Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 6, No. 12, December, 2020

Mechanical Properties of Corroded-Damaged Reinforced Concrete Pile-supporting Wharves

Cecielle N. Dacuan [a*], Virgilio Abellana [a], Hana Astrid Canseco [a]

[a] University of San Carlos, Cebu, 6000, Philippines.

Received 02 September 2020; Accepted 16 November 2020

Abstract

Corrosion is one of the significant deteriorations of reinforced concrete structures. It accelerated the performance loss of the structures, leading to a cross-sectional reduction of steel, which affects its mechanical properties, particularly its tensile capacity and ductility. The purpose of this study is to assess the serviceability and safety of corroded-damaged structures, particularly those exposed to aggressive marine environments. A total of 54 pcs of 150 mm-diameter and 300mm-height of cylindrical specimen were cast. Small-scaled specimens were accelerated to corrosion using impressed current techniques with a constant current density of 200 µA/cm^2. Samples were immersed in a simulated environment with a 5% solution of sodium bicarbonate during corrosion acceleration. Corrosion alters the surface configuration of the steel bar. Pitting corrosions due to chloride aggression causes the residual cross-sectional area of corroded rebars to no longer round and varies considerably along its circumference and length. The reduction of the steel cross-sectional area has a significant impact on the degradation of the strength and durability of reinforcing structures. The residual capacity of the corroded reinforcement decreases with the reduction of the cross-sectional area of the steel reinforcement. The rate of corrosion affects the extent of the remaining service life of a corroded reinforced concrete structure.

Keywords: Residual Capacity; Load Carrying Capacity; Corrosion Level; Durability; Ductility; Tensile Strength; Mass Loss Rate; Penetration Rate; Cross-sectional Area Reduction; Crack Width.

1. Introduction

The service life of structures carries a major role in the economy of concrete structures, and various studies using different methods have been developed to determine the residual life of the structure [1]. The selection of the right pile type for foundations is one of the primary concerns to evaluating its performance in terms of time, cost and quality. Further, improving the design efficiency and changing the traditional methods of pile production are some practical solutions for the reduction of cost in the construction of a superstructure that is about 5% to 20% of the overall project construction cost [2]. However, the degradation of material properties is one factor that causes the risk of failure [1]. This is particularly apparent in structures subjected to aggressive environments, such as piles and wharves, which are constructed in an aqueous environment.

Corrosion of steel reinforcement is one of the significant deteriorations of reinforced concrete structures, more significantly of those structures exposed to marine environments [3-5]. Corrosion affects the structural integrity of concrete structures, which results in degradation of the mechanical properties of reinforcing steel rebars [6, 7]. One significant deteriorating effect of corrosion is reduction of the useful cross-sectional area of reinforcing structural members [8, 9]. The loss of steel cross-sectional area is the disintegration of steel to its original state, which is rust

* Corresponding author: dcecielle@gmail.com

http://dx.doi.org/10.28991/cej-2020-03091624

[10]. Rust, which is the corrosion product, will expand the original volume of steel by 3 to 5 times. Due to expansion, it will cause internal pressure between the interfaces concrete and eventually cause cracking of the concrete covers [11]. Cracking and spalling of concrete are the two detrimental effects of corrosion on durability of the reinforced concrete structures [12]. Durability deterioration inevitably results in a reduction of the serviceability of reinforced concrete constructions [13].

The durability deterioration brought by corrosion progresses at a rapidly pace for structures exposed to aggressive environments [14]. Corrosion due to carbonation and chloride-induced corrosion is the primary cause of failure of reinforced concrete structures [15]. Reinforced concrete structures exposed to aggressive marine environments pose a high level of deterioration throughout their design life owing to chloride-induced corrosion [8, 14]. Coastal structures, such as bridges and port facilities, especially pier wharves that are severely exposed to marine waters, are easily susceptible to chloride-induced corrosion [15], and result in severe damage to the steel reinforcement and its surrounding concrete [14].

Corrosion typically starts when the amount of chloride at the surface of embedded steel exceeds a certain value, which is known as the chloride threshold value [16]. The continuous penetration of chloride ions in the long-term service period weakens the material strength and reduces the serviceability limit state of structures in a marine environment [13, 15]. Corrosion due to chloride attack is riskier to structural failures because of pitting corrosion [17]. Pitting corrosion is common in reinforcing steel bars subjected to chloride-induced corrosion. This can cause significant and highly localized loss of sections, which can be very detrimental to structural safety [18]. In pitting corrosion, the external surface of the steel bars alters and no longer rounds [5]. The value of area loss in pitting corrosion is higher than three times the average area loss of the entire bar because the attack does not occur uniformly [7]. Pitting corrosion is more dangerous than uniform corrosion because it progressively reduces its cross-sectional area to a point where the applied load may no longer be withstood [10]. It reduces the cross-section of reinforcing steel bars, which subsequently reduces its load-carrying capacity [19]. The evaluation of a considerable loss of cross-sectional area or even the total failure of specific fragments of the bars is possible in specific pitting points [17]. The reduction in the area of reinforcing steel rebars with time of exposure in an atmospheric environment follows a linear relationship [20]. Figure 1 shows a typical schematic of the deterioration of steel reinforcement in two phases: initiation phase and propagation phase.

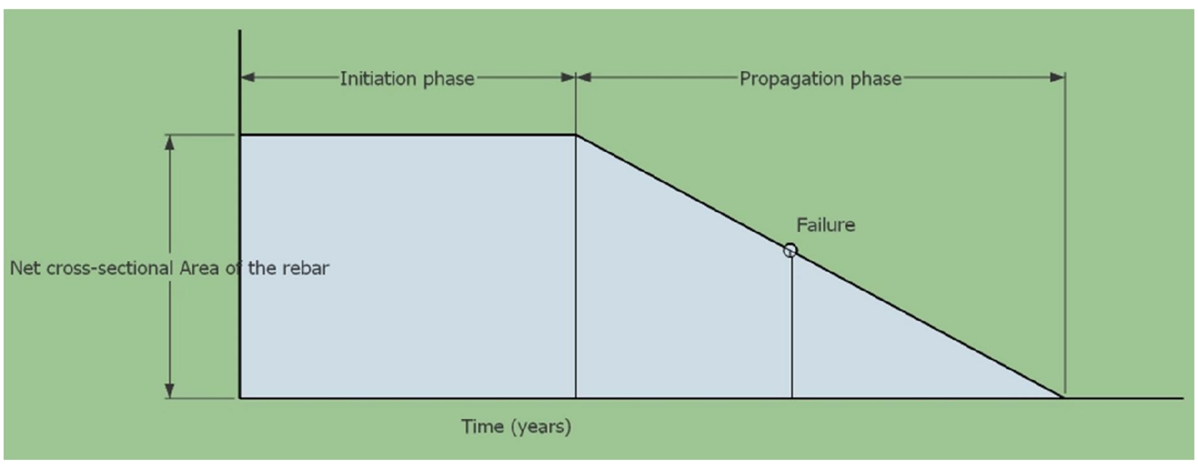

Figure 1. Deterioration process for steel rebar in concrete [16, 18]

The initiation and propagation phases are the two primary stages that cover the formation of corrosion. During these periods, corrosion causes a reduction in the steel reinforcement area, and affects its dynamics and static behavior or its mechanical behaviour [1]. The initiation phase is the phase from the construction of the structure to the initiation of corrosion. It is the period between the first appearances of cracks and ends with the depassivation of steel. The structural damage at the initiation phase may not occur, or it can be considered null. The assumption is that the corrosion intensity is very low in the initiation phase, and it does not represent a risk to the life cycle. On the other hand, the propagation phase is when the depassivation of steel is triggered. During this period, the corrosion current was established in the rebars and considered damaging to the life cycle of the structures. During the propagation phase, the expansive products form, and leads to the formation of cracks induced by corrosion. The time required to show initial distress due to the formation of rust, cracking, spalling of the concrete cover, and cross-sectional area loss of the rebar is termed as propagation time [18]. The propagation process should be interrupted to avoid the loss of structural performance, or in some critical situations, to prevent the failure of the structures [7].

Corroded-damaged structures show significant damage in their critical stage during the propagation phase, and although the corroded structures look like stable, it does not mean they are safe because corroded structures are vulnerable to ultimate loads or the design load [8]. When the corrosion of steel bars develops significantly, it does not only affect the structural serviceability by cracking, or even spalling of the concrete cover, but also it has an impact on the structural safety by decreasing the load-bearing capacity of reinforcement concrete members [6]. The reduction in the cross-sectional area reduced the performance under seismic and everyday loading of all the reinforced concrete elements [14].

Corrosion not only affects the load-carrying capacity of the reinforcing steel bars, but it may also impair the ductility [20]. The corrosion duration and rebar cross-sectional area size had a significant impact on the strength and ductility degradation of the specimens [6]. A transition from ductile mode behavior to a less ductile mode has been noted [21]. The effect of corrosion on the degradation of ductility was much greater than that of tensile strength [22]. A higher corrosion level significantly increased the reduction in the cross-sectional area of steel rebars [7]. A corrosion level of 12% indicates a brittle failure. The reduction in the cross-sectional area likewise affects the mechanical properties of reinforced concrete structures and its tensile strength [21]. There is a very high correlation between the degree of reinforcement corrosion and the mechanical properties of reinforcement [17]. The tensile behaviours of corroded bars are essential in the evaluation of the capacity of corroded reinforcing steel rebars [23]. The tensile strength for both the nominal yield and ultimate strength and percentage elongation decreases when the reduction in mass of steel increases [22].

The rate at which corrosion evolves is a crucial factor, which may depict the evolution pattern of residual safety and serviceability [24]. The effect of reinforcement corrosion on the residual strength of reinforcing steel bars has been of great interest; corrosion has a marginal effect on both the yield and ultimate strengths of reinforcing steel bars [20]. The residual forces of the corroded reinforcement decrease more rapidly than does their average cross-sectional area. As a result, the residual strength, measured in terms of stress, which can be resisted, of corroded reinforcement also reduces significantly. The residual capacity of corroded reinforcement not only decreases with the amount of corrosion, but also varies with the diameter and type of reinforcement [25].

The majority of the previous researchers mainly concerned on the mechanism of corrosion and its local effects on bond with concrete, rather than its effect on the mechanical properties of corroded reinforcement. Relatively little attention has been devoted to the residual capacity of corroded reinforcement. This paper study the influence of corrosion on the reduction of the cross-sectional area of steel bars, and consequently the effects of steel reinforcement corrosion on the structure deterioration rates. This study will provide remedies before the partial complete failure of the reinforced concrete structures, particularly those exposed to a severely aggressive marine environment, like facilities in ports, especially pile-supporting wharves. This is to determine the serviceability and safety of the structures with different corrosion levels that correlate to the cross-sectional reduction of reinforcing steel bars, and to avoid unstable structures.

Experimental procedures were employed in this study. Corrosion acceleration with the galvanostatic method in an artificially controlled environment was implemented. After a period of accelerating corrosions, the specimens were subjected to several measurements of data.

2. Materials and Methods

2.1. Research Flow Chart

The following were carried over during the experimental program, characterization of the materials and variables used in the research, corrosion acceleration method, and measurement of cross-sectional area reduction and mechanical properties resulting from the corrosion stimulation. The following are the flow charts for the research methodology.

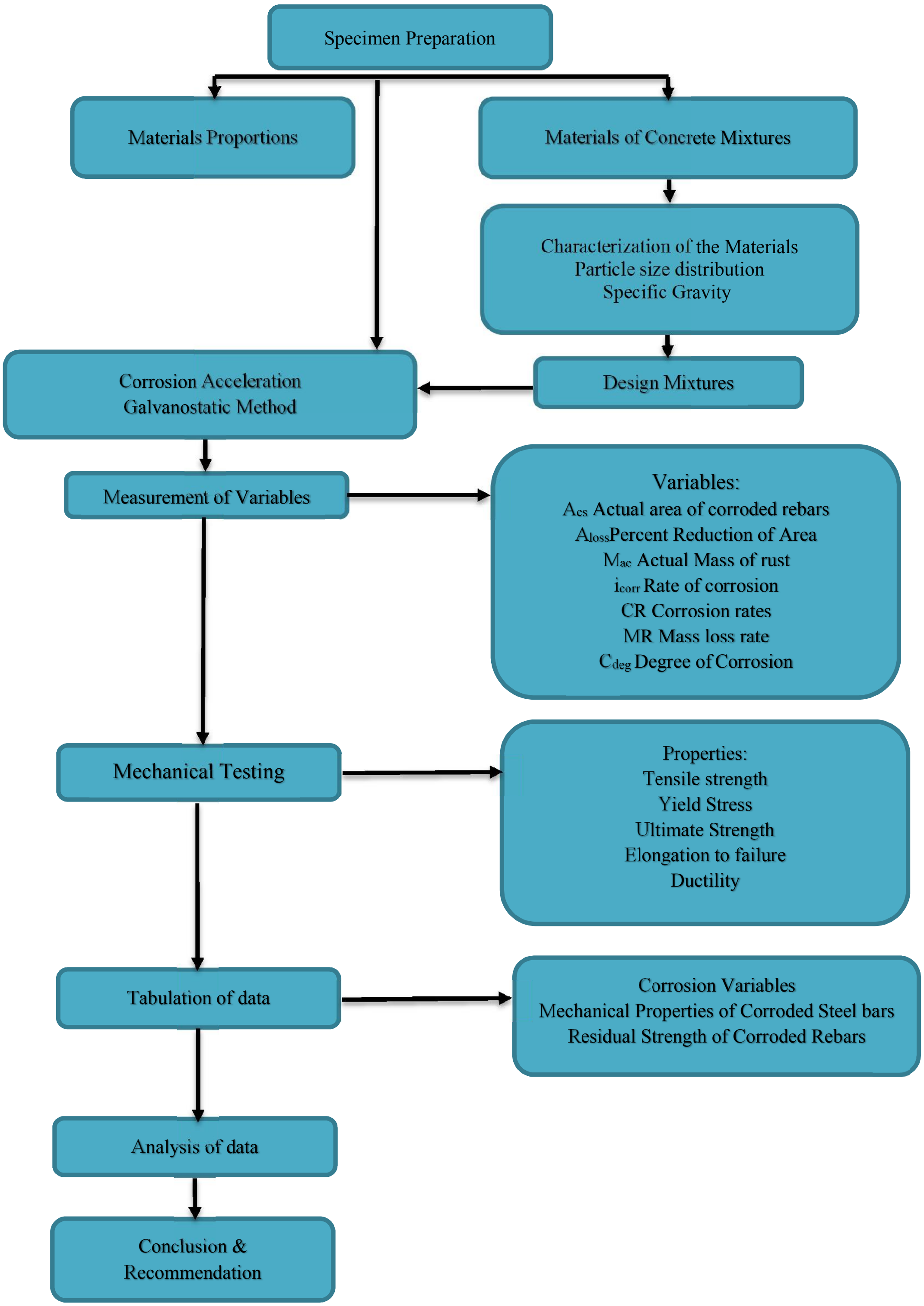

Figure 2. Research flow chart

2.2. Specimen Preparation

Table 1 shows the proportion of designed concrete mixtures that were used to produce 28 MPa designed strength over a 28 period. Table 2 shows the material mixtures used in the experiments. Figure 3 shows the gradation curves of the two materials used, the coarse and fine aggregates. Concrete specimen samples were cast with 150mm-diameter with 300mm-height of cylindrical specimen. The ratio of water to cement was considered constant throughout the experiments; it was 0.45 w/cm. It was based on ACI 211, 0.45 is the maximum permissible water-cement ratio for concrete in severe exposure to sea water. A total of 54 single reinforced bar specimens were corroded and examined under tension tests. The variables investigated were reinforcement diameter, area of steel reinforcement, corrosion rates, degree of corrosion and crack widths.

Table 1. Materials proportion of designed concrete mixture

Cement	Sand	Gravel	Water / Cement ratio
1	1.90	2.14	0.45

Table 2. Materials of concrete mixtures

Material	Kg per m³ of concrete
Cement	411
Fine Aggregates	783
Coarse Aggregate	992
Water	185

A single reinforcement steel bar of different diameter sizes at each group was placed in the midst of the cylindrical specimen. The specimens were categorized into three groups. Group I is a 16 mm-Ø deformed steel rebar, group II was 20 mm-Ø rebar, and group III was a 25 mm-Ø deformed steel rebar. Each group consisted of 18 test specimens. The length of each bar is 500 mm long, with a 250 mm length of bar embedded by concrete, and 35 mm, 50 mm and 75 mm covered thickness of concrete at the bottom.

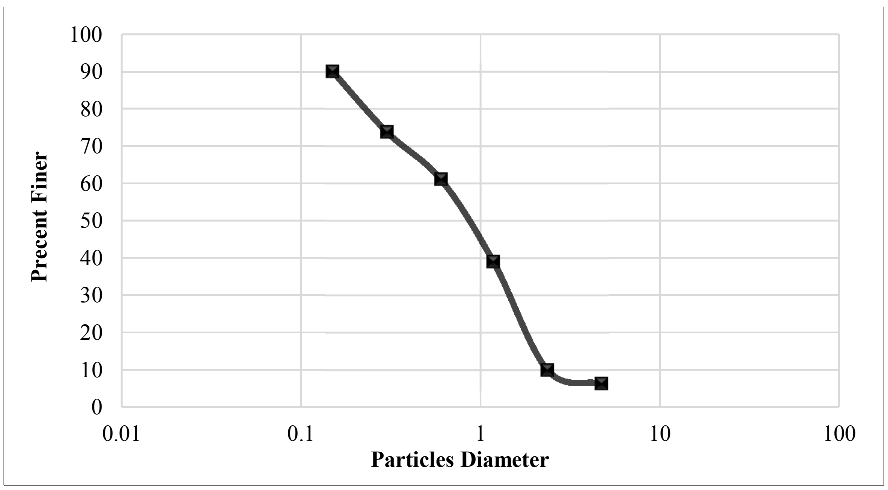

Figure 3. Gradation curves of fine aggregate

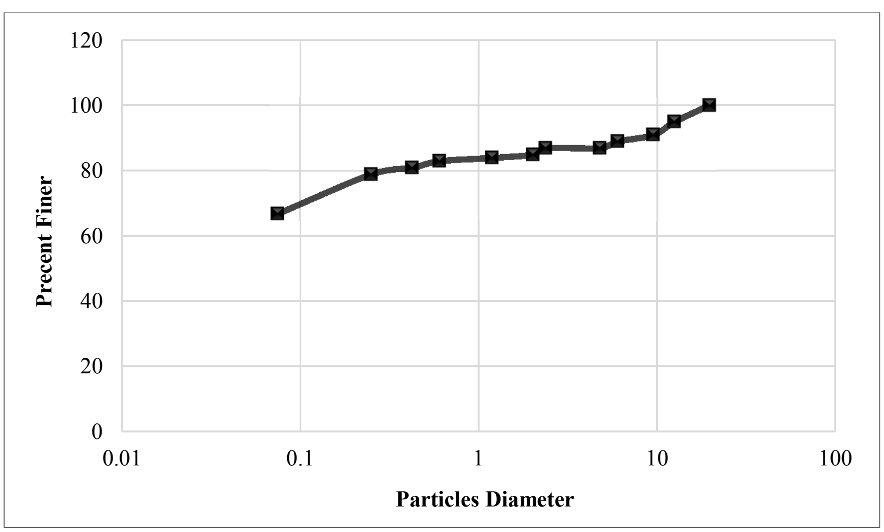

Figure 4. Gradation curves of course aggregate

The samples were left in the molds for 24 h after casting. The specimens were de-molded and placed in an open environment. After the first 24-hour curing, the specimens were soaked in clean water for curing. Figures 4 and 5 show the detail of the specimen and scheme of a cylinder, respectively.

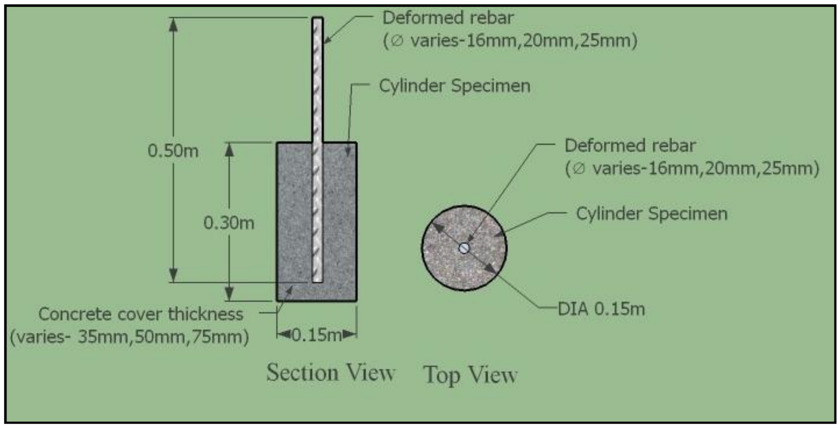

Figure 5. Detail of Specimen

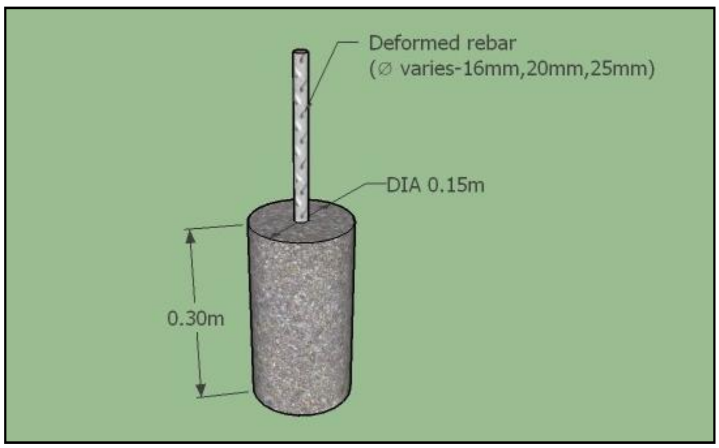

Figure 6. Scheme of Cylindrical Specimen

2.3. Corrosion Acceleration of the Samples

Corrosion is a slow process in a natural environment, and researchers have stimulated the nature of the oxidation reaction by using the galvanostatic method to accelerate the corrosion process in an artificially controlled environment. The method is an impressed current technique for accelerating steel bar corrosion inside the concrete. An electrochemical technique was adopted to accelerate the corrosion process of the reinforcement, as shown in Figure 6. After a period of 28-days water curing, samples were partially immersed with sodium chloride of 5 % solution with water. During the test, the wire was connected to the positive pole of the power supply, while the other copper wire was connected to the negative pole.

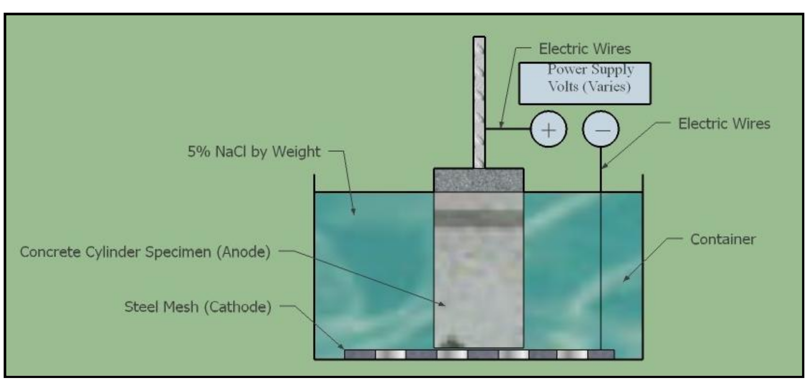

Figure 7. Test layout to accelerate corrosion

The total galvanizing time was determined using the linear Faraday's law (ASTM, 1999), which is more suitable than a non-linear expression for evaluating the generation of corrosion products [26]. The total galvanizing time t is given by:

$$t = \frac{\gamma_s ZF_e F\, d_s}{MF_e\, i} \tag{1}$$

Where:

t= total galvanizing time;

γ_s = 7850 kg/m³; is the density of the steel materials;

ZF_e= 2; is the valence of the iron element;

F = 96480 J/(V mol); is the Faraday's constant;

d_s= is the corrosion depth;

MF_e= 0.056 kg; is the atomic weight of the iron element;

i= 2 A/m²; is the current density applied to the bars.

More corrosion will be expected in the reinforcing steel bars for longer durations, so different corrosion damage levels can be achieved using different galvanizing times.

2.4. Measurement of Steel Cross-Sectional Area Reduction

After accelerating the cast specimen, the samples were broken to retrieve the rebar placed on its core. The excess concrete around the rebars was manually removed, and the bars were immersed in a solution of 3.50 g hexamethylene tetramine diluted in 500 ml of hydrochloric acid and 500ml reagent water according to the procedures of ASTM G1-03(2003) for a period of 40 minute-time. After this period, the bars were placed in an oven for 30min at an average temperature of 25 ºC.

The nominal diameters of the deformed bars are provided by the manufacturer, whereas the cross-sectional areas are actual areas calculated from the weighted mass divided by the steel density and the measured length. The bar was weighted and designated as W_f. Due to the irregularity of the bar diameter, the actual area of the corroded rebars was computed using Faraday's law:

$$A_{cs} = W_f/(L \times \gamma_{iron}) \tag{2}$$

Where:

A_{cs}= Actual area of corroded reinforcement bar;

W_f = is the weight of the reinforcement after corrosion, and rust removed (g);

L = is the length of the specimen (mm);

γ_{iron} = 0.00785 g/mm³ (steel).

The percentage reduction can be calculated using the original weight of the steel rebars and of the corroded rebars of the same length of bars.

$$A_{loss}(\%) = \frac{\left(\frac{W_o}{l_o} - \frac{W_c}{l_c}\right)}{\frac{W_o}{l_o}} \times 100 \tag{3}$$

Where:

W_o = Weight of Uncorroded bars;

W_c = Weight of Corroded bars;

l_o = Length of Uncorroded bars;

l_c = Length of Corroded bars.

The actual mass of rust per unit surface area in accordance with ASTM G1 on rebars extracted from the concrete specimen after the accelerated corrosion test was computed as:

$$Mac = \frac{(W_i - W_f)}{\pi DL} \tag{4}$$

Where:

M_{ac} = Actual mass of rust per unit surface area of the bar (g/cm²)

W_i = Initial weight of the bar before corrosion (g)

W_f= Weight after corrosion (g) for a given duration of induced corrosion (t)

D = Diameter of the rebar (cm)

L = Length of the rebar sample (cm)

Rate of corrosion was determined using corrosion current density, i_{corr}:

$$i_{corr} = \frac{M_{ac}F}{EWt} \quad (5)$$

Where:

i_{corr}= Corrosion current density (µAmp/cm²)

M_{ac} = Actual mass of rust per unit surface area of the bar (g/cm²)

F = Faraday's constant (96487 Amp-sec)

EW = Equivalent weigth of steel (27.925 for steel)

T = Time of accelerating corrosion (sec)

Corrosion rates was also determined in terms of Penetration rate, designated as CR:

$$CR = K_1 (i_{cor}/\rho)EW \quad (6)$$

Where:

CR= Penetration rate (mm/year)

i_{corr}= Corrosion current density (µAmp/cm²)

$K_1 = 3.27\times10^{-3}$ mm g/µA cm.yr

ρ = 7.85 g/cm³ for steel (density)

EW = Equivalent weight of element (27.93 for steel)

Mass loss rate was also determined using the formula:

$$MR = K_2\ i_{cor}\ EW\ (g/m^2d) \quad (7)$$

Where:

MR= Mass loss rate (g/m²d)

i_{corr}= corrosion current density (µAmp/cm²)

$K_2 = 8.954 \times 10^{-3}$ g.cm²/µA m² d

EW= Equivalent weigth of steel (27.925 for steel)

From the penetration rate formula, designated as CR, the real-time in year (s) and days of corrosion deterioration of structures can be determined equivalent to the accelerated time used in minutes.

$$\text{Accelerated Real-time (year)} = \text{Loss in diameter} / CR \quad (8)$$

2.5. Mechanical Test

After assessing the weight loss, the steel bars were tested under tension to evaluate their mechanical properties. The mechanical properties of each sample were evaluated using a servo-hydraulic MTS 250 kN universal testing machine of 250 kN capacity. All tensile specimens were prepared according to the DIN 488 specification, which requires a free length equal to 15 times the nominal diameter of the samples. The gage length was marked in each specimen, while the specimen total length and mass were recorded before the test to calculate the effective cross-section of each specimen.

The yield, ultimate strength and modulus of elasticity of the bars were obtained by standard tensile tests on three uncorroded reinforcing steel bars. The elongation is the tensile extension of the bar on a gauge length of five times its diameter near the rupture area.

Based on the assumption that the weight loss of the corroded reinforcements took place only within the length covered by sodium chloride solution, the amount of corrosion was measured by weight loss and determined by the degree of corrosion, designated as C_{deg}, and calculated as:

$$C_{deg} = (W_i - W_f)/W_0\ L\times100 \quad (9)$$

Where:

W_i = is the weight of the bar before Corrosion (g)

W_f = is the weight of the bar after Corrosion (g)

W_0 = Weight per unit length of the reinforcing rebar

L = Bond length

Once the corrosion has initiated, it was assumed that the yield strength of the bar changes due to corrosion, and the loss in strength of the rebar is due to a reduction in its cross-sectional area. The average cross-sectional area reduction was used to estimate the residual strength of the bars. A normalized cross-sectional area, which is the ratio of the corroded cross-sectional area to its original area, was used to determine the residual strength of corroded reinforcement structures in terms of its rebars cross-sectional area.

$$R.S = A_{st} / A_o \tag{10}$$

Where:

R.S = Residual strength

A_{st} = Area of the rebar at time t (years)

A_0 = Area before corrosion (t_0=0)

$$A_{st} = \frac{n\pi}{4}[\varphi - r_{corr}(t - t_0)]^2 \tag{11}$$

Where:

φ = Diameter of the rebar

n = Number of bars in a layer.

r_{corr} = Rate of corrosion in terms of penetration rate (mm/year)

t = Time of corrosion

t_0 = Corrosion initiation time

3. Results and Discussion

The following discusses the effects of corrosion on the reduction of steel reinforcement cross-sectional area, and the effects of cross-sectional area reductions on the mechanical properties of steel reinforcement, serviceability, durability and residual life of corroded-damaged reinforced concrete structures, particularly pile-supporting wharves that are exposed to severe aggressive marine environments throughout their lives.

3.1. Steel Cross-section Configuration

After the concrete cover was removed, the actual corrosion damage of all the steel reinforcements was observed. Figure 8 shows bare corroded steel reinforcement bars of different diameters that were subjected to corrosion acceleration. A reddish brown color, which is the corrosion product are visible along the rebars length.

Figure 8. Shows photos of corroded rebars

The above photographs show how corrosion reduced the cross-section of the steel rebars irregularly. Corrosion pits appeared in staggered locations along the length of the rebars, which formed notches of corrosion damage. Some ribs were lost over the bar length, but not entirely. Corrosion altered the rib shape on the ribbed bar surface. The reduction of steel cross-section is not uniform, but it has an abrupt change in bar geometry, thus a great variation in its cross-sectional area [25].

The accelerated procedures that was employed was effective in having this type of steel cross-sectional area alterations. It was verified that pitting corrosions will occur with chloride corrosion [7], since the environment was simulated during the experiment with seawater. According to Yuan et al. (2017) study, coastal structures like piers exposed to the marine environment always suffer from non-uniform corrosion along the elevation [15], while a uniform corrosion damage will occur with carbonation of concrete [6].

Pitting corrosion is regarded as localized corrosion, and is associated with chloride ingress and not with carbonation induced corrosion [18]. The cross section of steel is no longer round and varies considerably along its circumference and its length, so the residual diameter is better defined by loss of weight [5]. The reduction of the steel cross-sectional area induced by chlorine corrosion is difficult to assess. The percentage reduction can be calculated using the original weight of the steel rebars and of the weight of corroded rebars with the same length.

The compounds formed during pitting corrosion are different from those formed during general corrosion. These compounds have lesser volumetric expansion than the compounds formed during general corrosion [12]. In pitting corrosion, there is less tendency for concrete cover splitting or spalling, but there is an excessive loss of steel cross-sectional area [9]. Excessive reduction of steel cross-sectional area may occur without visible signs of deterioration on the surface of the concrete cover. Structures suffering from pitting corrosion exhibit reduced strength and ductility [19]. Table 3 tabulated the corrosion variables.

Table 3. Corrosion variables

Specimen ID No.	Concrete Cover Thickness (mm)	Corrosion rates (µAmpere/cm^2)	Penetration rates (mm/year)	Area Reduction (%)	Crack Width (mm)
1	35	0.7855	0.0091	4.58	0.15
2	35	0.783	0.0091	4.57	0.17
3	35	0.763	0.0088	4.46	0.13
4	35	0.741	0.0086	4.33	0.17
5	35	0.741	0.0086	4.33	0.14
6	35	0.719	0.0084	4.20	0.11
7	50	0.719	0.0084	4.20	0.20
8	50	0.697	0.0081	4.08	0.21
9	50	0.697	0.0081	4.08	0.21
10	50	0.697	0.0081	4.08	0.22
11	50	0.675	0.0079	3.95	0.23
12	50	0.653	0.0076	3.82	0.22
13	75	0.653	0.0076	3.82	0.29
14	75	0.631	0.0073	3.70	0.27
15	75	0.609	0.0070	3.57	0.30
16	75	0.604	0.0070	3.54	0.28
17	75	0.598	0.0069	3.51	0.30
18	75	0.604	0.007	3.54	0.31
19	35	0.395	0.0045	1.87	0.10
20	35	0.378	0.0044	1.79	0.08
21	35	0.343	0.0039	1.63	0.07
22	35	0.326	0.0038	1.55	0.06
23	35	0.361	0.0042	1.71	0.05
24	35	0.343	0.0039	1.63	0.03
25	50	0.275	0.0032	1.30	0.11
26	50	0.240	0.0028	1.14	0.10
27	50	0.240	0.0028	1.14	0.12
28	50	0.257	0.0030	1.22	0.13
29	50	0.266	0.0031	1.26	0.11
30	50	0.275	0.0032	1.30	0.13
31	75	0.221	0.0026	1.05	0.15
32	75	0.219	0.0026	1.04	0.17

33	75	0.300	0.0035	1.43	0.016
34	75	0.221	0.0026	1.05	0.15
35	75	0.309	0.0036	1.47	0.15
36	75	0.223	0.0026	1.06	0.17
37	75	0.130	0.0015	0.50	0.004
38	35	0.116	0.0013	0.44	0.005
39	35	0.098	0.0011	0.37	0.004
40	35	0.140	0.0016	0.53	0.003
41	35	0.132	0.0015	0.50	0.004
42	35	0.100	0.0012	0.38	0.004
43	35	0.091	0.0011	0.35	0.008
44	50	0.077	0.00089	0.30	0.01
45	50	0.050	0.00058	0.19	0.009
46	50	0.064	0.00074	0.24	0.008
47	50	0.036	0.00042	0.14	0.006
48	50	0.064	0.00074	0.24	0.007
49	75	0.023	0.00027	0.09	0.014
50	75	0.009	0.00011	0.04	0.032
51	75	0.021	0.00025	0.08	0.024
52	75	0.020	0.00023	0.08	0.024
53	75	0.020	0.00023	0.08	0.05
54	75	0.023	0.00027	0.09	0.014

3.2. Corrosion Rates

Figure 9 shows the linear correlation of the percentage reduction of the area of corroded rebars and its corrosion rates.

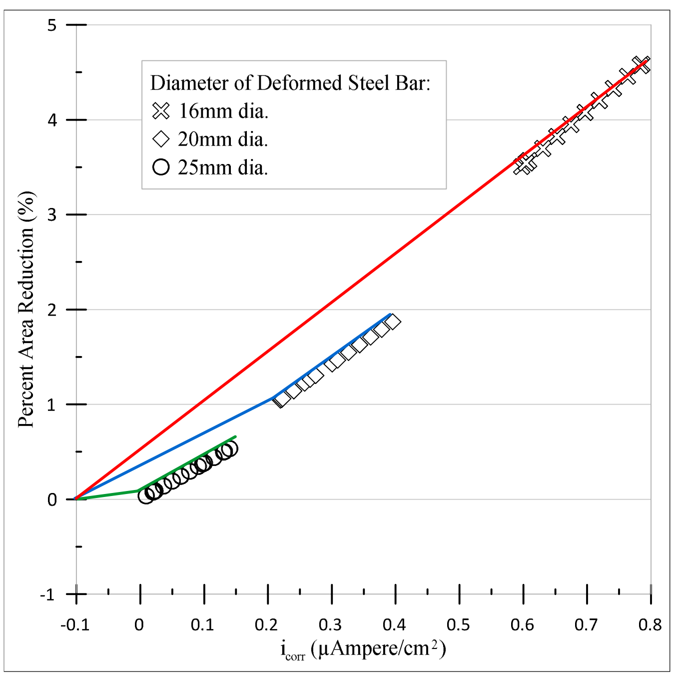

Figure 9. Influence of corrosion rates to percent (%) reduction of steel area

Corrosion rates have a significant influence on the area reduction of steel rebar reinforcement. A specimen with higher corrosion rates eventually has a lower resistance to corrosion, and it has a great reduction in the steel cross-sectional area. A group with a smaller reinforcement diameter (16mm) has the highest corrosion rates, and it has an excessive reduction of its cross-sectional area compared to the groups with larger reinforcement diameters (20 and 25 mm).

From Figure 9, 16 mm Ø has corrosion rates in the range of 0.598 – 0.786 µAmpere/cm^2; 20mm Ø has corrosion rates in the range of 0.219 – 0.395 µAmpere/cm^2, and 25mm Ø has a corrosion range of 0.023-0.139 µAmpere/cm^2. A smaller reinforcement diameter (16 mm) has high corrosion states, which is due to the smaller circumferential area used to resist the attack of deteriorating elements. The 16 mm Ø has steel area reduction of 3.51 % - 4.58 %; 20mm Ø has steel reduction of 1.04% - 1.87%, and 25 mm Ø has a steel area reduction of 0.04% - 0.50%. It was verified that the maximum loss of the cross-sectional area of the corroded reinforcement was 1.05 times the area of the uncorroded specimen.

Table 4 provides an interpretation of the corrosion rate measurements. A group of specimens with 16 mm Ø rebars are considered in a moderate to high state of corrosion; 20 mm-diameter rebars are considered in a low to moderate state of corrosion, and 25 mm Ø rebars are considered in a passive condition of corrosion state. A maximum of 5% reduction of the cross-section of the steel reinforcement was categorized in a moderate to high corrosion state of the reinforcement bar; a reduction of 2% steel reinforcement area is in the low to moderate state of corrosion, and 0.50% reduction of steel rebars is in the passive condition of corrosion state.

Table 4. Interpretation of corrosion rate measurements [27]

Current density:µA/cm^2	Corrosion State
<0.10	Passive condition
0.20 – 0.50	Low to Moderate
0.5– 1.0	Moderate to high
>1.0	High

Moderate to high state of corrosion has a maximum increment value of cross-sectional reduction of 9.215 mm^2, a low to moderate state has a maximum increment cross-sectional reduction of 5.62 mm^2, and a passive corrosion state has a maximum increment cross-sectional reduction of 2.467mm^2.

Some researchers found in the literature suggest a linear correlation between the loss of cross-sectional area and the corrosion level [6, 7]. An increment in the cross-sectional loss was noticed with a higher corrosion level [7]. Graeff et al. (2008) [7] disclosed from his work that with corrosion level of 10%, a approximate 7.50% of steel cross-sectional area decreases considerable. Furthermore, the observed values of area loss are higher than three times the mean of the area loss of the entire bar [7]. These points are considerably critical and can cause structural failure. With this study, 15.09% corrosion level, reduces 4.58% of steel cross-sectional area.

3.3. Crack Width

The correlation of crack width with the reduction of steel cross-sectional area is shown in Figure 10.

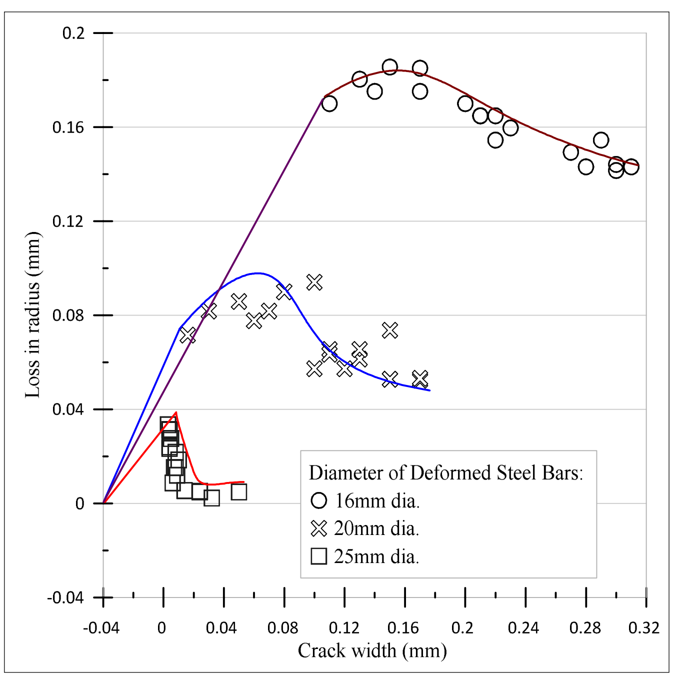

Figure 10. Influence of crack widths to radius loss of steel rebars

With an increase in the crack width, the reduction in the reinforcement steel area also increases. A larger crack width speeded up the penetration of deteriorating elements into the concrete specimen, which led to a significant reduction in the steel cross-sectional area of reinforcement due to corrosion deterioration. With an increase in the crack widths, the greater surface area of steel bars will be exposed. The exposed rebars of the specimen corrode faster than the rebars protected by the concrete cover. Wider cracks opening of concrete significantly exposed the surface area of the reinforcement steel to air, water, and some deterrent agents in the atmosphere. Steel rusted in a direction facing cracks on the concrete surface. Exposed steel rebars due to wider cracks have more conceivability to accumulate deteriorating agents and lead to its faster deterioration through corrosion.

A group of specimens with 16 mm Ø has a range of crack widths of 0.11 mm - 0.31 mm with loss in diameter of 0.286-0.37 mm; group of 20 mm Ø has a range of crack widths of 0.016-0.17 mm with loss in diameter of 0.106-0.188 mm; and a group of 25 mm Ø has a range of crack widths 0.003 - 0.050 mm with a reduction in diameter of 0.010 - 0.062 mm. The results verified that only a few micrometers of loss in the rebar cross-section can induce visible cover cracks.

In the Alonso et al. (1998) study, a radius loss of approximately 15-50 µm is necessary to generate the first visible crack, which is greater than 0.10 mm width. In this study a radius loss of 143-185 µm can generates a crack of 0.21mm; a radius loss of 53-94 µm can generate a crack with 0.093 mm; and a radius loss of 5-31 µm can generate a crack of 0.0265 mm. The value obtained from this experiment was almost the same as the results disclosed by Alonso et al. (1998) [24], which has a crack width of 0.10 mm, which is almost the same width of 0.093 mm crack width.

Further, it was also revealed from Figure 10 that a smaller reinforcement diameter (16 mm) has a more dispersed range of cracks with diverse widths compared with larger reinforcement diameters (20 and 25 mm). Specimens with higher corrosion rates, those with smaller reinforcement diameters can be predicted to have a great reduction in its steel reinforcement area, a more corroded damaged and deteriorated structure.

3.4. Mechanical Properties

The mechanical properties of corroded-damaged reinforced concrete structures depend on the rebar cross-sectional area size and corrosion level. The active cross-section of the steel is reduced in proportion to the degree of corrosion, with modification of its mechanical properties.

3.4.1. Tensile Strength

The tensile behaviours of corroded bars are essential in evaluating the capacity of corroded reinforced concrete structures. The reduction in the effective steel bar diameter has an essential influence on the tensile strength of reinforced concrete structures.

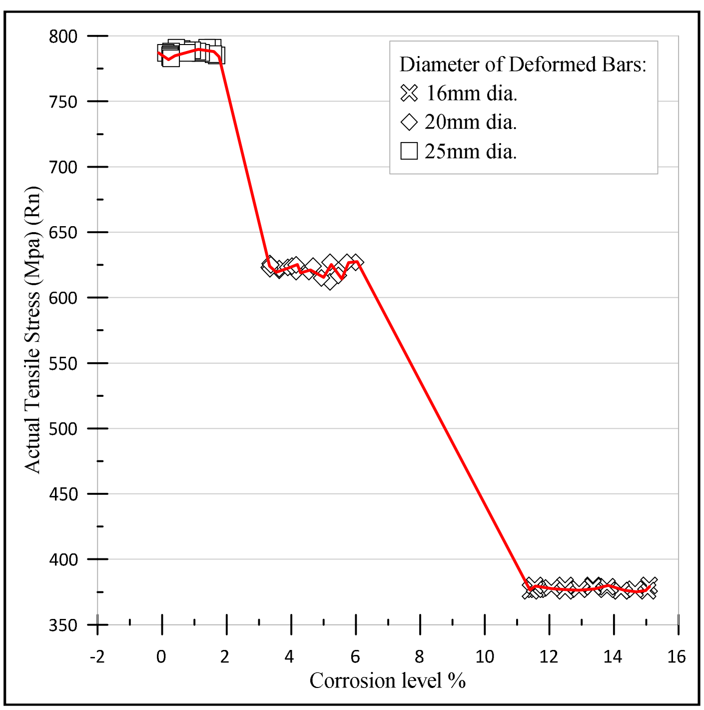

Figure 11. Effects of degree of corrosion to the actual tensile stress

From Figure 11, a group of specimens with 16mm Ø had the highest level of corrosion and lowest tensile strength. A group with larger reinforcement diameters (20 and 25 mm) has the lowest corrosion level and higher tensile strength. The group with 16 mm Ø had an 11.41-15.09% range level of corrosion with a tensile strength of 376-380 MPa. It has a lower strength to resist the level of its deterioration through corrosion disintegration. A group of specimens with 20 mm Ø has 3.31-5.99% range level of corrosion with tensile strength of 620-627 MPa. A group of 25mm Ø has 0.11-1.69% corrosion level with a tensile strength of 783-791 MPa. The result shows an inverse correlation between the corrosion level and the actual tensile strength of the group specimen. However, according to Almusallam (2001) research [21], the level of corrosion does not influence the tensile strength of steel bars. Corrosion, according to Almusallam (2001) research [28], does not significantly change the mechanical properties of steel bars significantly. However, corrosion rates according to Loreto et al. (2011) study [10] are inversely related to the tensile capacity; that is, increasing the corrosion rates, will decreases the tensile strength, which conforms to this study.

Further, a smaller reinforcement diameter (16 mm) has a dispersed value of corrosion level in the range of 11.54-15.09%, but it has a lower tensile strength; a larger reinforcement diameter (25 mm) has a closer range of corrosion level of 0.27-1.57%, but it has a higher tensile strength.

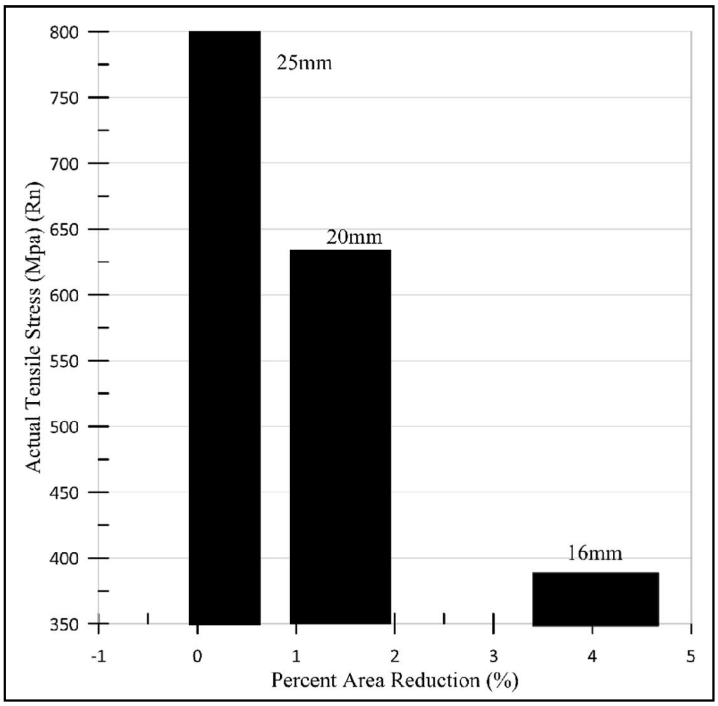

Figure 12. Percent reduction of area vs tensile strength

Figure 12 shows that a group of specimens of 16 mm Ø has a significant percent reduction of area of 3.54-4.58%, and it has a maximum tensile stress of 380 MPa. The specimen of 20 mm Ø has a range of 1.04-1.87% reduction of area with maximum tensile stress of 627 MPa. A specimen of 25 mm Ø has a range of 0.09-0.50% with a maximum tensile stress of 791 MPa. This reveals that a higher percent reduction in area leads to a decrease in its tensile stresses. Steel area reduction is linearly correlated with the actual tensile strength. It was verified that the tensile strength of corroded rebars was found to be more affected by the reduction in the cross-sectional area. Thus, there is a significant change in the tensile strength of bars calculated using the actual cross section [6].

3.4.2. Yield Stress & Ultimate Strength

The correlation of steel cross-sectional area reduction with yield stress is shown in Figure 13.

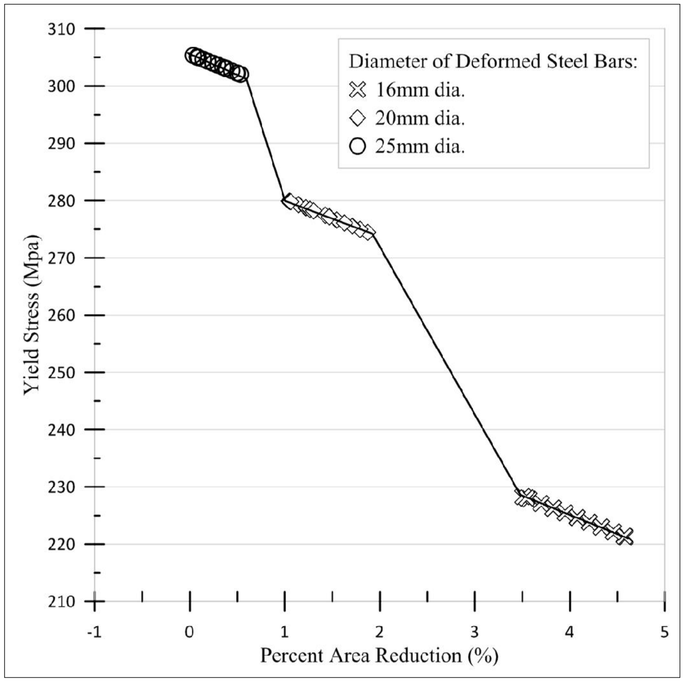

Figure 13. Influence of steel area reduction to yield stress

In Figure 13, a group of specimens with the highest percent reduction in area has a lower yield stress, while the group of specimens with a lower percent reduction in area has a higher yield stress. The percent reduction in area and yield stress are inversely related. The result reveals that the yield plateau of the corroded bars decreases with an increase in corrosion rates. It is clear from the results that the yield stress decreases remarkably with the increase in the level of corrosion for all tested diameters. However, according to Tang et al. (2014) study [28], corrosion did not affect the yield and ultimate strength based on the critical cross-sectional area reduction.

A group of 16 mm Ø has a penetration rate in the range of 0.007-0.00913 mm/year, it has a yield stress of 333.07-350.83 MPa; the group of 20 mm Ø has a penetration rate in the range of 0.002-0.0045 mm/year, it has a yield stress of 302.01-311.73 MPa; and a group of 25mm Ø has a penetration rate in the range of 0.00023-0.0036 mm/year, with a yield stress of 253.47-257.11MPa. Penetration rates have an inverse correlation with yield stress. A specimen with higher penetration rates has a lower yield stress, whereas the specimen with lower penetration rates has a higher yield stress.

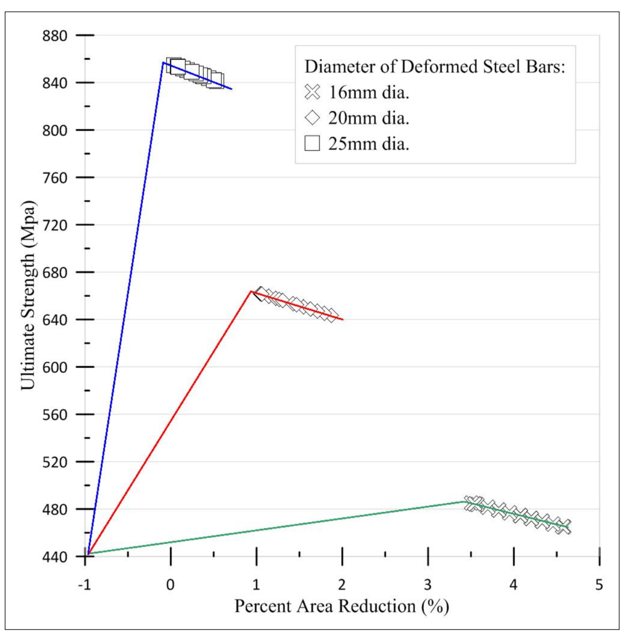

Figure 14. Percent (%) area reduction & ultimate strength

From Figure 14, a group of 16 mm Ø has Ultimate strength with a range of 464.94 - 484.36 MPa; 20 mm Ø has ultimate strength with a range of 643.45 - 661.41 MPa; and 25mm Ø has ultimate strength with a range of 841.16 - 854.63 MPa. A group of specimens which has a higher steel area reduction has a lower ultimate strength, and the specimen with lower area reduction has a higher ultimate strength. Area reduction and ultimate strength are inversely related and correlated. The ultimate strength decreases with an increase in the corrosion level based on the average cross-sectional area loss. With an increase amount of corrosion, the ultimate forces of steel reinforcement decrease more rapidly than does the average cross-sectional area.

3.4.3. Elongation to Failure

Figure 15 shows the correlation of elongation to failure and reduction of steel cross-sectional area.

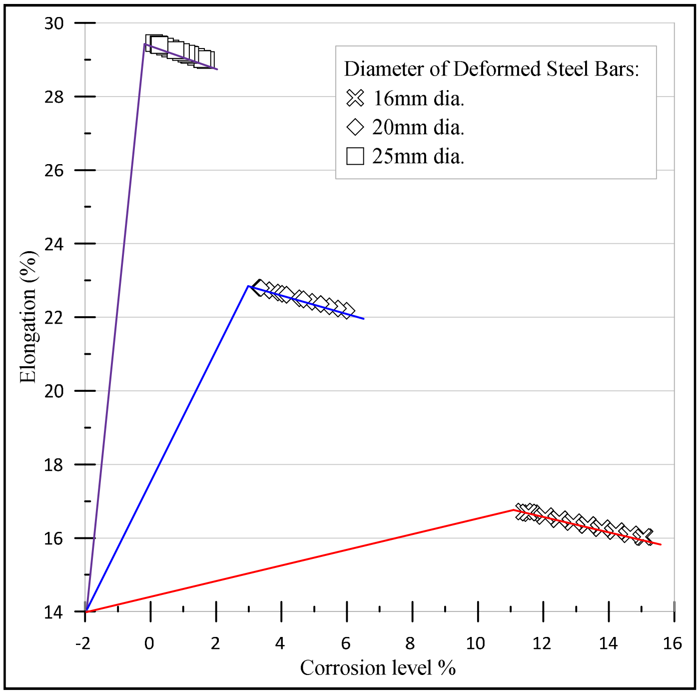

Figure 15. Correlations of elongation to failure & corrosion level

From Figure 15, steel reinforcement with a smaller diameter (16 mm) has a lower percent elongation, and steel reinforcement with larger diameters (20 and 25 mm) has a higher percent elongation. A group of 16mm Ø has a range of 16.02-16.72% elongation with a corrosion level of 11.54-15.09 %; the group of 20mm Ø has a range of 22.17-22.80% elongation with a corrosion level of 3.37-5.99%; and 25mm Ø has a range of 29.02-29.45% elongation with corrosion level of 0.11-1.57%. It was verified that when the corrosion level decreased, the elongation ratio increased; that is, when an increase of corrosion level, the elongation to failure of the steel reinforcement decreased. The corrosion rate is inversely related to elongation to failure. The results conformed to Chen et al. (2018) study [23], and the elongation to failure of the corroded-damaged specimen lengthened as the corrosion level decreased.

Further, a great reduction in the steel cross-sectional area has a shorter elongation time prior to failure. Specimens that have a smaller area reduction and larger reinforcement diameter, has a longer time to elongate prior to failure. Table 5 tabulated the mechanical properties of corroded steel bars.

Table 5. Mechanical properties of corroded steel bars

Specimen ID No.	Nominal bar diameter (mm)	Corrosion degree	Actual corroded diameter (mm)	Actual Tensile Stress (MPa)	Yield forces (KN)	Yield stress (MPa)	Ultimate strength (MPa)	Modulus of elasticity (KN/mm^2)	Yield strain	Ultimate strain	Elongation (%)
1	16	15.09	15.62	380	68.78	304.20	464.94	156234.96	0.0020	0.0662	16.02
2		15.05	15.63	376	68.82	306.43	465.18	156315.41	0.0020	0.0663	16.03
3		14.65	15.64	377	69.14	308.83	467.33	157038.44	0.0020	0.0666	16.10
4		14.22	15.65	376	69.49	310.87	469.72	157839.78	0.0020	0.0669	16.19
5		14.22	15.65	376	69.49	313.15	469.72	157839.78	0.0020	0.0669	16.19
6		13.78	15.66	377	69.84	315.41	472.10	158639.01	0.0020	0.0672	16.27

7		13.78	15.66	379	69.84	328.70	472.10	158639.01	0.0020	0.0672	16.27
8		13.35	15.67	379	70.19	330.88	474.47	159436.12	0.0020	0.0676	16.35
9		13.35	15.67	380	70.19	333.04	474.47	159436.12	0.0020	0.0676	16.35
10		13.35	15.67	379	70.19	335.18	474.47	159436.12	0.0020	0.0676	16.35
11		12.92	15.68	377	70.54	337.32	476.84	160231.14	0.0020	0.0679	16.43
12		12.49	15.69	380	70.89	339.44	479.20	161024.05	0.0020	0.0683	16.51
13		12.49	15.69	376	70.89	349.81	479.20	161024.05	0.0020	0.0683	16.51
14		12.06	15.70	378	71.24	351.86	481.55	161814.88	0.0020	0.0686	16.59
15		11.63	15.71	377	71.59	353.90	483.90	162603.63	0.0020	0.0689	16.68
16		11.54	15.71	377	71.66	353.90	484.36	162761.13	0.0020	0.0690	16.69
17		11.41	15.72	376	71.76	349.81	485.07	162997.23	0.0020	0.0691	16.72
18		11.54	15.71	380	71.66	347.43	484.36	162761.13	0.0020	0.0690	16.69
19		5.99	19.81	627	95.54	302.01	643.45	216220.45	0.0027	0.0917	22.17
20		5.73	19.82	627	95.81	303.21	645.26	216828.50	0.0027	0.0919	22.24
21		5.20	19.84	612	96.34	304.89	648.87	218041.59	0.0027	0.0924	22.36
22		4.94	19.84	615	96.61	305.86	650.67	218646.64	0.0027	0.0927	22.42
23		5.46	19.82	617	96.07	303.95	647.07	217435.54	0.0027	0.0922	22.30
24		5.20	19.84	719	96.34	304.89	648.87	218041.59	0.0027	0.0924	22.36
25		4.15	19.87	620	97.41	308.73	656.06	220455.81	0.0028	0.0935	22.61
26		3.63	19.89	621	97.94	310.62	659.63	221656.98	0.0028	0.0940	22.73
27	20	3.63	19.89	622	97.94	310.62	659.63	221656.98	0.0028	0.0940	22.73
28		3.89	19.88	623	97.67	309.68	657.85	221056.89	0.0028	0.0937	22.67
29		4.02	19.87	624	97.54	307.77	656.95	220756.47	0.0028	0.0936	22.64
30		4.15	19.87	625	97.41	307.73	656.06	220455.81	0.0028	0.0935	22.61
31		3.35	19.89	626	98.23	312.83	661.59	222315.94	0.0028	0.0942	22.80
32		3.31	19.89	623	98.26	313.41	661.77	222375.79	0.0028	0.0943	22.81
33		4.54	19.86	620	97.01	313.41	653.37	219552.34	0.0027	0.0931	22.52
34		3.34	19.89	622	98.23	315.15	661.59	222315.94	0.0028	0.0942	23.80
35		4.67	19.85	624	96.88	314.28	652.47	219250.69	0.0027	0.0929	22.49
36		3.37	19.89	625	98.20	312.53	661.41	222256.08	0.0028	0.0942	22.79
37		1.57	24.94	791	123.77	124.59	842.15	282986.54	0.0035	0.1200	29.02
38		1.39	24.94	791	124.06	124.82	843.70	283507.08	0.0035	0.1202	29.07
39		1.18	24.95	787	124.35	125.09	845.53	284121.49	0.0036	0.1204	29.14
40		1.69	24.93	785	123.48	124.45	841.16	282654.98	0.0035	0.1198	28.99
41		1.59	24.94	786	123.77	124.57	842.01	282939.19	0.0036	0.1199	29.02
42		1.21	24.95	787	124.35	125.05	845.24	284027.02	0.0036	0.1203	29.13
43		1.09	24.96	788	124.93	125.20	846.23	284357.58	0.0036	0.1205	29.16
44		0.93	24.96	789	125.51	125.40	847.63	284829.39	0.0036	0.1207	29.21
45	25	0.60	24.98	790	125.22	125.82	850.44	285771.55	0.0036	0.1211	29.31
46		0.76	24.97	789	126.09	125.61	849.04	285300.72	0.0036	0.1209	29.26
47		0.44	24.98	791	126.38	126.03	851.84	286241.89	0.0036	0.1213	29.35
48		0.76	24.97	787	126.12	125.61	849.04	285300.72	0.0036	0.1209	29.26
49		0.27	24.99	788	126.15	126.23	853.23	286711.74	0.0036	0.1215	29.40
50		0.11	25.00	787	126.15	126.44	854.63	287181.11	0.0036	0.1217	29.45
51		0.26	24.99	786	126.09	126.25	853.37	286758.70	0.0036	0.1216	29.41
52		0.24	24.99	785	126.27	126.27	853.51	286805.66	0.0036	0.1216	29.41
53		0.24	24.99	784	126.27	126.27	853.51	286805.66	0.0036	0.1216	29.41
54		0.27	24.99	783	126.23	126.23	853.23	286711.74	0.0036	0.1215	29.40

Note: *EW (for steel) = 27.925; Unit weight of steel 7850 kg/m*^{3}*; t (for* acceleration) 64800000 s

3.4.4. Ductility

Local attack of chloride results in a significant variation in the residual steel cross-sectional area, and consequently reduces the ductility of the reinforcement; Pitting corrosion affects ductility [25]. Chloride penetration creates pits and notches, resulting in stress concentration and progressive reduction of ductility [6]. The ductility of reinforcement substantially affects the deformation capacity of a structure and, in turn, substantially determine whether the structure can survive without collapse if it were to experience a moderate earthquake. With significant ductility, a structure can be prevented from failing and collapsing in a brittle fashion without warning, which can save both the lives of people in the area and reduce repair costs. Hence, particular care should be paid to the ductility of a structure in its design [25].

The ductility of reinforcing steel is normally represented by two parameters: the ratio between the yield and ultimate strength and the elongation ratio. Figure 16 shows the correlations of f_y/f_u with a reduction in the steel cross-sectional area.

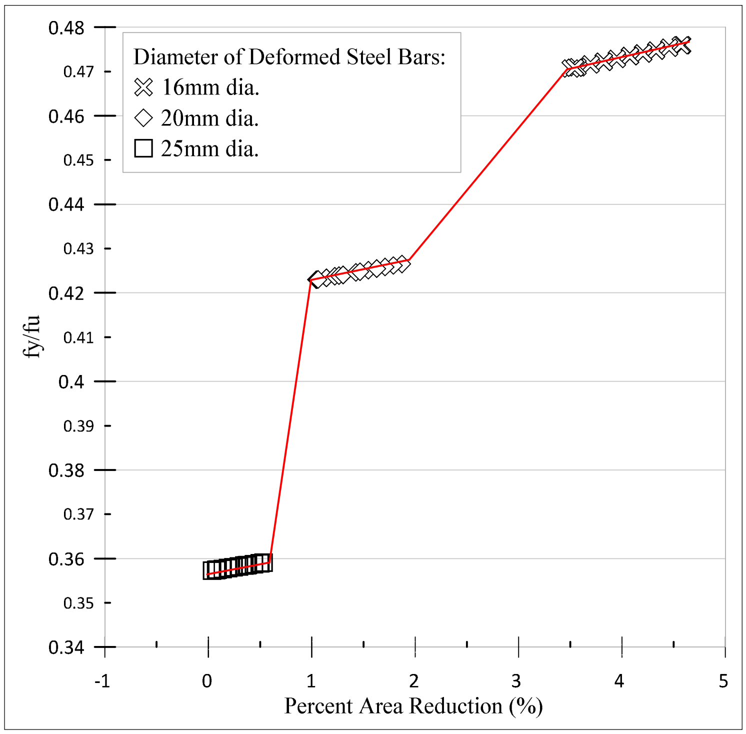

Figure 16. Ratio of yield strength to ultimate strength f_y/f_u vs percent (%) reduction of area

The yield-to-ultimate strength ratio f_y/f_u reflects the deformation capacity of the steel bar and is the most desirable warning prior to the failure of a reinforcing steel bar. Usually, as f_y/f_u increases, the deformation capacity of a corroded steel bar decreases. From Figure 16, a smaller reinforcement diameter (16mm) has a great reduction in its cross-sectional area. It has a higher ratio of f_y/f_u compared with larger reinforcement diameters (20 and 25mm), and it has a smaller area reduction of its steel cross-sectional area and it has a lower value of its f_y/f_u ratio.

Corrosion changed the failure mode of the corroded member [19]. Corrosion changes the fracture mode from mixed ductile or brittle to brittle. Mixed brittle and ductile fractures occurred in uncorroded steel bars while brittle initiated at corrosion pits and propagated outwards in corroded steel bars [28]. Only an average value of 10% non-uniform corrosion is sufficient to reduce the ductility of bars embedded in concrete [25]. The decrease in ductility with an increase in the percent loss reduction of the area was more rapid than the decrease in the mechanical strength when the corrosion level was more than 10% [6]. A corrosion level of 12% of steel rebars indicates brittle failure [21]. Brittle failure of the structures can be observed when the area of corrosion exceeds 50% [11].

The elongation and ductility of corroded reinforcement reduces much more significantly than their yield and ultimate strength. Elongation and ductility decrease exponentially with an increase in corrosion loss [28]. Even though the elongation, ultimate strength and ductile area parameter of the corroded small diameter and/or plain bars reduce more than those of large diameter and / or ribbed ones, such differences are not significant and can be neglected [25].

3.4.5. Residual life of structures

Corrosion of the reinforcement not only altered the approximately round cross sections into very irregular ones, but it also caused the residual sections to vary significantly along its length [25].

Once the corrosion has initiated, it was assumed that the yield strength of the bar changes due to corrosion, and the loss in strength of the rebar is due to a reduction in its cross-sectional area. The average cross-sectional area reduction was used to estimate the residual strength of the bars. A normalized cross-sectional area, which is the ratio of the corroded cross-sectional area to its original area, was used to determination of the residual strength of the corroded reinforcement structures. Figure 17 shows the time-variant reduction in the strength of steel rebars.

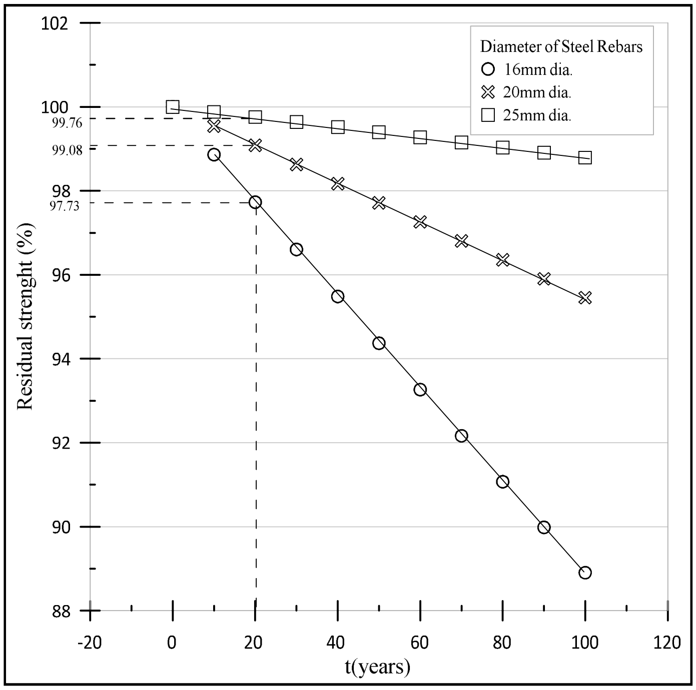

Figure 17. Time-variant reduction in strength of steel bars

From Figure 17, steel rebars with 16 mm Ø can lose 2.27% of their strength at approximately 20-years after corrosion initiation; 20 mm Ø can lose 0.92% of their strength at about 20 years time; and for 25mm Ø can lose 0.24% of their strength at about 20 years time. Smaller reinforcement (16mm) reduces its strength with a larger percentage than larger steel reinforcement diameters (20mm and 25mm). This clearly indicates that structures with smaller reinforcement rebars require more frequent inspection and need immediate repair / rehabilitation practices to ensure safety. Table 6 tabulated the residual strength of corroded rebars.

Table 6. Residual strength of corroded rebars

Penetration rate (mm/year)			T (years)	A_{st} (mm)			A_o(mm)			Residual Strength (%)		
For 16mm	For 20mm	For 25mm		For 16mm	For 20mm	For 25mm	For 16mm	For 20mm	For 25mm	For 16mm	For 20mm	For 25mm
			0	201.06	314.16	490.87	201.06	314.16	490.87	100	100	100
			10	198.77	312.72	490.28	201.06	314.16	490.87	98.86	99.54	99.88
			20	196.49	311.28	489.68	201.06	314.16	490.87	97.73	99.08	99.76
			30	194.23	309.84	489.09	201.06	314.16	490.87	96.60	98.63	99.64
			40	191.98	308.41	488.49	201.06	314.16	490.87	95.48	98.17	99.52
0.013	0.005	0.002	50	189.74	306.98	487.90	201.06	314.16	490.87	94.37	97.71	99.39
			60	187.52	305.55	487.31	201.06	314.16	490.87	93.26	97.26	99.27
			70	185.31	304.13	486.71	201.06	314.16	490.87	92.16	96.81	99.15
			80	183.11	302.71	486.12	201.06	314.16	490.87	91.07	96.35	99.03
			90	180.92	301.29	485.53	201.06	314.16	490.87	89.98	95.90	98.91
			100	178.75	299.88	484.94	201.06	314.16	490.87	88.90	95.45	98.79

Steel cross-sectional area reduction due to corrosion causes the reinforcement bars to buckle before reaching their yield capacity. The residual forces of the corroded reinforcement decrease more rapidly with their cross-sectional area reduction. As a result, the residual strength, measured in terms of stress, which can be resisted, of corroded reinforcement also reduces significantly. The residual capacity of corroded reinforcement not only decreases with the increase of corrosion level but also varies with the reduction in diameter and type of reinforcement steel rebar. The maximum corrosion rates, which causes collapse of structure is no more than 16% [18].

In case the main reinforcement is corroded, the strength of the reinforced concrete structure damaged by reinforcement corrosion cannot only be evaluated by conventional cross-section analysis of reinforced concrete structures, not only because in the reduction of the bond strength and bond rigidity between the corroded reinforcement and concrete, but also because of the reduction of the mechanical properties of reinforcement due to their reduced cross-sectional areas [17]. The rate of corrosion is one of the important parameters required to estimate the residual cross-sectional area and then the residual tensile strength of the rebar, which in turn is necessary for predicting the service life of RC structures [16].

Further, the rate at which corrosion evolves is a crucial factor, which may depict the evolution pattern of residual safety and serviceability. Once corrosion initiated in the reinforcement, it shortens the service life at a steady rate as it is progresses. Surface cracking and subsequent spalling of the concrete cover due to the expansion of the corrosion products cause to shorten the service life of the structure. Thus, the rate of corrosion directly affects the extent of the remaining service life of a corroded reinforced concrete structure.

4. Conclusions

Corrosion of steel reinforcement bars is one of the significant causes of the deterioration of reinforced concrete structures. It is considered as a negative contributor to the structural integrity of concrete structures, which results in degradation of the mechanical strength and properties of structural elements. The following were the conclusions:

- Corrosion alters the configuration of steel rebars irregularly. It altered the rib shape on the ribbed bar surface.
- Corrosion rates have a linear correlation with the cross-sectional reduction of corroded steel rebars. A higher corrosion level significantly increased the reduction of the cross-sectional area. The active cross-section of the steel is reduced in proportion to the degree of corrosion, with modification of its mechanical properties.
- Sizes of the steel reinforcement diameter influences the corrosion rates of the specimen. A smaller reinforcement diameter (16mm) has higher corrosion rates compared to larger reinforcement diameters (20mm and 25mm). A smaller reinforcement diameter has a higher current density, and it has a higher mass-loss rate. The mass-loss rate decreased with an increase in the bar diameter whenever the reinforcing bar was corroded.
- A larger crack width speeded up the penetration of deteriorating elements into the specimen, which led to a significant reduction in the steel cross-sectional area. The exposed rebars corrode faster compared to the protected by-the-cement rebar's. With an increase in crack openings, the greater surface area of steel bars will be exposed, leading to rapid deterioration.
- The reduction of the steel cross-sectional area significantly influences the mechanical properties of corroded steel rebars. The ultimate tensile strength of the corroded rebars is significantly affected by the reduction in the steel cross-sectional area.
- The yield stress and ultimate strength decrease with an increase in corrosion level based on the average cross-sectional area loss. With an increase of amount of corrosion, the yield and ultimate forces of steel reinforcement decrease more rapidly than does the average cross-sectional area.
- The elongation to failure of the corroded-damaged specimen lengthened as the corrosion level decreased.
- The effects of corrosion on the reduction of steel cross-sectional area have a significant impact on the degradation of the strength and ductility of concrete. The elongation and ductility of corroded steel bars decreased exponentially with an increase in the cross-sectional area loss.
- The yield-to-ultimate strength ratio f_y/f_u reflects the deformation capacity of the steel bar and is the most desirable warning prior to the failure of a reinforcing steel bar. Usually, as f_y/f_u increases, the deformation capacity of a corroded steel bar decreases.
- The rate of corrosion directly affects the extent of the remaining service life of a corroded reinforced concrete structure. The residual capacity of corroded reinforcement not only decreases with the amount of corrosion, but also varies with the diameter and type of reinforcement used.

It is recommended to study the reduction of the cross-sectional area of pre-stressing wires due to corrosion, corrosion level, and the rate of its deteriorations.

5. Funding

The study was funded by ERDT-DOST in the School of Engineering at the University of San Carlos.

6. Acknowledgment

The authors acknowledge the graduate scholarship funding from ERDT-DOST by the School of Engineering at the University of San Carlos.

7. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] Nayak, Chittaranjan Birabar, Nivedita Sunil Throat, and Sunil Bhimrao Thakare. "Corrosion Impact Analysis on Residual Life of Structure Using Cathodic Technique and Algor Simulation Software." Engineering Structures and Technologies 10, no. 1 (April 27, 2018): 18–26. doi:10.3846/est.2018.1468.

[2] Lateef, Hanaa H., and Abbas Mohammed Burhan. "Time-Cost-Quality Trade-Off Model for Optimal Pile Type Selection Using Discrete Particle Swarm Optimization Algorithm." Civil Engineering Journal 5, no. 11 (November 1, 2019): 2461-2471. doi:10.28991/cej-2019-03091424.

[3] Castel, A., R. François, and G. Arliguie. "Mechanical Behaviour of Corroded Reinforced Concrete beams—Part 1: Experimental Study of Corroded Beams." Materials and Structures 33, no. 9 (November 2000): 539–544. doi: 10.1007/bf02480533.

[4] Molina, F. J., C. Alonso, and C. Andrade. "Cover Cracking as a Function of Rebar Corrosion: Part 2—Numerical Model." Materials and Structures 26, no. 9 (November 1993): 532–548. doi:10.1007/bf02472864.

[5] Taha, Nihal Abdelhamid, and Mohammed Morsy. "Study of the Behavior of Corroded Steel Bar and Convenient Method of Repairing." HBRC Journal 12, no. 2 (August 2016): 107–113. doi:10.1016/j.hbrcj.2014.11.004.

[6] Apostolopoulos, Ch. Alk. "The Influence of Corrosion and Cross-Section Diameter on the Mechanical Properties of B500c Steel." Journal of Materials Engineering and Performance 18, no. 2 (July 25, 2008): 190–195. doi:10.1007/s11665-008-9281-x.

[7] Graeff, Angela Gaio, L. Carlos, and P. Silva. "Analysis of rebar cross sectional area loss by reinforced concrete corrosion." In 11DBMC International Conference on Durability of Building Materials and Components, Istanbul, Turkey, vol. 44. (2008).

[8] Holly, Ivan, & Bilcik, Juraj. "Bond Reduction due to Reinforcement Corrosion in Concrete." RILEM International workshop on performance-based specification and control of concrete durability, Zagreb, Croatia, 11-13 June (2014).

[9] Sæther, Irina. "Bond Deterioration of Corroded Steel Bars in Concrete." Structure and Infrastructure Engineering 7, no. 6 (June 2011): 415–429. doi:10.1080/15732470802674836.

[10] Loreto, G., M. Di Benedetti, R. Iovino, A. Nanni, and M. A. Gonzalez. "Evaluation of Corrosion Effect in Reinforced Concrete by Chloride Exposure." Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2011 (March 24, 2011). doi:10.1117/12.880156.

[11] Choi, Yoon Suk, Seong-Tae Yi, Myung Yu Kim, Woo Young Jung, and Eun Ik Yang. "Effect of Corrosion Method of the Reinforcing Bar on Bond Characteristics in Reinforced Concrete Specimens." Construction and Building Materials 54 (March 2014): 180–189. doi:10.1016/j.conbuildmat.2013.12.065.

[12] Auyeung, YuBun, Perumalsamy Balaguru, and Lan Chung. "Bond behavior of corroded reinforcement bars." ACI Materials Journal 97, no. 2 (2000): 214-220.

[13] Zhu, Wenjun. "Effect of corrosion on the mechanical properties of the corroded reinforcement and the residual structural performance of the corroded beams." PhD diss., Civil Engineering. INSA de Toulouse, (2014).

[14] Kivell, Anton Richard Lean. "Effects of bond deterioration due to corrosion on seismic performance of reinforced concrete structures." University of Canterbury, New Zealand, (2012).

[15] Yuan, Wei, Anxin Guo, and Hui Li. "Experimental Investigation on the Cyclic Behaviors of Corroded Coastal Bridge Piers with Transfer of Plastic Hinge Due to Non-Uniform Corrosion." Soil Dynamics and Earthquake Engineering 102 (November 2017): 112–123. doi:10.1016/j.soildyn.2017.08.019.

[16] Pillai, R.G., M.D. Hueste, P. Gardoni, D. Trejo, and K.F. Reinschmidt. "Time-Variant Service Reliability of Post-Tensioned, Segmental, Concrete Bridges Exposed to Corrosive Environments." Engineering Structures 32, no. 9 (September 2010): 2596–2605. doi:10.1016/j.engstruct.2010.04.032.

[17] Lee, Han-Seung, Takafumi Noguchi, and Fuminori Tomosawa. “Evaluation of the Bond Properties Between Concrete and Reinforcement as a Function of the Degree of Reinforcement Corrosion.” Cement and Concrete Research 32, no. 8 (August 2002): 1313–1318. doi:10.1016/s0008-8846(02)00783-4.

[18] Stewart, Mark G., and Ali Al-Harthy. “Pitting Corrosion and Structural Reliability of Corroding RC Structures: Experimental Data and Probabilistic Analysis.” Reliability Engineering & System Safety 93, no. 3 (March 2008): 373–382. doi:10.1016/j.ress.2006.12.013.

[19] Azam, Rizwan. "Behaviour of shear critical RC beams with corroded longitudinal steel reinforcement." Master's thesis, University of Waterloo, Ontario, Canada, (2010).

[20] Xia, Jin, Wei-liang Jin, Yu-xi Zhao, and Long-yuan Li. “Mechanical Performance of Corroded Steel Bars in Concrete.” Proceedings of the Institution of Civil Engineers - Structures and Buildings 166, no. 5 (May 2013): 235–246. doi:10.1680/stbu.11.00048.

[21] Almusallam, Abdullah A. “Effect of Degree of Corrosion on the Properties of Reinforcing Steel Bars.” Construction and Building Materials 15, no. 8 (December 2001): 361–368. doi:10.1016/s0950-0618(01)00009-5.

[22] Lu, Zhao-Hui, Yi-Bin Ou, Yan-Gang Zhao, and Chun-Qing Li. “Investigation of Corrosion of Steel Stirrups in Reinforced Concrete Structures.” Construction and Building Materials 127 (November 2016): 293–305. doi:10.1016/j.conbuildmat.2016.09.128.

[23] Chen, Hui, Jinjin Zhang, Jin Yang, and Feilong Ye. “Experimental Investigation into Corrosion Effect on Mechanical Properties of High Strength Steel Bars under Dynamic Loadings.” International Journal of Corrosion 2018 (2018): 1–12. doi:10.1155/2018/7169681.

[24] Alonso, C., C. Andrade, J. Rodriguez, and J. M. Diez. “Factors Controlling Cracking of Concrete Affected by Reinforcement Corrosion.” Materials and Structures 31, no. 7 (August 1998): 435–441. doi:10.1007/bf02480466.

[25] Du, Y. G., L. A. Clark, and A. H. C. Chan. “Effect of Corrosion on Ductility of Reinforcing Bars.” Magazine of Concrete Research 57, no. 7 (September 2005): 407–419. doi:10.1680/macr.2005.57.7.407.

[26] Lu, Chun-hua, Wei-liang Jin, and Rong-gui Liu. “Probabilistic Lifetime Assessment of Marine Reinforced Concrete with Steel Corrosion and Cover Cracking.” China Ocean Engineering 25, no. 2 (June 2011): 305–318. doi:10.1007/s13344-011-0025-6.

[27] Rodriguez, J, LM Ortega, and J Casal. “Load Carrying Capacity of Concrete Structures with Corroded Reinforcement.” Construction and Building Materials 11, no. 4 (June 1997): 239–248. doi:10.1016/s0950-0618(97)00043-3.

[28] Tang, Fujian, Zhibin Lin, Genda Chen, and Weijian Yi. “Three-Dimensional Corrosion Pit Measurement and Statistical Mechanical Degradation Analysis of Deformed Steel Bars Subjected to Accelerated Corrosion.” Construction and Building Materials 70 (November 2014): 104–117. doi:10.1016/j.conbuildmat.2014.08.001.