, the ultimate strength, and final strain of reinforced concrete columns decreases as the increases corrosion level. The decrease in strength and strain of corroded columns was coming mainly from the effect of corrosion on the section area of steel reinforcement. Xia et al. [12] studied the performance 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 illustrated that the crack width of the corroded columns increases as the level of corrosion increases. Both the stiffness and ultimate strength of the reinforced columns were reduced as the level of corrosion damage increase. Likewise, Altoubat et al. [13] present a research to simulate the effect of the corrosion on the reinforced circular columns. Small scale reinforced concrete columns were fabricated, corroded and tested under compression load. The result obtained 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. [14]

Despite the fact that the one source of the deterioration of concrete structures is the corrosion of the reinforcing steel in concrete, a limited number of local studies that focused on the effect of corrosion process on the performance of concrete structures, especially concrete columns.

2. Research Objectives

The main objective of this work is to evaluate the condition of corrosion-damaged structures and assess the effect of selected level of corrosion of longitudinal bars and lateral ties reinforcement on the performance of square reinforced concrete columns. Also, Study the mode of failure of corroded reinforced concrete column and Investigate the load. Bearing capacity of reinforced concrete column in case of longitudinal rebar corrosion or / and lateral rebar corrosion.
3. Experimental program

3.1. Specimens details
A total of 5 RC columns were tested in this study which included 4 corroded columns were subjected to 8% degree of corrosion damage and 1 uncorroded column. Each sample was designed 500mm long with a rectangular cross-section of b×h=150mm×150mm. throughout the length of the uniform cross-section, all columns have four 12mm diameter deformed steel bars were symmetrically located and served as longitudinal bars and have 35 Mpa concrete compressive strength. all five columns have ties reinforcement consisted of 8mm diameter plain stirrups spaced at 150 mm shown in figure 1.

Column specimens were identified with a series of letters and number which referred to the number of specimen and type of parameter. Where, (col) represented the abbreviation of column word. The numbers (1, 2, 3, 4, and 5) represented the number of specimen. The next number represent the value of parameter While the letters (L%, T%) referred to the abbreviation of parameter where (L%) represent the change in corrosion level of longitudinal bars and T% represent the change in corrosion level of the lateral tie’s reinforcement.

3.2. Mixing, casting and curing of specimens
A summary of the properties of concrete constituent materials and steel reinforcement that have been used in this research including cement, sand, gravel, and reinforcing bars. sulfate resistance cement type v, meet to ASTM-C150-17 [15], The chemical properties and physical composition of this cement are shown in Tables (2) and (3), respectively. Al-Ukhaider natural sand was used as fine aggregate confirmed the requirements of ASTM-C33-16 [16], with 2.93 fineness modulus and 0.3 sulfate content. Al-Nebai crushed black gravel was used as coarse aggregate compatible to ASTM-C33-16 [16], with 9.5 mm maximum and 0.07 sulfate content. The approved concrete mix proportion was based on several trial mixes were made to achieve a specified concrete compressive strength (35Mpa). based on 150 mm cubes (equivalent of 28 MPa for cylinder) at 28 days. The mix was 1:1.8:3.5 (cement: sand: gravel) and the water to cement ratio equaled to 0.38. The 12mm diameter deformed bar had yield stress and ultimate strength of 545Mpa and 641 Mpa, respectively; while the 10mm diameter plain bar had yield stress and ultimate strength of 522Mpa and 621Mpa respectively.

Sika products was used as a high range water-reducing admixture and it add 1.5 % by the cement weight. Sika ViscoCrete is deliberated and complies with ASTM C494-15 [18]. All reinforced concrete columns were cured in tap water for 28 days.

3.3. Accelerated corrosion
Previous researchers have utilized impressed electrical current methods for accelerating the corrosion of reinforcement steel bars in reinforced concrete. The idea of using external electrical currents is extremely simple and include creating an electrochemical circuit using an external D.C power supply. The steel reinforcing bars act as an anode in the cell and another material acts as the cathode. After that the specimens were cured for 28 days four small-scale reinforced columns were corroded artificially by impressed current technique to investigate the compressive performance of columns affected by corrosion the concrete columns specimens were immersed in 5% sodium chloride solution in a tank for 3 days to depassivate the steel embedded in column by removed the protective layer [19] as shown in figure 3. The stainless-steel plate was placed in the tank in such a manner that it covered both the sides of the columns throughout the length. This arrangement ensured a uniform distribution of current along the whole length of the bar. figure 3 shows the configuration of the column in the accelerated corrosion set-up. The samples were connected to an external DC power supply acting as an
anode (+), while a steel plate was positioned around the samples as a cathode (−). The samples were connected as parallel connections to the circuit board to maintain a constant voltage of 12 volts throughout the whole experiment. The applied DC currents were 400 μA/cm².

| Specimen       | L % | T % |
|----------------|-----|-----|
| Col-1-control  | 0   | 0   |
| Col-2-8% -L    | 8%  | 0%  |
| Col-3-15% -L   | 15% | 0%  |
| Col-4-8% -T    | 8%  | 8%  |
| Col-5-15% -T   | 8%  | 15% |

**Table 1.** specimen design details and designations

| Composition of Oxide | Abbreviation | Percentage by Weight | ASTM C150 -17 |
|----------------------|--------------|----------------------|---------------|
| Lime                 | CaO          | 51.3                 | -             |
| Silica               | SiO2         | 22.6                 | -             |
| Alumina              | Al2O3        | 3.43                 | -             |
| Iron oxide           | Fe2O3        | 4.32                 | -             |
| Sulphate             | SO3          | 1.6                  | ≤ 2.3 %       |
| Magnesia             | MgO          | 3.24                 | ≤ 6 %         |
| Loss on ignition     | L.O. I       | 2.51                 | ≤ 3 %         |
| Lime Saturation Factor| L.S.F       | 0.715                | 0.66 – 1.02   |
| Insoluble Residue    | I.R.         | 1.36                 | ≤ 0.75 %      |

**Table 2.** Chemical composition and main compounds of cement

| Main Compounds (Bogue’s equation) | % by Wt. |
|-----------------------------------|----------|
| Tricalcium Silicate               | 69.29    |
| Dicalcium Silicate                | 6.15     |
| Tricalcium Aluminate              | 1.78     |
| Tetracalcium Aluminoferrite       | 9.63     |

**Table 3.** Physical properties of cement

| Physical properties                     | Test results | ASTM C150-17 |
|-----------------------------------------|--------------|---------------|
| Fineness (Blaine Method), m²/kg         | 263          | ≥ 260         |
| Setting time (Vicat’s Method) min       |              |               |
| Initial                                | 124          | ≥ 45 min      |
| Final                                  | 207          | ≤ 375 min     |
| Soundness Autoclave Method%            | 0.06         | ≤ 0.8         |
| Compressive strength, MPa | 3 days | 7 days |
|--------------------------|--------|--------|
|                          | 17.6   | ≥ 15   |
|                          | 24.4   | ≥ 21   |

3.4. Steel mass loss

Many previously researchers have effectively employed the Faraday’s law to theoretically calculate the required time for acquiring a specific level of corrosion in the steel reinforcement of concrete columns or assessment steel mass loss. In the current study, the Faraday’s law was used theoretically calculate the loss in mass of steel bars due to the steel corrosion process from the accelerated system in the corroded reinforced concrete columns based on the impressed current technique. Where the times in which 8% and 15% corroded are achieved was 14 days and 29 days respectively. Faraday’s law as follow (eq. 1) [20]:

\[ T = \frac{(\Delta m \times F \times Z)}{(M \times I)} \]  

Where:

\((M)\) is the steel molar mass which about 56 g, \((\Delta m)\) theoretical steel mass loss caused by the accelerated corrosion regime, \((i)\) is the impressed accelerated corrosion regime in Am. \((Z)\) is the ionic charge in iron equal 2. \((T)\) is the required time for corrosion in second. \((F)\) is the Faraday’s law constant 96500 A/s.
4. Test setup
A 2500 kN capacity compression testing machine (AVERY) located at the Structural Laboratory of the Building and Construction Engineering Department of the University of Technology, was used to apply monotonically compressive load to the column specimens similar method to previous studies. A total of three centrifugal linear variable differential transducers (LVDTs) were located at mid height of concrete samples were used for all specimen, the gross axial shortening of the column specimen was measured by applying a (LVDTs) placed at the bottom surface of the testing machine while the other (LVDTs) located at the mid height of the columns was used to measure the lateral displacement. figure (4) and figure (5) display the arrangements of the testing process. Throughout testing process, an automatic information acquirement system was utilizing for recording the axial loads and corresponding displacements. All the RC columns were capped at their upper end using a thin high-strength material to prevent non-uniform load distribution during the test. Furthermore, the unconfined RC columns were confined by steel rings at both ends to prevent premature failure in the regions adjacent to their ends.[21],[22]

5. Results and Discussion
the outcomes obtained after accelerated steel corrosion for the five columns. Steel loss, observable cracks configuration was adopted as indicators for steel bars corrosion. Table 4 summarizes the remark of the steel corrosion in the current study.

5.1. Load Carrying Capacity
Reinforced concrete column specimens were tested under uniaxial compression after subjected artificially to accelerated corrosion process 14 days and 29 days to achieve required level of corrosion damage (mass loss) (8% and 15%) then compared with control columns. The influence of reinforcement corrosion on load capacity of the corroded concrete columns related with the unaffected
columns is very clear, as displayed in Figure (6). The tested columns illustrated a decline in the ultimate load carrying capacity with increasing the mass loss of the steel corrosion. The percent of the decreasing in the ultimate capacity for the columns samples (Col-2-8\% -L, Col-3-15\% -L, Col-4-8\% -T, and Col-5-15\% -T) with corrosion damage level of 8\% and 15\% were about 13.4\%, 24.6 \%, 22.5\% and 45.34\% correspondingly. This reduction in the load capacity due to detrimental influence of the corrosion on the steel bars section, the damage of concrete section, and the deteriorate of the bond between the concrete and the steel bars. This trend of behavior in the reinforced corroded concrete columns in some way similar trending that indicated by other researchers [11], [23].

The chemical half-cell reactions occurring at the anodic and cathodic areas are as follows

\[
\text{At the anode: } \text{Fe} \rightarrow \text{Fe}^{2+} + 2e^- \quad (2)
\]
\[
\text{At the cathode: } 2e^- + \text{H}_2\text{O} + (1/2) \text{O}_2 \rightarrow 2(\text{OH})^- \quad (3)
\]

The hydroxyl ions, OH\(^{-}\) arriving at the anodic area electrically neutralize the Fe\(^{2+}\) ions dissolved in pore water and from a solution of ferrous hydroxide at the anode: Fe\(^{2+}\) + 2(\text{OH})\(^{-}\) → Fe(\text{OH})\(_2\). This compound Fe(\text{OH})\(_2\) reacts further with additional hydroxide and available oxygen, to form the water insoluble red rust: Red rust is not the only product of corrosion of steel in concrete. Compounds such as black rust Fe\(_3\)O\(_4\), green rust, FeCl\(_2\) and other ferric and ferrous oxides, hydroxides, chlorides hydrates are also formed.[24]

**Table 4.** The results of concrete columns in the current study

| Column parameter | Ultimate load (KN) | Axial displacement (mm) | Lateral displacement (mm) |
|------------------|--------------------|-------------------------|--------------------------|
| Col-1-control    | Control            | 770                     | 4.5                      | 0.91                     |
| Col-2-8\% -L     | L-8\%              | 666.7                   | 5.31                     | 1.06                     |
| Col-3-15\% -L    | L-15\%             | 580.3                   | 5.6                      | 1.12                     |
| Col-4-8\% -T     | T-8\%              | 596.7                   | 5.84                     | 1.16                     |
| Col-5-15\% -T    | T-15\%             | 420.85                  | 6.43                     | 1.28                     |

5.2 **Axial and Lateral Deformation**

The corrosion effect of steel on the axial displacement of the corroded columns Compared to the non-corroded columns is very clear, as proved in Figure (7) and Figure (8). The tested reinforced concrete columns illustrated an increase in the axial displacement with rising level of the steel bars corrosion. The percent of the increment in the axial displacement for the specimens Col-2-8\% -L, Col-3-15\% -L, Col-4-8\% -T, and Col-5-15\% -T have been about 18\%, 24.4\%, 29.77 and 42.88\%, correspondingly. While The percent of the increment in the lateral displacement were about 16.48\%, 23.07\%, 27.47 and 40.56\%, respectively. This reduction in the axial 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 [12], [13].
Figure 6. Effect of corrosion on the failure load

Figure 7. The effect of the corrosion on the axial displacement of columns.

Figure 8. The effect of the corrosion on the lateral displacement of columns.
5.3. Load –displacement Curves

Load –displacement curves were plotted for corroded and non-corroded reinforced concrete columns, and are presented in Figure (9) and Figure (10) to indicate the effect of the steel corrosion on the mechanical performance of the reinforced concrete column. The relationship between the axial load and displacements was considerably affected by corrosion owing to loss in the strength capacity of corroded reinforced concrete columns. The stiffness of the load-vertical displacement and load-horizontal displacement decrease with corrosion of rebar increasing. The ultimate capacity of corroded columns was reduced with increase in level of corrosion demolition. The slope of the load and displacement curves decreases as the corrosion level increase, that means reduction in the stiffness and ductility of corroded reinforced concrete columns.

Figure 9. Load – Axial displacement curves of the corroded columns.

Figure 10. Load – Lateral displacement curves of the corroded columns.
5.4. Mode of Failure
The mode of failure presents an essential information for assessment of the ultimate situations of different types of reinforced concrete column. Figure 11 displays the failure mode for each column. Variance in the mode of failure was identified between the non-corroded and corroded reinforced concrete columns. The failure of uncorroded column starts with the axial deformation in both concrete column and longitudinal rebar. After that, the longitudinal rebar buckled outside in the middle of the column causing splitting of the concrete cover. The splitting failure moves towards the ends of columns causing column failure. Meanwhile, the failure of the corroded column starts with splitting cracks at both ends due to reach the concrete ultimate tensile strength. These cracks move towards the middle of the column causing failure. Due to loss of mass of rebar and bonding between concrete and rebar, the failure of corroded column controlled by the splitting strength of concrete material. The mode of failure of the concrete columns gradually transformed from pure compression failure mode to splitting and debonding mode as the corrosion level increase.
Figure 11. The mode of failure at different corrosion level. (a) without corrosion. (b) 8 % level for longitudinal bars. (c) 15 % level for longitudinal bars. (d) 8 % level for longitudinal bars and ties. (e) 8 % level for longitudinal bars and 15% for ties.
6. conclusion

Depending upon the results 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 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 13.4%, 24.6%,22.5 and 45.34% at level of corrosion damage of 8% and 15% respectively for longitudinal bars only and for longitudinal and ties reinforcement.
2-The increasing in corrosion level damage led to increase in the axial displacement. The increment of the axial displacement under compression test for corroded reinforced concrete columns was around 18%, 24.4, 29.77 and 42.88%, at level of corrosion damage of 8%, and 15%, one-to-one.
3- The increasing in corrosion level damage led to increase in the lateral displacement. The increment of the axial and lateral displacement under compression test for corroded reinforced concrete columns was around 16.48%, 23.07%, 27.47 and 40.56% at level of corrosion damage of 8% and 15%, one-to-one.
4-The slope of the load and displacement 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 pure compression failure mode (traditional) to splitting and debonding mode as the corrosion level increase.

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