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**Technical Research**

# PERFORMANCE OF CORRODED THIN-WALLED STEEL TUBULAR COLUMNS FILLED WITH CONCRETE UNDER DIRECT MONOTONIC LOADING

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**Abstract:** The current experimental work investigates the structural behavior of steel tubular columns filled with concrete (STCFC) subjected to corrosion conditions as well as direct axial and uniaxial loading. To find out the ultimate capacity for bearing corroded columns, eight steel tubular square columns filled with normal strength concrete (NSC) having a cross section of (100×100mm), a thickness of (1.5mm) and a length of (1000-1200mm) were tested under concentric and eccentric loads. The main variables that were adopted in this experiment are the column type (slender or short), the type of the applied loads (concentric or eccentric), and the thickness of the steel columns (before and after corrosion). The experimental results indicated that, after the steel columns were exposed to (5%) dilute sulfuric acid for (8 days), it was found that the thickness of the steel columns had decreased by about (55%), which led to a decrease in the bearing capacity of the tested corroded steel columns by about (48% and 43%) for slender columns subjected to concentric and eccentric loads respectively, and by about (47% and 44%) for short columns subjected to concentric and eccentric loads respectively.

**Keywords**: *Steel tubular columns; corrosion; concrete; short column; axial and uniaxial loading.*

## 1. Introduction

Steel tubular columns filled with concrete have attracted special attention among the structural columns installed by engineers. A hollow steel tube filled with concrete is formed by filling a hollow steel tube, whether rectangular, square, or circular, with concrete. Steel tubes with a circular tube section were used at the beginning of the last century, while square or rectangular tubes were used more recently, and most of the tests were conducted on circular columns. The hollow steel tube surrounds the concrete, which acts as a longitudinal and lateral reinforcement, which exposes the steel part to biaxial stresses, represented by longitudinal stress and ring tension, which affect the mechanical behavior of the hollow columns. These steel tubes can also be used in the case of seismic loading due to the large capacity of the hollow steel tubes [1]. The effect of height on columns has different meanings for both the designer and the executor. For the designer, the thin column means more accuracy in the design and the use of an amplification factor for torque, and then calculating the critical load for screeding. The rectangular or square element is considered long if the ratio of its length to its dimension increases in the direction dependent on (Le/B ≥12) [2]. corrosion is the biggest problem in steel structures, which can have an effect on metal

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properties. Corrosion is the damage of a metal through chemical attack or reaction in the environment in which it is present. Corrosion is a major problem and is difficult to eliminate completely [3]. The effect of corrosion varies with the location and type of structure and the extent of deterioration. Steel structures are affected by corrosion in many ways, including the main effects of losing materials from the surface of the steel member, which leads to the formation of thin areas in some parts of the steel structure. Part loss can also occur as a result of regular wear over a large area of the steel structural member. Corrosion causes reductions in the properties of steel sections such as cross-sectional area, section modulus, moment of inertia, and radius of gyration, which reduce the carrying capacity of the steel structure [4]. When steel corrodes, corrosion products form on the surface, leaving a poor-quality steel layer on the surface of steel and steel reinforcement; this layer works to form a weak bond with the concrete surrounding the steel section or steel reinforcement, which leads to reducing the section capacity. In some cases, including lap joints or anchorage, this may lead to a reduction in the effective anchorage length, which leads to premature failure in some sections [5].

**Zhao et al. (2018) [6]** investigate the compressive behavior of thin-walled square columns strengthened with steel bars without pouring concrete inside steel tubular columns. Six specimens with dimensions of (200mm×200mm), a thickness of about (2mm) (thickness of the hollow steel column), and a length of about (1200mm) were used to conduct this study. In terms of specimen strengthening, steel bars of diameters (12-16 mm) are used, where weak stiffener steel bars are welded inside the hollow steel column, while high stiffener steel bars are welded outside the hollow steel column. An axial load is applied to the columns to know the type of failure, load-displacement relationship, ultimate load, ductility, and local buckling of each test specimen. if a load of (1/10) is shed at the beginning of the test, and then a load of (1/20) of the maximum load is applied.

**Katie (2014) [7]** studied the behavior of axially loaded steel tubular columns filled with five different types of concrete. Seventy-four specimens of steel tubular columns with different sections (square, rectangular, and circular) were tested. All the tested specimens with circular, square, and rectangular sections have a length of (300mm), (500mm), and (1000mm) respectively, while the thickness of the hollow steel column section is selected with different values of (1.6mm), (3.2mm), and (4.8mm). From the other side, the diameter of the circular columns is fixed at about (114mm). The square-section columns were manufactured with dimensions of (102mm×102mm) and (51mm×51mm), and the dimensions of the rectangular section were (102mm×51mm). As for the concrete that is poured into the column, The axial load is applied to each specimen to know the patterns and types of failure that will be obtained and compared to each other to find out the most effective hollow steel columns. At the end of the test program and after performing a comparison between the test results, it was found that the hollow steel columns filled with ultra-resistant concrete had little effect on the axial load.

**Mahmud et al. (2020) [8]** studied the bending behavior of thin-walled cylindrical tanks. The tested tanks are exposed to sulfuric acid to get a layer of corrosion. The concentration of the acid used (sulfuric acid) is divided into two percentages; the first percentage is about (5%) and the second percentage is about (10%). These tanks are exposed to acid for a period of about 24 hours (a whole day). The study was conducted on twelve models with dimensions divided into three groups. The greater the percentage of acid used, the greater the loss in initial buckling will increase.

**Omid et al. (2020) [9]** studied experimentally the behavior of hollow steel columns of circular cross-section subjected to central load and partial corrosion at different distances along the length of the tested hollow steel column. Eight circular specimens with a radius of about (88mm) and a thickness of about (2.06mm) and a length of (3000mm) were tested. The corrosion process, as mentioned previously, is partial (corrosion is done in the middle of the steel column, at a distance of 1500 mm from the support, and the corrosion process is also carried out at a distance of 90 mm from the support), and the DC method is used to conduct the partial corrosion process. The corrosion process is performed at different times (12, 18, and 24 hours), and the percentage of corrosion that occurs at these times is determined. It was found that the slender columns have a comprehensive curvature under the axial load, and the corrosion process reduced the capacity and ductility of the tested columns.

**Yuan et al. (2018) [10]** studied the performance of hollow steel columns exposed to heavy rain under cyclic loading as well as to find out whether acid rain attack has an effect on the bearing of the steel columns. Twelve specimens with different heavy corrosion rates were adopted. All tested column specimens have a circular section with a diameter of about (114mm), a length of (1500mm), and a thickness of (4mm). The process of corrosion creation is done through the use of a DC system, as the specimens are placed in plastic basins with the passing of a continuous electric current in the presence of an acid rain solution, which is made through the following:

$Na_2So_4$ , $(NH_4)_2So_4$ , $MgSo_4$ , $Ca(No_3)_2$ $and$ $HNO_3$

At the end of the experiment, it was found that corrosion reduces the yield strength, elastic modulus, and tensile stress capacity of the steel sheets, as well as reduce the load bearing, ductility, and energy dissipation of the tested steel columns. It was also found that with the increase in the axial force, the deformation of the tested columns increased.

We can mention that there are few researchers who study the corrosion of steel tubular columns filled with concrete under axial and uniaxial loads. Therefore, the mechanism of action of corroded columns and the extent to which they bear the applied forces are almost unknown and not well understood.

## 2.Experimental Work

### 2.1. Experimental Program

The experimental program consists of the pouring and testing of eight steel tubular column specimens as well as a series of control specimens (cubes, cylinders, and prisms) to evaluate the mechanical properties of hardened normal-strength concrete (NSC). The adopted variables include the type of loading (concentric or eccentric), the thickness of steel columns (before and after corrosion), and the type of column specimens (slender and short).

### 2.2. Column Specimens Description

The cross-section of all the tested steel tubular column specimens is (100×100 mm). The length and thickness of the steel tubular columns were considered as variables. The tested specimens were divided into two groups. the first group contains four specimens that are not exposed to the corrosion process, with a thickness of (1.5mm) and a length of (1200 mm) for the slender columns and (1000 mm) for the short columns. The specimens of the second group have the same geometrical properties as the first group, but they were exposed to corrosion conditions so that the thickness of the steel tubes was reached (reduced) to about (0.68 mm). In the first step, the corrosive and non-corrosive steel tubular columns are cast using normal strength concrete and then subjected to a certain type of load, whether it is a concentric or eccentric load. It may be noted that, to find out whether the column is slender or short, the following equation is used (Le/B ≥12) [2]. The details and descriptions of the tested steel tubular column specimens are summarized and presented in Table (1) and Figure (1).

**Table 1.** Details of the Tested STCFC

| Column Coding | Dimension (mm) L | B | t | L/B* Ratio | Type of Column | Type of Loading |
|---|---|---|---|---|---|---|
| **LC-A** | 1200 | 100 | 1.5 | 12 | Slender | Axial |
| **LC-U** | 1200 | 100 | 1.5 | 12 | Slender | Uniaxial |
| **SC-A** | 1000 | 100 | 1.5 | 10 | Short | Axial |
| **SC-U** | 1000 | 100 | 1.5 | 10 | Short | Uniaxial |
| **LC-A-C** | 1200 | 100 | 0.68 | 12 | Slender | Axial |
| **LC-U-C** | 1200 | 100 | 0.68 | 12 | Slender | Uniaxial |
| **SC-A-C** | 1000 | 100 | 0.68 | 10 | Short | Axial |
| **SC-U-C** | 1000 | 100 | 0.68 | 10 | Short | Uniaxial |

*Slenderness-ratio [2]; LC=Long Column; SC= Short Column; A=Axially Loaded; U=Uniaxially Loaded; C=Corroded.

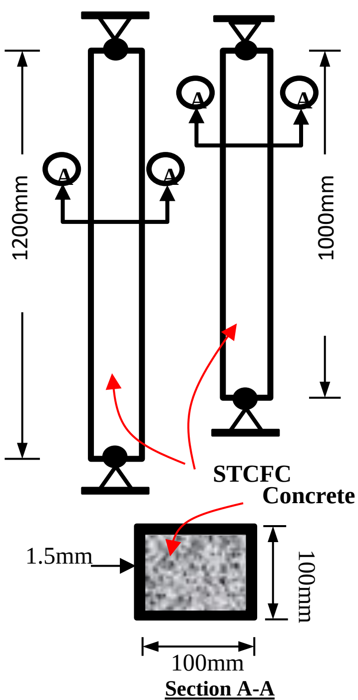


**Figure 1.** Details of the Tested STCFC

### 2.3. Materials

For the preparation of steel column specimens and control specimens, ordinary Portland cement (Type-I) made in Iraq was used. Tests were executed on cement were executed on cement and it was found that it conforms to the Iraqi specification (No.5/1984) [11]. Natural sand free of salts and impurities with a maximum size of (4.75mm) was used as a fine aggregate. Natural gravel with a maximum size of (12 mm) was used as a course aggregate. It may be noted that the gravel and sand conformed to the Iraqi specification (No.45/1984) [12]. Both the concrete mixes and the curing of the concrete control specimens were made with clean tap water. Regarding the steel sections, hollow square steel sections (Trade mark SHS) with a thickness of (1.5mm) and a length of (1000mm-1200mm) are used to manufacture the tested column specimens .

### 2.4. Corrosion Processing (Creation)

As a scientific theory, the process of steel corrosion of steel structures in real life may require many years to achieve significant and effective corrosion. In the current study, to carry out the corrosion process in a rather short time, the method of accelerated corrosion (chemical corrosion) is used. A chemical solution known as this method of corrosion is easy, but at the same time it is dangerous. Therefore, protective sulfuric acid ($H_2SO_4$) is used and diluted to a certain percentage to obtain rapid corrosion. A large plastic basin was used to ensure its validity and to close the open areas from the bottom using silicon material to prevent any leakage of sulfuric acid. The plastic basin is also cut from the top for easy insertion of the tested specimens and removal from the basin. Two to four specimens (thin-walled steel tubular columns) are placed inside the plastic tank. A (5%) dilute sulfuric acid solution is added inside the tank, as all the samples are immersed in a dilute sulfuric acid solution, Figure (2). It may be noted that the safety equipment, mask and gloves, were used to avoid the danger of rising fumes and to avoid direct hand contact with the diluted acid solution. The reduction of thin steel tube thickness was measured periodically every day to know the percentage of reduction that occurs in the steel thickness and to reach the required thickness as a result of corrosion. A digital vernier is used to measure the reduction values in different locations of steel tubular columns, Figure (3). The required thickness (less than 50% of the origin thickness) resulting from the corrosion process was reached within (8 days), from the beginning of setting the specimens and immersing them in a sulfuric acid solution. Figure (4) shows the reduction in thickness with time (day) and reaching the required thickness (0.68 mm) (≈45% of the origin thickness) at (8 days).

**Figure 2.** Accelerated Corrosion Processing

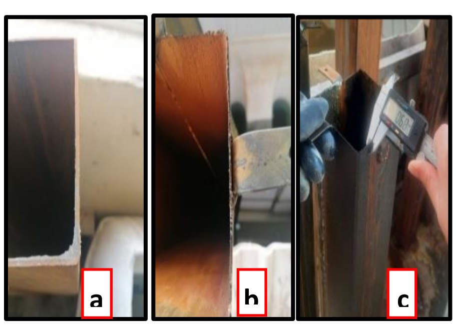


**Figure 3.** Steel tubular columns: (a) before corrosion; (b) after corrosion; (c) Thickness measured by digital vernier

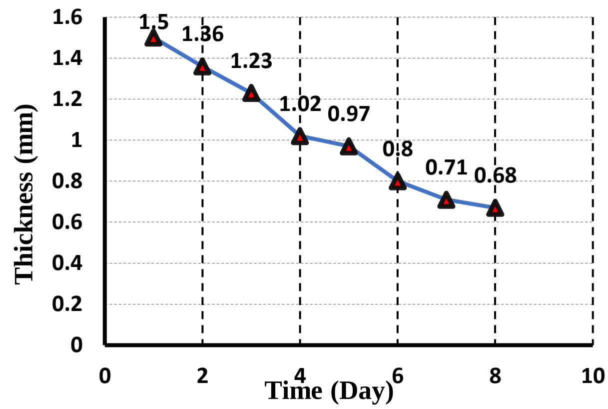


**Figure 4.** corrosion rate and a decrease in steel section thickness

### 2.5. Concrete Mix Proportion and Casting

One concrete mix of (400kg), (600kg), (1200kg) and (180 letter) for cement, sand, gravel, and water, respectively, was used to cast the tested column specimens. A rotary mixer was used to mix the raw materials and produce the required concrete. Since the structure of steel columns is sufficient to pour concrete inside, the filling (casting) of the thin-walled steel columns was performed directly without the need to use the wooden molds. Wooden boards of 18 mm thickness and dimensions (300×300mm) were used to prevent concrete exodus at the bottom open end of the thin-walled steel tubular columns. The specimens are attached to the wooden boards using L-shaped clamps that are welded to the outside surface of the steel columns from the bottom to connect the specimen with the wooden board using steel bolts. For the first group, the cast process was performed directly because this group is considered as a reference without considering the effect of corrosion processing. For group two, before the casting process is executed, they were exposed to the corrosion process, which was previously mentioned, and after obtaining the required and remarkable corrosion, all the thin-walled steel tubular columns are washed by water to remove the diluted sulfuric acid residues that may be stuck on the inner surface of the hollow column, which may have an effect on the properties of the concrete mixture later when pouring concrete inside the thin-walled steel tubular columns, and then the concrete casting is performed directly. Figure (5) shows the cast process of the tested column specimens.

**Figure 5.** The concrete casting for the specimens tested

**2.6. Instrumentation and Measurements**

All column specimens as well as the control specimens were tested concentrically and eccentrically using a hydraulic universal testing machine with a load capacity of (3000 kN), Figure (6).

**Figure 6.** The column specimens are set up.

The lateral displacement of the tested column specimens is measured by using a dial gauge with an accuracy of (0.01mm/div). The dial gauges were installed at mid-height (center) on the front and side faces of the tested steel column specimen. Steel caps with thicknesses of 15 mm and dimensions of (100 mm, 100 mm, and 50 mm), for length, width, and depth, respectively, were used to project the concentric and eccentric loads at the top edge of the tested specimens. The steel cap consists of two pieces: the first piece is the piece that has the same dimensions as the steel columns filled with concrete, as it is inserted from the top and bottom of the specimen, while the second piece is the piece that is in contact with the base of the hydraulic device from the top and bottom that transfers the load from the hydraulic machine to the cap and, then, to the tested specimens. It may be noted that the second piece consists of a steel plate with a thickness of (15 mm) welded on its surface at the middle with a steel roller to represent the boundary condition. To apply the axial load, the steel plate is placed in the middle and the load is applied until the specimen fails. When the eccentric load is applied, the steel plate is placed at a distance of (40 mm) from the center of the cap, and the load is applied until the tested specimen fails. Figure (7) shows the shape of the used steel cap and its components.

**Figure 7.** the steel cap and its components

### 2.7. Column and Control Specimens Tests

*2.7.1. Column Specimen Tests*

As mentioned earlier in the experimental program, eight steel tubular columns filled with concrete were tested under the effect of concentric or eccentric loads. As a first step, the tested columns are arranged and adjusted so that the column axis coincides with the axis of the applied load and avoids tilting of the columns because this leads to problems while applying the load. Then, the dial gauges are placed in their required places. The applied loads were conducted by hydraulic testing machines using load control criteria. After that, step-by-step load was applied with constant incremental load for each step up to the failure; the experiment terminated when the tested specimens reached their ultimate bearing capacity.

*2.7.2. Concrete Control Specimens Tests*

The compressive strength associated with concrete cube specimens ($f_{cu}$) and cylinders ($f'_c$) was performed at the age of (28 days), in accordance with (BS 1881-116 1983) [13] and (ASTM C39/C39M-01) [14], respectively. Pouring and testing of standard cylindrical specimens according to (ASTM C496-2004) [15] were used to determine the splitting tensile strength (ft). The flexural tensile strength of concrete ($f_r$) was performed using standard prisms according to the (ASTMC78-02) [16] for two-point loads. The dry density (dry unit weight) of concrete was determined using standard cylinders (ASTM-C138) [17]. Test results of the control specimens are provided and presented in Table (3).

**Table 3.** Test Results for Control Specimens

| Property | Test Results |
|---|---|
| f'c (MPa) | 33.69 |
| $f_{cu}$ (MPa) | 44.435 |
| f'c / fcu | 0.758 |
| γc (Kg/m3) | 2490 |
| fr (MPa) | 3.5 |
| $f_t$ (MPa) | 2.378 |

### 2.8. Yield Stress of Steel Tube Tests

Tensile strength testing was done on the employed thin-walled steel tube by taking (cutting) a longitudinal steel strip with a length of (400mm) and a width of (30 mm). The obtained steel strips were directly evaluated using tensile strength test equipment in accordance with ASTM A615/A615M-86a [18]. The tensile test results for the utilised steel plates were presented in Tables (4) The test results demonstrate that the steel bars utilized complied with (ASTM A615-86) [18], Figure (8). It should be noted that the tensile inspection test for the steel plates was carried out in the construction materials laboratory of Mustansiriyah University's College of Engineering.

**Figure 8.** Steel Plate Tensile Testing Machine

**Table 4. Steel Plate Tensile Test Results**

| Properties | Test result |
|---|---|
| **Steel Plate Sample (mm)** | 400x30 |
| **Fy (MPa)** | 560.12 |
| **Fu (MPa)** | 741.8 |
| **Ey (mm/mm)** | 0.07615 |

## 3. Test results and Discussion

### 3.1. Effect of Loading Type

For comparison, the column specimens (LC-A) and (LC-U) are considered as a reference for the slender steel tubular columns subjected to concentric and eccentric loads, respectively. Also, the column specimens (SC-A) and (SC-U) are considered as a reference for the short steel tubular columns subjected to concentric and eccentric loads, respectively. Loads are applied sequentially and incrementally until the tested specimens reach failure. The load capacity is a very important part in order to make a comparison between the concentric and eccentric load of the corroded and non-corroded specimens.  Table (5) shows the test results obtained from the experiment. It was found that steel tubular columns filled with concrete and subjected to a concentric load showed higher resistance in comparison with steel tubular columns filled with concrete and subjected to an eccentric load that reached the stage of failure faster. Whereas the ultimate loading capacity ($P_u$) of the steel tubular columns filled with concrete was decreased by about (36%), (28%) for slender and short columns, respectively, when the applied load changed from concentric to eccentric load. The reason for the failure of steel tubular columns which are subjected to an eccentric load is due to the effect of a combination of both, an axial load in addition to a uniaxial moment at a distance of (40mm), on the exposed section, which leads to rapid (quick) failure compared to the steel tubular columns subjected to a concentric load. In addition, the columns subjected to uniaxial force at a distance of 40 mm leads to the formation of two areas subjected to tension and compression, whereas the columns subjected to axial force only leads to the formation of a compressive area only. when steel tubular columns are subjected to eccentric force, two components of the forces mentioned earlier (central compressive force and axial moment) are combined, which leads to a faster failure compared to steel tubular columns subjected to axial load. The results of the tests showed that the work conforms to Zhao et al. (2018) [6].

**Table 5.** The Ultimate Load Capacity of the Tested Specimens

| Column Coding | $P_u$ (kN) | $(P_u/(P_u)_r$ (%) | Note |
|---|---|---|---|
| **LC-A** | 380 | - | - |
| **LC-U** | 245 | 0.64 | With respect to (LC-A) |
| **SC-A** | 450 | - | - |
| **SC-U** | 325 | 0.72 | with respect to (SC-A) |
| **LC-A-C** | 200 | 0.52 | With respect to (LC-A) |
| **LC-U-C** | 140 | 0.57 | with respect to (LC-U) |
| **SC-A-C** | 240 | 0.53 | with respect to (SC-A) |
| **SC-U-C** | 185 | 0.56 | with respect to (SC-U) |

### 3.2. Effect of Corrosion

After exposure to the corrosion process, the thickness of the steel tubular columns was decreased by about (55%). The ultimate loading capacity was decreased for the tested specimens (LC-A-C), (LC-U-C), (SC-A-C), and (SC-U-C) by about (48%), (43%), (47%), and (44%), respectively, compared to the ultimate loading capacity of the reference specimens (non-corroded specimens), (LC-A), (LC-U), (SC-A), and (SC-U) respectively. This indicates that the decrease in the thickness of the steel tubular columns, as a result of the effect of the corrosion process (sulfuric acid), leads to a decrease in the ultimate loading capacity as a result of an increase in the loss of steel material, in addition to a decrease in the yield tensile strength of the steel section. As it is known, if the thickness of the steel tubular column is higher, the ultimate loading capacity is higher (as there is a proportional relationship between the steel thickness of the columns and the ultimate load capacity), and as a result of the decrease in thickness from 1.5mm to 0.68mm, the ultimate load capacity was significantly reduced when compared with the non-corroded columns. The results of the tests showed that the sulfuric acid used conforms to Mahmud et al. (2020) [8].

### 3.3. Load-Displacement Curves

At the beginning, the main target is to use two dial gauges at the mid-height (in front and on the side) to identify the plane at which the failure may occur. Therefore, the plot of the load-lateral displacement will be done based on the maximum recorded data regardless of the direction of the dial gauge (in front or on the side). For comparison between the corroded and non-corroded short column specimens under the axial and uniaxial loads, Figures (9) and (10) are plotted. Also, to make a comparison between the corroded and non-corroded slender column specimens under the axial and uniaxial loads, Figures (11) and (12) are plotted. It can be seen from the load displacement curves obtained from the experimental data that for specimens subjected to eccentric loading, The displacement is greater in comparison with specimens subjected to concentric loading. This may be due to the effect of the combination of the direct load and transferred moment, which leads to an increase in the lateral displacement in the plane of failure. While for the tested specimens which are subjected to a concentric load, the displacement becomes small due to the higher axial stiffness of these columns. In comparison between the corroded specimens and the non-corroded specimens, it can be noted that the displacement is larger for the corroded specimen due to the reduction in steel column thickness, which leads to a decrease in the column axial stiffness. Generally, the change of load type from concentric to eccentric load leads to an increase in the lateral displacement. This may be due to the effect of the combination of the direct load and transferred moment, as shown in Figure (13) to Figure (16).

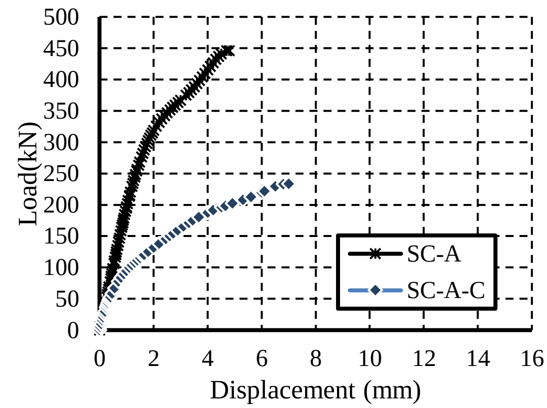


**Figure 9**. Load-deflection curves for axially loaded specimens (SC-A) and (SC-A-C)

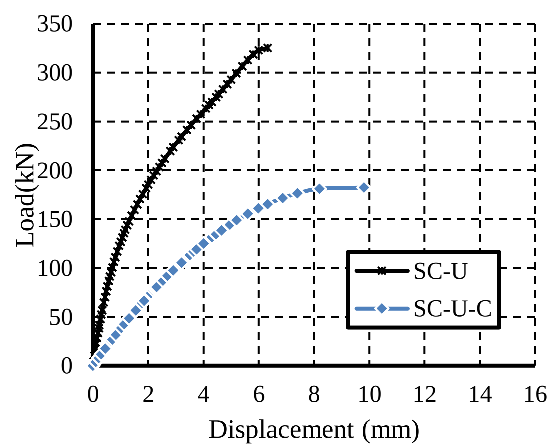


**Figure 10**. Load-deflection curves for uniaxially loaded specimens (SC-U) and (SC-U-C)

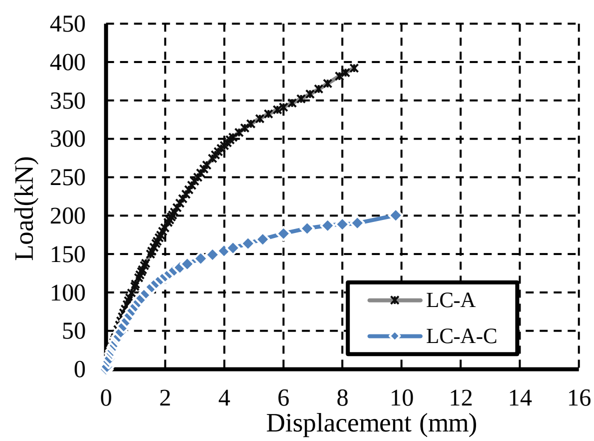


**Figure 11**. Load-deflection curves for axially loaded specimens (LC-A) and (LC-A-C)

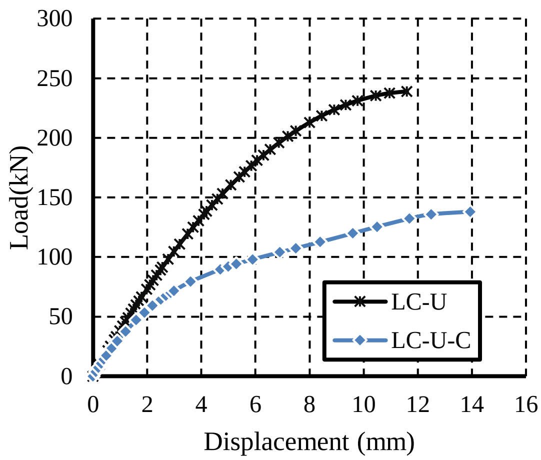


**Figure 12**. Load-deflection curves for uniaxially loaded specimens (LC-U) and (LC-U-C)

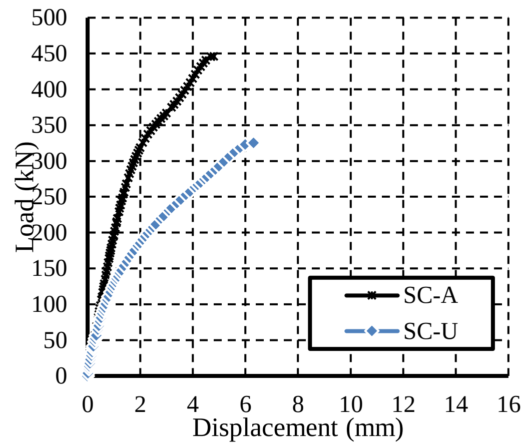


**Figure 15**. Load-deflection curves for specimens (SC-A) and (SC-U)

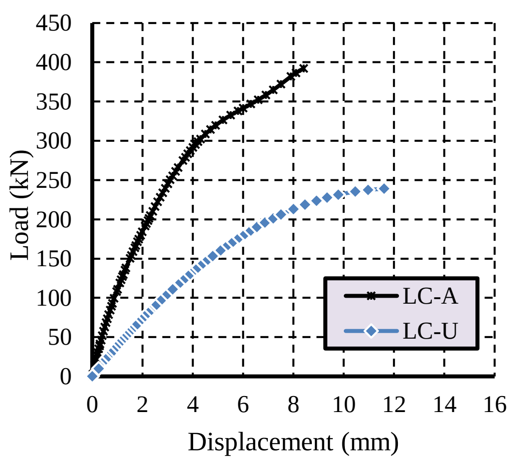


**Figure 13**. Load-deflection curves for specimens (LC-A) and (LC-U)

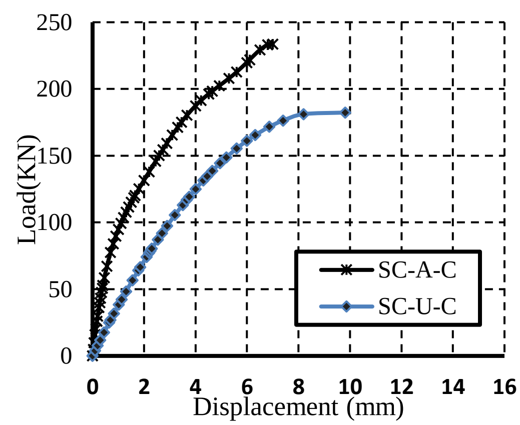


**Figure 16**. Load-deflection curves for specimens (SC-A-C) and (SC-U-C)

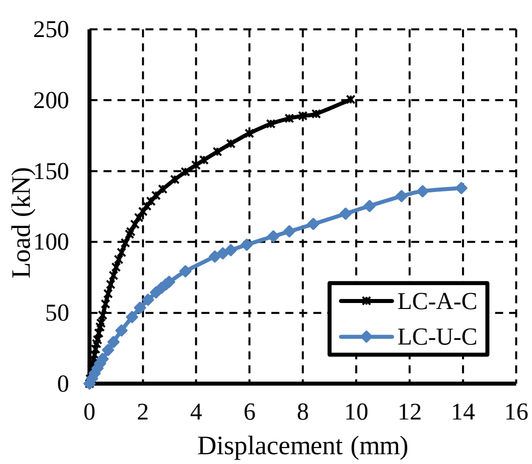


**Figure 14**. Load-deflection curves for specimens (LC-A-C) and (LC-U-C)

### 3.4. Failure Mode

After completing the test process and the failure took place, two different patterns of buckling failure were obtained (global buckling and local buckling), which occurred depending on the type of the applied load and the length of the tested columns. The column specimen (LC-A) has a local buckling in the lower part of the column (from the front and back sides), in addition to a local buckling in the middle length of the steel tubular column from the back. The local buckling in the lower part can be referred to as the local buckling waves. For the column specimen (LC-U), two types of buckling failure took place; the first is a global buckling failure along the steel tubular column and in the middle; the second failure is a local buckling failure at the bottom of the steel tubular column; and both failures occurred on the front and back side of the model. While for the column specimen (SC-A), local buckling failure only occurred at the bottom of the specimen on both sides of the steel tubular column. On the other hand, for the column specimens (SC-U), global buckling and a slight local buckling failure at the top of the model took place. For the column specimens (LC-A-C), local buckling waves failure in the upper part of a steel tubular column is occurred. The specimen (LC-U-C) has global buckling failure for steel tubular columns. The column specimens (SC-A-C) and (SC-U-C) had similar local buckling failures but in different places. For the first specimen, the local buckling wave failure occurred at the top of the specimen, and for the second specimen, the local buckling failure occurred at the bottom of the specimen in addition to a failure in the welding area. It can be concluded from the types of failures and the type of the applied load that the column specimens which are subjected to the concentric axial load have a local buckling failure, while the column specimens which are subjected to the eccentric load have a global buckling failure or a global buckling failure with a local buckling failure. Table (6), and Figures (17) to (20) show the buckling pattern for the tested column specimens.

**Table 6**. Mode of Failure of Column Specimens

| Column Coding | Mode Of Failure |
|---|---|
| **LC-A** | Local Buckling in Bottom |
| **LC-U** | Global Buckling |
| **SC-A** | Local Buckling in Bottom |
| **SC-U** | Global And Local Buckling |
| **LC-A-C** | Local (Waves) Buckling in Top |
| **LC-U-C** | Global Buckling |
| **SC-A-C** | Local (Waves) Buckling |
| **SC-U-C** | Local Buckling in Bottom |

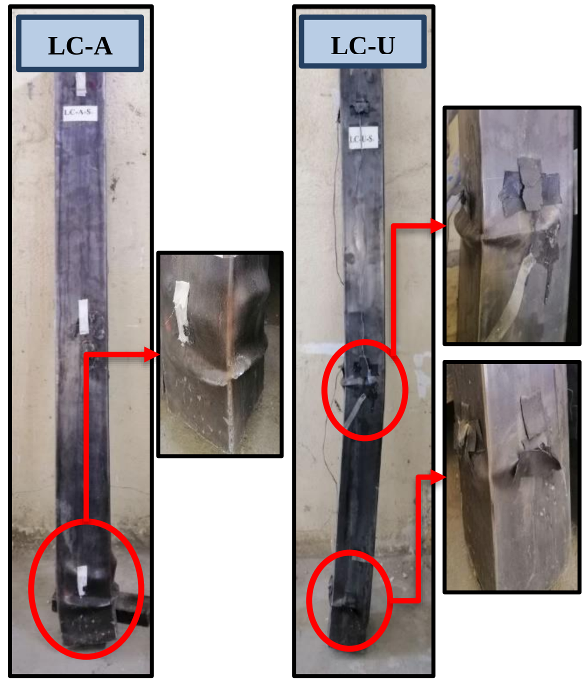


**Figure 17**. Buckling Pattern for (LC-A) And (LC-U)


**Figure 18. Buckling Pattern for (SC-A) and (SC-U)**


**Figure 19**. Buckling Pattern for (LC-A-C) And (LC-U-C)


**Figure 20. Buckling Pattern for (SC-A-C) and (SC-U-C)**

## 4. Conclusions

When the type of loading changes from concentric to eccentric, the ultimate load capacity of the tested slender and short steel tubular columns filled with concrete is reduced by 53% and 47%, respectively.
When the tested specimens were subjected to the corrosion process, the ultimate load capacity was decreased by (48%-43%) and (47%-44%) for the concentrically loaded slender columns and eccentrically loaded short columns, respectively. The main reason for the ultimate load capacity decreasing is due to the reduction in steel tubular column thickness after being immersed in (5%) dilute sulfuric acid for a period of (8days) which leads to a decrease in the thickness by about (55%).

Two types of failure modes were recorded; the tested specimens subjected to the concentric load were failed by the local buckling failure in different places in columns body, while for the tested columns which subjected to the eccentric load the failure occurred at a distance of (40mm) get a global buckling failure or with both global and local buckling failure.
The tested column specimens which are subjected to eccentric load show greater deformation compared to the column specimens that are subjected to concentric load; also, the tested specimens exposed to the corrosion process have greater deformation than the non-exposed specimens.

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**Conflict of interest**

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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**Appendix-A:**

The steel tubular columns filled with normal concrete subjected to central force, have a compressive strength of f'c=33.69 MPa, and steel tubular yield is fy=560.12 MPa. The details of the cross-section are shown in figure (1).

L1=1200mm, L2=1000mm, t=1.5mm

D=B-2t............. (A-1)

=100-2(1.5) → D=97mm

$A_S = (100)^2 - (97)^2 \rightarrow A_S = 591\ mm^2$

$A_C = (97)^2 = 9409\ mm^2$

Where,

D= the cross-section of concrete.

$A_S$= area of steel section.

$A_C$= area of concrete section.

$$I_S = \frac{(100)^4}{12} - \frac{(97)^4}{12} \rightarrow I_S = 955893.25\ mm^4$$

$$r = \sqrt{\frac{I_S}{A_S}} \cong 0.3b \text{............ (A-2)}$$

$$r = \sqrt{\frac{955893.25}{591}} \rightarrow r = 40.217mm$$

$0.3b = 0.3(100) = 30$, Use $r = 30mm$

$P_\circ = 0.85F'c\, A_C + A_S\, F_y$........ (A-3)

$$P_\circ = [0.85(33.69)(9409) + (591)(560.12)] \times 10^{-3}$$

$$P_\circ = [269440.8 + 331030.9] \times 10^{-3}$$

$P_\circ = 600\ KN$ , Ultimate axial capacity for non-corroded section.

After completing the calculation of the ultimate loading capacity for the non-corroded column, now calculate the ultimate loading capacity for the corroded section by taking the same compressive strength and steel yield that were approved for the non-corroded section:

L1=1200mm, L2=1000mm, t=0.68mm

$D = B - 2t = 100 - 2(0.68)$

$D = 98.64mm$

$A_S = (100)^2 - (98.64)^2 \rightarrow A_S = 270.15\ mm^2$

$A_C = (98.64)^2 = 9729.8\ mm^2$

$$I_S = \frac{(100)^4}{12} - \frac{(98.64)^4}{12}$$

$I_S = 444168.89\ mm^4$

$$r = \sqrt{\frac{I_S}{A_S}} \cong 0.3b \rightarrow r = \sqrt{\frac{444168.89}{591}}$$

$r = 40.5mm$ , $0.3b = 0.3(100) = 30$

Use $r = 30mm$

$P_\circ = 0.85F'c\, A_C + A_S\, F_y$

$$P_\circ = [0.85(33.69)(9729.8) + (270.15)(560.12)] \times 10^{-3}$$

$$P_\circ = [278627.4 + 151316.4] \times 10^{-3}$$

$P_\circ = 430\ KN$ , Ultimate axial capacity for corroded section.