Experimental and analytical investigations on seismic behavior of corroded reinforced concrete members

Vu Ngoc Son

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NANYANG
TECHNOLOGICAL
UNIVERSITY

**EXPERIMENTAL AND ANALYTICAL
INVESTIGATIONS ON SEISMIC BEHAVIOR OF
CORRODED REINFORCED CONCRETE
MEMBERS**

VU NGOC SON

School of Civil and Environmental Engineering

2017

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INVESTIGATIONS ON SEISMIC BEHAVIOR OF
CORRODED REINFORCED CONCRETE
MEMBERS**

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ABSTRACT

Corrosion of reinforcement is recognized as one of the major deterioration problems for reinforced concrete (RC) structures which seriously affects their serviceability and durability. The corrosion of reinforcement happens in RC structures due to the carbonation of concrete or diffusion of chloride. A large number of RC building and bridge structures in the coastal areas are under serious chloride attack, and even more so the humid and sultry environment in these regions could further speed up the corrosion process of reinforcement. Therefore, there has been rising concern to assess the durability and safety of these existing corroded RC structures, especially when they are subjected to seismic loading.

In this research, three segments of the experimental program were conducted. The first test series was carried out on 36 small-scale columns specimens to study the stress-strain relations of confined concrete with corroded transverse reinforcement. The variables of interest of this test series were the corrosion level of transverse reinforcement, cross sectional shape of confined concrete, as well as arrangement and configuration of confining transverse reinforcing bars. The test results indicated that four key parameters of the complete stress-strain relation were significantly affected due to the corrosion of transverse reinforcement, including the maximum concrete strength and corresponding axial concrete strain, maximum concrete strain at the fracture of the first hoops, and descending branch of the stress-strain curve after exceeding the maximum strength. Based on the test data, an analytical stress-strain model for confined concrete with corroded transverse reinforcement was proposed. A good agreement between analytical and experimental results was obtained.

To understand the seismic response of RC slender columns with corroded reinforcement which fail in flexural manners, the second test series was conducted on 8 full-scale un-corroded and corroded specimens with the special focus on the possibility of change in their failure modes due to severe corrosion and high axial forces. The experimental results highlighted that the seismic performance of RC slender columns was significantly affected by the corrosion of reinforcement,

particularly their lateral load resistance and ultimate drift capacity. It is remarkable to observe the change of failure modes of corroded columns from typical flexural failure in un-corroded columns to flexural-shear failure and sudden axial failure when these columns were highly corroded and subjected to high axial force. In addition, based on the experimental results, an equation to predict the residual flexural strength of corroded slender columns was proposed which is based on the maximum pit depth of corroded longitudinal reinforcing bars.

The last test series consisting of 8 full-scale un-corroded and corroded short columns were tested under the simulated seismic loading to investigate the effects of corrosion on the seismic performance of short columns which failed in shear. Based on the shear strength model proposed in ASCE/SEI 41-13 standard, a shear strength assessment for corroded columns was proposed in this study which considered the contribution reductions to the shear strength of transverse reinforcement and concrete due to corrosion. Adopting this proposed shear strength assessment, the shear strength prediction based on the minimum cross-sectional area of transverse reinforcing bars showed good and reliable agreement with the test results in this study, including four corroded slender columns failed in flexural-shear failure and axial failure in the second test series and six corroded short columns failed in shear in the last test series.

Finally, a three-dimensional (3D) non-linear finite element was proposed in this study to further study the seismic behavior of RC columns with corroded reinforcement, considering the material properties deteriorations of reinforcement and concrete induced by corrosion. An extensive parametric investigation, consisting of the FE models of 192 RC columns subjected to the simulated seismic loading was carried out to study the influence of various crucial parameters on the seismic performance of both corroded slender and short columns, particularly their lateral load resistance and ultimate drift capacity deteriorations. Three prediction equations of the lateral load resistance and ultimate drift capacity for both corroded slender columns and short columns were proposed based on the multivariable regression analysis of the numerical results of 192 FE models.

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Chapter 1. INTRODUCTION

1.1 Problem Statements

Corrosion of steel reinforcement has been found to be one of the most significant causes of deteriorations for reinforced concrete (RC) structures subjected to various corrosive environmental actions. The corrosion products expand the volume of corroded steel reinforcement, leading to the tensile stresses at the interfacial regions between reinforcement and concrete, causing the cover concrete of these RC structures to crack and spall off. Additionally, the deterioration of strength and ductility of reinforcement due to corrosion also results in the significant reduction of the confinement effectiveness for confined concrete and buckling resistance of longitudinal reinforcement. As a result, the durability and safety performance of RC structures will be adversely affected especially since these structures usually exist in severely corrosive environments and earthquake prone regions. **Figure 1.1** summarizes the adverse effects of corrosion on the performance of RC structures.

Past earthquakes have proven that inadequate confinement of core concrete results in brittle characteristics under severe earthquake which should be avoided in design. The amount and arrangement of confining transverse reinforcement play a significant role in enhancing the performance of RC structures, especially in their inelastic ranges. During the service life of RC structures, their strength and ductility often deteriorate due to reinforcement corrosion, hence these deteriorations should be accurately predicted and taken into account from the outset of the design process, even more so for structures built in corrosive environments. It is also clearly recognized that the stress-strain relations of reinforcement and confined concrete material are important input parameters to predict the performance of RC members, particularly their flexural and shear behavior. While the stress-strain relations for corroded reinforcement have been well studied in the literature [D2], [D3], [S8], [O4], to the author's knowledge, so far there is no analytical stress-strain model for confined concrete with corroded transverse reinforcement.

Regarding the corrosion and earthquake induced disasters, Cagatay (2005) [C2] provided an interesting report on RC buildings damaged during the 17th August 1999 Izmit earthquake. An important conclusion drawn from this research is that the use of sea sand, and consequently the presence of chlorides inside the concrete mix, resulted in severe reinforcement corrosion and even in some cases complete loss of bond between reinforcement and surrounding concrete, as depicted in **Figure 1.2**. In the literature, the behavior of reinforced concrete beams with corroded reinforcement has been well investigated, particularly their flexural and shear strength deteriorations due to corrosion of reinforcement [M6], [T2], [O2], [E1]. On the other hand, the experimental research about the effects of corrosion on the performance of RC columns subjected to seismic loading is still minimal. Among these limited research, the studies conducted by Meda *et al.* (2014) [M9], Goksu and Ilki (2016) [G1] were devoted to investigate the effects of corroded longitudinal reinforcement on the seismic behavior of flexural dominated columns. The test results in these studies showed that although the flexural strength and deformation capacity significantly deteriorated when the corrosion level of reinforcement increased, the failure mode did not change as compared to un-corroded columns. It is noted that in these studies, only longitudinal reinforcing bars were corroded which did not simulate the corrosion phenomenon of RC columns in reality where the transverse reinforcement is even more corroded because of its smaller diameter and shorter distance to the corrosive environment. On the other hand, the other studies conducted by Bousias *et al.* (2004) [B3], Li *et al.* (2009) [L8], Meda *et al.* (2016) [M10] have focused on the effectiveness of strengthening methods on corroded columns under cyclic loading. Therefore, there is a shortfall of research on the seismic performance of RC columns with both corroded transverse and longitudinal reinforcing bars, particularly in terms of investigations on their strength and deformation capacity deteriorations, especially the possibility of change in failure modes due to severe corrosion and high applied axial forces. In addition, most experimental studies in the literature focus on flexural dominated columns with corroded reinforcement. There is clearly a shortfall of research on the seismic performance of RC short columns which fail in shear in corrosive environment, particularly in terms of investigations on their shear strength and

deformation capacity deteriorations due to reinforcement corrosion. Therefore, seismic assessment of corroded RC columns draws an urgent need for international research attention.

Figure 1.1 Corrosion effects on the structural performance [S6]

Figure 1.2 Corrosion of reinforcement in RC structures during Izmit earthquake [C2]

1.2 Objectives and Scope

The overall objective of this research is to evaluate and model the behavior of RC structures in corrosive environment, including the stress-strain relations of confined concrete with corroded transverse reinforcement, the seismic performance of RC columns with corroded reinforcement. To obtain these objectives, the scope of this research is as follows:

1. To experimentally study the stress-strain relations of confined concrete with corroded transverse reinforcement and develop an analytical stress-strain model for corroded confined concrete based on the test results.
2. To experimentally study the effects of corrosion on the seismic performance of slender columns which fail in flexural manners, particularly in terms of investigations on their strength and deformation capacity deteriorations, especially the possibility of change in failure modes due to severe corrosion and high applied axial forces. Furthermore, an empirical equation to predict the residual flexural strength of corroded columns was proposed which is based on the maximum pit depth of corroded longitudinal reinforcing bars.
3. To experimentally study the effects of corrosion on the seismic performance of short columns which fail in shear. Methods were proposed to estimate the shear strength of corroded columns failed in flexural-shear and shear failures that consider the reductions of contribution to the shear strength of transverse reinforcement and concrete due to corrosion
4. To develop three-dimensional (3D) non-linear Finite Element (FE) analysis that can model the seismic behavior of RC columns with corroded reinforcement, considering the material properties deteriorations of reinforcement and concrete induced by corrosion.

1.3 Organization of Dissertation

This dissertation consists of eight chapters, including this introduction **Chapter 1** which covers problem statements, objectives and scope.

Chapter 2 provides a background on corrosion and its effects on mechanical properties of reinforcement and reinforced concrete. A literature review on stress-strain models for confined and unconfined concrete is also given in the later part of

this chapter. In addition, this chapter presents an overview on previous experimental studies on RC columns with corroded reinforcement under cyclic loading.

Chapter 3 describes an experimental program including the design of three test series, particularly the test setup, instrumentation and measurement. The first test series will be carried out to investigate the stress-strain relations of confined concrete with corroded transverse reinforcement. The main variables of this test series are the corrosion level of transverse reinforcement, cross sectional shape of confined concrete, as well as arrangement and configuration of confining transverse reinforcing bars. The second test series will be conducted to study the effects of corrosion on the seismic performance of slender columns which fail in flexure. Finally, the last test series aims at investigating the seismic performance of corroded short columns which fail in shear. The main parameters of the second and third test series are the corrosion levels of reinforcement and applied axial force ratios. In addition, the corrosion measurement results of test specimens will be also presented in this chapter.

Chapter 4 discusses the experimental results of the first test series. The effects of test parameters on the stress-strain relations of corroded confined concrete are discussed, including corrosion level, volumetric ratio of transverse reinforcement, confinement reinforcement configuration, and cross sectional shape of confined concrete. Based on the test data and regression analysis, an analytical stress-strain model for confined concrete with corroded transverse reinforcement is proposed.

Chapter 5 presents the test results of the second test series. The seismic performance of test specimens is assessed in terms of crack pattern, hysteretic response, yield displacement, lateral load resistance, drift capacity, and energy dissipation capacity. The change of the failure modes due to severe corrosion and high axial load is also presented. In addition, an empirical equation to predict the residual flexural strength of corroded columns is proposed which is based on the maximum pit depth of corroded longitudinal reinforcing bars.

Chapter 6 discusses the experimental results of the third test series, particularly the effects of corrosion on the seismic performance of short columns which fail in

shear. The key variables are the corrosion level of reinforcement and the applied axial force ratio. Based on the shear strength model suggested in ASCE/SEI 41-13 code, a shear strength assessment is proposed to estimate the shear strength of corroded columns which considers the reduction of contribution to the shear strength of transverse reinforcement and concrete due to corrosion. The proposed shear strength assessment shows good and reliable agreement with the test results in this study, including four corroded slender columns failed in flexural-shear and axial failures in the second test series and six corroded short columns failed in shear in the third test series.

Chapter 7 proposes a three-dimensional FE modeling to simulate the behavior of corroded columns subjected to seismic loading, considering the material properties deterioration of reinforcement and concrete induced by corrosion. The experimental results of test specimens in current study and literature are selected to verify the accuracy of the proposed 3D non-linear FE model. Thereafter, an extensive parametric investigation, including the FE models of 192 RC columns subjected to the simulated seismic loading is performed to study the influence of various crucial parameters on the seismic performance of corroded RC columns, particularly their lateral load resistance and ultimate drift capacity deteriorations. Finally, these key parameters are incorporated into three prediction equations of the lateral load resistance and ultimate drift capacity for both corroded short and slender columns.

Chapter 8 describes the major conclusions from the current study and some suggestions for future work. **Appendix A** illustrates the details of test specimens and the database of test results of specimens in Series 1. **Appendix B** presents the details of test results of specimens in Series 2 while **Appendix C** provides the data of test results of specimens in Series 3. Finally, **Appendix D** summaries the corrosion measurement results of reinforcement for test specimens.

Chapter 2. BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

This chapter presents the background of reinforcement corrosion and its effects on reinforced concrete structures, as well as literature review on reinforced concrete columns with corroded reinforcement subjected to simulated seismic loading which are organized in five sections. In Section 2.2, the background of corrosion and its effects on reinforced concrete structures is reviewed. After that, the available stress-strain models for confined concrete are presented in Section 2.3. Section 2.4 reviews the previous experimental studies on reinforced concrete columns with corroded reinforcement subjected to cyclic loading. Finally, the last section summarizes the shortcomings in the previous studies which motivate the current study.

2.2 Background of Reinforcement Corrosion and Its Effects on Reinforced Concrete Structures

2.2.1 Reinforcement corrosion

According to ASTM G15 (2004) [A8], corrosion can be defined as the chemical or electro-chemical reaction between a material, usually a metal, and its environment that produces a deterioration of material and its properties. The reinforcement corrosion process can be expressed by four main electro-chemical reactions as follows:

where Fe^{2+} is ferrous oxide and $\gamma - FeOOH$ or Fe^{3+} is ferric oxide. This electro-chemical process consists of two half-cell reactions, namely anode and cathode reactions. Eq. (2.1) shows the anode half-cell reaction of producing electrons that is the ionization of iron to form ferrous ions. On the other hand, Eq. (2.2)

demonstrates the cathode half-cell reaction of consuming electrons that is the reduction of oxygen to form hydroxyl ions. Finally, the ferrous ions and hydroxyl ions react with each other to form hydrated ferric oxide as illustrated in Eq. (2.3) and Eq. (2.4), generally known as rust, or corrosion product.

In general, there are two types of corrosion in reinforced concrete, as shown in **Figure 2.1**. The first type of corrosion is the uniform corrosion caused by the carbonation attack on RC structures, so-called carbonation induced corrosion. The second type of corrosion is pitting corrosion due to the chloride penetration, namely chloride induced corrosion. In both cases, the main adverse effect of corrosion is to reduce the resistance and loading capacity of RC structures.

Figure 2.1 Types and morphology of corrosion in reinforced concrete [R1]

2.2.2 Corrosion types

2.2.2.1 Chloride induced corrosion

The highly alkaline environment in concrete protects reinforcement from corrosion by creating the thin passive layer which can prevent the oxygen from accessing the *Fe* elements. However, the acidity from the environment penetrates into the reinforced concrete through its pores and then reduces the pH-value of the surrounding area of reinforcement. Therefore, the alkaline environment in concrete is neutralized, resulting in the damage of the passive layer on reinforcement surface.

One of the major causes of reinforcement corrosion is the exposure of RC structures to chloride ions which results in the breakdown of the passive film of reinforcement. The chlorides possibly come from the accelerating admixtures, contaminants, deicing salt, coastal vapor, or marine environments. It is noted that the chloride acts as catalyst in the corrosion process and it is not contained in any corrosion products. The mechanism of the chloride induced corrosion process can be expressed as followings:

2.2.2.2 Carbonation induced corrosion

Carbon dioxide in atmosphere penetrates into the concrete and has the chemical reaction with the calcium hydroxide of cement paste to form calcium carbonate, which is the so-called carbonation process. This chemical reaction can be expressed as follows:

Carbonation reduces the pH-value of the pore solution to such a range at which the passive film of embedded steel is damaged, and then the corrosion of reinforcement gradually initiates.

2.2.3 Corrosion product

Corrosion product, generally known as rust, consists of different kinds of elements and its volume is much larger than that of the metal iron. Jaffer and Hansson (2009) [J1] investigated various corrosion products with different densities and volume expansion as shown in **Figure 2.2**. For reinforced concrete structures, it is noted that the corrosion products expand the volume of corroded steel reinforcement, leading to tensile stresses that develop at the interfacial regions between steel reinforcement and concrete, causing the cover concrete of these structures to crack and spall off.

Figure 2.2 Different types of corrosion products of iron [J1]

2.2.4 Corrosion rate measurement and prediction

The corrosion rate $I_{corr} (\mu\text{A}/\text{cm}^2)$ or corrosion current density is defined as the quantity of metal which transforms into oxide by unit of reinforcement surface and time. The current density of the natural corrosion process is from 0.1 to $1.0 \mu\text{A}/\text{cm}^2$. If the value of corrosion rate is smaller than $0.1 \mu\text{A}/\text{cm}^2$, the corrosion level of reinforcement can be neglected. Values of corrosion rate above $1.0 \mu\text{A}/\text{cm}^2$ are seldom measured in reality and those values higher than $10 \mu\text{A}/\text{cm}^2$ have almost never been recorded for on-site corrosion rate measurements [A5]. In the literature, several studies have proposed non-destructive tests of steel corrosion in RC structures [L9], [Y3], [A5], [K2], [H2]. Among the existing non-destructive methods, the method so-called Polarization Resistance technique is commonly used for on-site corrosion rate measurement in real structures. More details of this method can be seen in Andrade *et al.* (2004) [A5]. Although these non-destructive tests can provide reasonable results of corrosion level of reinforcement in reality, they may need time-consuming and expensive equipments. Without conducting the experiment, a number of models have been suggested to predict the corrosion rate in literature, including constant rate models and variable rate models, as indicated in **Table 2.1**. It is noted that almost existing corrosion rate models in literature are empirical expressions. Among these models, the corrosion rate model proposed by Vu and Stewart (2000) [V1] is commonly used to predict the corrosion rate of RC

structures with an acceptable accuracy. Following this model, the corrosion rate can be expressed as a function of the water to cement ratio w/c , the thickness of the concrete cover d_c , and the corrosion time as follows:

$$I_{corr}(1) = \frac{37.8(1 - w/c)^{-1.64}}{d_c} \quad (2.10)$$

$$I_{corr}(t) = I_{corr}(1) * 0.85t_p^{-0.29} \quad (2.11)$$

$$t_p = t - t_i \quad (2.12)$$

where $I_{corr}(1)$ is the corrosion rate at the beginning of corrosion propagation, $\mu A/cm^2$; t is the time at which the corrosion rate $I_{corr}(t)$ is predicted; t_i is the time to corrosion initiation. **Figure 2.3** shows an example of the relationship between time after corrosion initiation and corrosion rate with $d_c = 50$ mm and $w/c = 0.4$. When the corrosion rate is measured or predicted, the average penetration of corrosion attack P_x and the maximum corrosion pit depth P_{pit} can be calculated as follows:

$$P_x = 0.0116 * I_{corr}(t) * t_p \quad (2.13)$$

$$P_{pit} = \alpha * P_x \quad (2.14)$$

where α is the pitting factor which varies from 3 to 10 [G2], [A3], depending on the degree of localized pitting corrosion. In addition, the rebar diameter loss can be estimated as follows:

$$D_{ave} = D_0 - 2P_x \quad (2.15)$$

$$D_{min} = D_0 - \alpha * P_x \quad (2.16)$$

where D_0 is the original diameter of rebar; D_{ave} is the average residual diameter of the rebar for uniform corrosion; D_{min} is the minimum residual diameter of the rebar for pitting corrosion. Finally, the deterioration of RC structures can be evaluated when the corrosion levels in terms of average penetration attack P_x and localized attack P_{pit} are known.

Figure 2.3 Relations between corrosion rate and time after corrosion initiation [V1]

Table 2.1 Available predicted corrosion rate models in literature

Author(s)	Type	Models
Alonso <i>et al.</i> (1988) [A2]	Constant	$I_{corr} = \frac{1000}{R_{ohm}}$ R_{ohm} is the resistivity of concrete.
Yalcyn and Ergun (1996) [Y1]	Exponential decrease	$I_{corr}(t) = I_{corr,0} * e^{-Ct}$ $I_{corr}(t)$ is the corrosion rate at time t ; $I_{corr,0}$ is the initial corrosion rate; C is the corrosion constant, depending on the cover concrete thickness, pH of environment conditions, permeability, and degree of concrete pore saturation. $C = 1.1 * 10^{-3} day^{-1}$ is recommended to use.
Stewart and Rosowsky (1998) [S9]	Constant	$I_{corr} = 1.5$
Li (2004) [L7]	Logarithmic increase	$I_{corr}(t) = 0.3683 \ln(t) + 1.1305$

Breysse <i>et al.</i> (2008) [B5]	Exponential decrease	$\ln I_{corr} = 0.0444RH - 3346/T + 2.506w/c - 0.3928d + A$ <p>RH is the air relative humidity (%); T is the air temperature; w/c is the water to cement ratio; d is the cover depth (cm); A is constant.</p>
Martinez and Andrade (2009) [M7]	Constant	$I_{corr} = \frac{B}{R_p}$ <p>R_p is the polarization resistance of a reinforcement embedded in concrete; B is a constant $B = 26mV$ is recommended for on-site measurement.</p>

2.2.5 Accelerated corrosion process in laboratory

Corrosion of reinforcement in concrete is due to the oxidation process that results in the loss of reinforcement at the anode and the transfer of electrons from anode to cathode. The movement of the electrons causes a small current which is often divided by the surface area of the reinforcement to give current density. In laboratory corrosion tests, to accelerate the corrosion process, researchers often apply a larger current density than that of corrosion rate in real structures. The value of current density varies greatly among researchers from $10 \mu A/cm^2$ to $10000 \mu A/cm^2$. **Table 2.2** summaries several previous accelerated corrosion tests in literature. As observed, the electro-chemical method has been commonly used to accelerate corrosion of reinforcement. Following this method, reinforcement which needs to be corroded is connected to a positive terminal of DC power supplies, acting as an anode. On the other hand, a stainless steel or a copper plate is connected to a negative terminal of DC power supplies, acting as a cathode. A salt solution (NaCl or $CaCl_2$) is used to generate the electrical environment between cathode and anode. Furthermore, to speed up the corrosion process, concrete is mixed with NaCl from 1% to 5% by weight of cement. Faraday's law can be used to predict the weight loss of reinforcement based on the applied current density and accelerated corrosion time. According to this method, the relationship between impressed current density and the weight loss of metal due to corrosion can be estimated as following:

$$\Delta W = \frac{MIt}{ZF} \quad (2.17)$$

where ΔW is mass loss of steel reinforcement (g); M is the atomic weight of metal (equal to 56 g for steel); I is the current (amperes); t is the accelerated corrosion time (seconds); Z is the ionic charge (equal to 2); F is the Faraday constant (equal to 96,500 C/mol).

Table 2.2 Previous accelerated corrosion tests in literature

Author(s)	Specimen types	Current density $\mu A / cm^2$	Cathode types	Corrosion environment
Cabrera (1996) [C1]	Pull-out test and beams	76-674	External stainless steel bar	2% NaCl by weight of cement was added to the concrete mix; Specimens immersed in 5% NaCl solution.
Sanchun Yoon and Surendra (2000) [S2]	Beams	370	External copper plate	Tensile face of specimens constantly wetted with 3% NaCl solution.
El Maaddawy and Soudki (2003) [E3]	RC prisms	100 to 500	Internal stainless steel bar	5% NaCl by weight of cement was added to the concrete mix; Specimens were wrapped with burlap sheets and wetted daily with fresh water.
Fang <i>et al.</i> (2004) [F1]	Pull-out test	1214	External stainless steel bar	Specimens immersed in 5% NaCl solution.
Badawi and Soudki (2005) [B1]	Beams	150	Internal stainless steel bar	100% humidity chamber.
Masoud <i>et al.</i> (2005) [M8]	Beams	140	Internal stainless steel bar	2.15% NaCl by weight of cement was added to the concrete mix. Specimens subjected to 2-1/2 day wet (with water) and 1-day dry cycles.

El Maaddawy <i>et al.</i> (2005) [E2]	Beams	150	Internal stainless steel bar	2.25% NaCl by weight of cement was added to the concrete mix; Concrete sprayed with mist during the corrosion process.
Azad <i>et al.</i> (2007) [A9]	Beams	2000-3000	External stainless steel bar	2% NaCl by weight of cement was added to the concrete mix; Specimens immersed in 5% NaCl solution.
Malumbela <i>et al.</i> (2010) [M3]	Beams	189	External stainless steel bar	Constant wetting cycles (four days) with 5% NaCl solution and two different drying cycles (two days in some and four days in others).
Ou and Chen (2014) [O2]	Beams	600	External copper plate	The specimens immersed in a water tank filled with 5% NaCl solution.
Meda <i>et al.</i> (2014) [M9]	Columns	500	External steel bar	Specimens immersed in 3% NaCl solution.
Goksu and Ilki (2016) [G1]	Columns	500	Outer steel mesh	CaCl ₂ solution was sprayed over the external surfaces of the specimens. A foam rubber cover was used to keep the surfaces of the specimens damped with CaCl ₂ .
Yang <i>et al.</i> (2016) [Y2]	Columns	609	Outer stainless steel net	The 30mm thickness sponge was used to cover the specimen and 3-5% salt water was poured into the sponge every 2 hours.

2.2.6 Effects of corrosion on mechanical properties of reinforcement

2.2.6.1 Reduction of cross-sectional area of corroded reinforcement

In general, the average cross-sectional area of a corroded reinforcement is estimated as following:

$$A_s(X) = \frac{\pi D_0^2}{4} (1 - 0.01 X_{corr}) \quad (2.18)$$

where $A_s(X)$ is the cross-sectional area of corroded reinforcement; X_{corr} is the corrosion level of reinforcement; D_0 is the original diameter of reinforcement.

2.2.6.2 Reduction of strength and ductility of corroded reinforcement

In literature, many researchers have confirmed that the relationship between the mechanical properties of corroded reinforcement and the corrosion level can be expressed as following:

$$f_{yc} = (1 - \alpha_y * X_{corr}) f_{yo} \quad (2.19)$$

$$f_{uc} = (1 - \alpha_u * X_{corr}) f_{uo} \quad (2.20)$$

$$\varepsilon_{uc} = (1 - \beta * X_{corr}) \varepsilon_0 \quad (2.21)$$

$$X_{corr} = \frac{W_0 - W_1}{W_0} \quad (2.22)$$

where α_y , α_u and β are empirical coefficients which are slightly various among researchers. **Table 2.3** presents the values of these empirical coefficients which have been investigated by researchers in literature.

Table 2.3 Empirical coefficients for strength and ductility reduction of corroded reinforcement proposed in literature

Authors	Testing specimen	Reinforcement (Diameter)	Exposure (Corrosive environment)	X_{corr} (%)	α_y	α_u	β
Andrade <i>et al.</i> (1991) [A4]	Bare bars	Ribbed (12)	Accelerated (1.0 mA/cm ²)	0-11	0.0045	0.0033	0.0166
Zhang <i>et al.</i> (1995) [Z1]	Embedded Bars in concrete	Plain (8-14) Ribbed (10-25)	Service carbonation	0-67	0.0004	0.0005	0.0137
Morinaga (1996) [M13]	Embedded Bars in concrete	Not stated	Service chloride	0-25	0.006	0.0063	0.0603
Lee <i>et al.</i> (1996) [L4]	Embedded Bars in concrete	Ribbed (10)	Accelerated (13.0 mA/cm ²)	0-25	0.0021	Not stated	Not stated
Du <i>et al.</i> (2005) [D2]	Bare bars	Plain (8, 16)	Accelerated (0.5 to 2.0 mA/cm ²)	0-25	0.0049	0.0065	0.03
Du <i>et al.</i> (2005) [D3]	Embedded Bars in concrete	Ribbed (8, 16, 32)			0.0012	0.0015	0.03
Lee and Cho (2009) [L1]	Embedded Bars in concrete	Ribbed (10, 13)	Accelerated by impressing direct current Chloride induced corrosion (Cyclic wetting & dry curing at high temperature)	0-30	0.0124 (Uniform) 0.0198 (Pitting)	0.0107 (Uniform) 0.0157 (Pitting)	0.0195 (Uniform) 0.0259 (Pitting)
Jin <i>et al.</i> (2013) [J2]	Bare bars	Plain (6, 8, 10)	Accelerated (2A/m ²)	0-60	0.012	0.012	0.002
	Embedded Bars in concrete	Ribbed (12, 14, 16, 20)		0-16	0.021	0.021	0.008

2.2.6.3 Reduction of bond strength of corroded reinforcement

The volumetric expansion of reinforcement due to corrosion causes splitting stresses on the surrounding concrete that leads to the reduction in bond properties. From the literature research, it is clearly seen that there are some main parameters which influence the bond strength of corroded reinforcement, particularly the corrosion level or corrosion penetration, concrete cover thickness, confinement effectiveness, and impressed current density. Various existing bond strength models, taking into account the reduction of bond strength, have been proposed in literature, as indicated in **Table 2.4**.

In the current study, the model proposed by Maaddawy *et al.* (2005) [M2] will be adopted to estimate the maximum bond strength of corroded RC members. Over other empirical models in the literature, some of advantages of this bond strength model include its ability to take into account the contributions from concrete and stirrup independently and also consider the effect of impressed current density for accelerating corrosion on the reduction in bond strength. According to this bond strength model, the maximum bond stress $\tau_{\max c}$ can be expressed as follows:

$$\tau_{\max c} = R(0.55 + 0.24 \frac{c_c}{d_b}) \sqrt{f'_c} + 0.191 \frac{A_v f_{yh}}{S d_b} \quad (2.23)$$

$$R = (A_1 + A_2 X_{corr}) \quad (2.24)$$

where c_c is the smaller of concrete cover and one-half spacing between reinforcing bars; d_b is the diameter of reinforcing bar; A_v is the cross-sectional area of transverse reinforcement; f_{yh} is the yield strength of stirrup; S is the spacing between stirrups; R is the empirical factor that predicts the change of bond strength due to the corroded reinforcement. This factor considers an initial increase in bond strength before cracking of concrete and reduction in bond strength when the corrosion level increases; A_1 and A_2 are the variables, depending on the impressed current density used to accelerated corrosion process, as indicated in **Table 2.5**.

Table 2.4 Available empirical models to estimate the bond strength of corroded reinforcement

Authors	Empirical Models
Cabrera (1996) [C1]	$\tau_{bu} = 23.478 - 1.313X_{corr}$
Lee <i>et al.</i> (2002) [L3]	$\tau_{bu} = 5.21e^{(-0.0561X_{corr})}$
Stanish <i>et al.</i> (1999) [S7]	$\frac{\tau_{bu}}{\sqrt{f'_c}} = 0.77 - 0.027X_{corr}$
Chung <i>et al.</i> (2004) [C5]	$R = 2.09X_{corr}^{(-1.06)}$ for $X_{corr} > 2.0\%$ R is the normalized bond strength
Chung <i>et al.</i> (2008) [C6]	$\tau_{bu} = 16.87$ for $X_{corr} \leq 2$ $\tau_{bu} = 24.7X_{corr}^{-0.55}$ for $X_{corr} > 2$ Based on the experimental data of pullout tests (Model 'M_Pull') $R = 1.0$ for $X_{corr} \leq 1.5\%$
Bhargava <i>et al.</i> (2008) [B2]	$R = 1.192e^{-0.117X_p}$ for $X_{corr} > 1.5\%$ Based on the experimental data of flexural tests (Model 'M_Flex') $R = 1.0$ for $X_{corr} \leq 1.5\%$ $R = 1.346e^{-0.198X_p}$ for $X_{corr} > 1.5\%$ R is the normalized bond strength

Table 2.5 Values of A_1 and A_2 using in bond strength model proposed by Maaddawy *et al.* (2005) [M2]

Current density $\mu A / cm^2$	A_1	A_2
40	1.003	-0.037
90	1.104	-0.024
150	1.152	-0.021
250	1.163	-0.011
500	0.953	-0.014
1000	0.861	-0.014
2000	0.677	-0.009
4000	0.551	-0.010

2.2.7 Effects of corrosion on concrete

Corrosion process transforms steel into rust, resulting in volumetric expansion that can develop splitting stresses in concrete. These stresses lead to the cracking and spalling of cover concrete in RC structures. There are several methods to quantify the effect of cracked cover concrete induced by reinforcement corrosion in literature. Coronelli and Gambarova (2004) [C8] proposed the following equations to estimate the reduction of cover concrete strength of corroded RC beams as follows:

$$f'_{c,crack} = \frac{f'_c}{1 + k \frac{\varepsilon_1}{\varepsilon_{cco}}} \quad (2.25)$$

$$\varepsilon_1 = \frac{b_f - b_0}{b_0} \quad (2.26)$$

$$b_f - b_0 = n_{bars} W_{cr} \quad (2.27)$$

$$W_{cr} = 2\pi(v_{cr} - 1)X \quad (2.28)$$

where k is the coefficient regarding to bar roughness and diameter. Cape (1999) [C3] proposed a value $k = 0.1$ for medium-diameter ribbed bars; ε_1 is the average (smeared) tensile strain in the cracked concrete at right angles to the direction of the applied compression; b_0 is the width of un-corroded beam; b_f is the width of corroded beam increased due to expansion of corrosion product; n_{bars} is the number of reinforcing bars in the compression region; W_{cr} is total crack width corresponding to the depth of the corrosion attack X ; v_{cr} is the ratio of volumetric expansion of the oxides regarding to virgin material which depends on corrosion product; $v_{cr} = 2$ proposed by Molina *et al.* (1993) [M11] is commonly used in literature. On the other hand, Ou and Chen (2014) [O2] suggested that the effect of cover concrete crack induced by corrosion of corroded RC beams can be taken into consideration by using the softening theory proposed by Hsu and Mo (2010) [H4], as follows:

$$f'_{c,crack} = \zeta f'_c \quad (2.29)$$

$$\zeta = \frac{0.9}{\sqrt{1 + 600\varepsilon_r}} \quad (2.30)$$

$$\varepsilon_r = \frac{W_{cr}}{p_{cp}} \quad (2.31)$$

$$W_{cr} = \alpha \frac{\Delta w / \gamma_{steel}}{s C_c} \quad (2.32)$$

where ε_r is the tensile strain induced by the cracks of cover concrete; W_{cr} is the total crack width; p_{cp} is the outside perimeter of the beam cross section; s is the spacing of stirrups; C_c is the clear cover of stirrups; Δw is the weight loss; γ_{steel} is the specific weight of steel; α is correction factor, $\alpha=0.25$ is based on test results.

2.3 Available Stress-Strain Models for Confined Concrete

Some existing stress-strain models for confined concrete in literature are summarized in **Table 2.6**. Among these available models, the stress-strain model proposed by Mander *et al.* (1988) [M5] has a number of advantages compared to other proposed models: (1) The complete stress-strain curve can be represented by one single polynomial function; (2) The model can be applied to various shape of concrete member sections confined by different arrangements of transverse reinforcement such as spirals, cross ties, circular or rectangular hoops. Generally, Mander *et al.* (1988) [M5] used the equations proposed by Popovics (1973) [P2] to define the complete monotonic stress-strain relation, as shown in **Figure 2.4**. According to this model, the longitudinal compressive concrete stress is expressed as follows:

$$f_c = \frac{f'_{cc} x^r}{r - 1 + x^r} \quad (2.33)$$

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}} \quad (2.34)$$

$$\varepsilon_{cc} = \varepsilon_{co} \left[1 + 5 \left(\frac{f'_{cc}}{f'_{co}} - 1 \right) \right] \quad (2.35)$$

$$r = \frac{E_c}{E_c - E_{sec}} \quad (2.36)$$

$$E_c = 5,000 \sqrt{f'_{co}} \quad (2.37)$$

$$E_{\text{sec}} = \frac{f'_{cc}}{\epsilon_{cc}} \quad (2.38)$$

When the concrete core is confined with equal effective lateral confining stresses f'_l from spirals or circular hoops, the confine compressive strength f'_{cc} is given by:

$$f'_{cc} = f'_{co} \left(-1.254 + 2.254 \sqrt{1 + \frac{7.94 f'_l}{f'_{co}}} - 2 \frac{f'_l}{f'_{co}} \right) \quad (2.39)$$

The effective lateral confining pressure f'_l for sections confined by spirals or circular hoops can be calculated as following:

$$f'_l = \frac{1}{2} k_e \rho_s f_{yh} \quad (2.40)$$

where k_e is the effective lateral confining pressure which depends on the arrangement of transverse reinforcement.

For circular confined sections with circular or spirals hoops:

$$k_e = \frac{\left(1 - \frac{s'}{2d_s} \right)^2}{1 - \rho_{cc}} \quad (2.41)$$

For circular confined sections with spirals:

$$k_e = \frac{1 - \frac{s'}{2d_s}}{1 - \rho_{cc}} \quad (2.42)$$

For the confinement of rectangular section, the confine compressive strength f'_{cc} is given by:

$$f'_{cc} = K * f'_c \quad (2.43)$$

where K is the confinement strength ratio which can be obtained in **Figure 2.5** based on effective lateral confining stresses in the X-direction f'_{lx} and Y-direction f'_{ly} as follows:

$$f'_{lx} = k_e \rho_x f_{yh} \quad (2.44)$$

$$f'_{ly} = k_e \rho_y f_{yh} \quad (2.45)$$

$$k_e = \frac{\left(1 - \sum_{i=1}^n \frac{(w_i')^2}{6b_c d_c}\right) \left(1 - \frac{s'}{2b_c}\right) \left(1 - \frac{s'}{2d_c}\right)}{1 - \rho_{cc}} \quad (2.46)$$

$$\rho_x = \frac{A_{sx}}{s d_c} \quad (2.47)$$

$$\rho_y = \frac{A_{sy}}{s b_c} \quad (2.48)$$

where A_{sx} and A_{sy} are the total areas of transverse reinforcing bars corresponding to the X-direction and X-direction, respectively.

Table 2.6 Existing stress-strain models for confined concrete in literature

Authors	Stress-strain relations of confined concrete		Cross-sectional shape
	Ascending branch	Descending branch	
Scott <i>et al.</i> (1982) [S3]	$f_c = Kf_c' \left[\frac{2\varepsilon}{0.002K} - \left(\frac{\varepsilon}{0.002K} \right)^2 \right]$	$f_c = Kf_c' [1 - Z(\varepsilon - 0.002K)]$	Square
Muguruma <i>et al.</i> (1980) [M14]	$f_c = E_c \varepsilon + \frac{(f_c' - E_c \varepsilon_c)}{\varepsilon_c^2} \varepsilon^2$ $f_c = \frac{(f_c' - f_{cc})}{(\varepsilon_c - \varepsilon_{cc})^2} (\varepsilon_c - \varepsilon_{cc})^2 + f_{cc}$	$f_c = \frac{(f_{cu} - f_{cc})}{(\varepsilon_c - \varepsilon_{cc})^2} (\varepsilon_c - \varepsilon_{cc})^2 + f_{cc}$	Square Circular
Sheikh and Uzumeri (1982) [S5]	$f_c = f_{cc}' \left[\frac{2\varepsilon_c}{K_s \varepsilon_{s1}} - \left(\frac{\varepsilon_c}{K_s \varepsilon_{s1}} \right)^2 \right]$	$f_c = f_{cc}' \left[1 - \frac{0.15^* (\varepsilon_c - \varepsilon_{s2})}{(\varepsilon_{s85} - \varepsilon_{s2})} \right]$	Square
Mander <i>et al.</i> (1988) [M5]	$f_c = \frac{f_{cc}' x r}{r - 1 + x^r}$	$f_c = \frac{f_{cc}' x r}{r - 1 + x^r}$	Square Circular Wall-type
Saatcioglu and Razvi (1992) [S1]	$f_c = f_{cc} \left[2 \left(\frac{\varepsilon}{\varepsilon_{cc}} \right) - \left(\frac{\varepsilon}{\varepsilon_{s1}} \right)^2 \right]^{1/(1+2K)}$	$f_c = f_{cc} \frac{0.15 f_{cc}}{(\varepsilon_{85} - \varepsilon_{cc})} (\varepsilon - \varepsilon_{cc})$	Square Circular Wall-type
Hoshikuma <i>et al.</i> (1997) [H3]	$f_c = E_c \varepsilon_c \left[1 + \frac{1}{n} \left(\frac{\varepsilon_c}{\varepsilon_{cc}} \right)^{n-1} \right]$	$f_c = f_{cc} - E_{des} (\varepsilon - \varepsilon_{cc})$	Circle square

Montoya *et al.* (2006)
[M12]

$$f_c = E_c \varepsilon_c \left[1 + \frac{1}{n} \left(\frac{\varepsilon_c}{\varepsilon_{cc}} \right)^{n-1} \right]$$

$$f_c = \frac{f_{cc}}{A \left(\frac{\varepsilon_c}{f_{cc}} \right)^2 - B \left(\frac{\varepsilon_c}{f_{cc}} \right) + C + 1.0}$$

Circle
square

Figure 2.4 Unconfined and confined concrete stress-strain relations [M5]

Figure 2.5 Confined strength estimation from lateral confining stresses for rectangular sections [M5]

2.4 Previous Experimental Studies on Corroded Reinforced Concrete Columns under Cyclic Loading

This section presents a literature review on the relevant topics of seismic behavior of RC columns with corroded reinforcement. It is noted that although there are a number of researches on the effectiveness of retrofitting and strengthening methods

on corroded columns under cyclic loading in literature conducted by Bousias *et al.* (2004) [B3], Li *et al.* (2009) [L8], Meda *et al.* (2016) [M10], and Lee *et al.* (2003) [L2], these studies are not mentioned in this section being out of scope for the current study.

2.4.1 Research conducted by Ma *et al.* (2012) [M1]

Ma *et al.* (2012) [M1] conducted an experimental study on 13 RC circular columns under cyclic loading after being subjected to accelerated corrosion process. The RC columns were tested as cantilevers with an aspect ratio of about 3.15 and their details are shown in **Figure 2.6**. A constant current was applied to induce corrosion in the specimens. Two parameters in this research were corrosion level and axial load ratio. Particularly, the corrosion level in terms of mass loss varied from 0% to 15.1% while the axial load ratio ranged from 0.15 to 0.9. The test results revealed that corroded RC columns subjected to high axial load exhibited a more brittle response. In addition, more severe degradation can be observed for corroded columns under higher corrosion levels which are from 10% to 20% and higher axial load, particularly in terms of stiffness, descending branch of the backbone curves, ductility, and energy dissipation capacity.

Figure 2.6 Details of specimens tested by Ma *et al.* (2012) [M1]

2.4.2 Research conducted by Goksu and Ilki (2016) [G1]

Goksu and Ilki (2016) [G1] conducted an experimental program consisting of six specimens which were subjected to various corrosion levels in terms of maximum cross-sectional area loss of longitudinal reinforcing bars from 0% to 54% and tested with constant axial force and horizontal cyclic loading. **Figure 2.7** indicates the details of test specimens. The test results showed that the increase of corrosion levels resulted in the reduction of drift capacity and energy dissipation capacity. In addition, a higher pinching effect in the hysteresis curves was observed for corroded columns. Finally, based on the test results, a relationship between corrosion level and drift capacity of RC columns with corroded reinforcement was proposed in this study.

Figure 2.7 Details of specimens tested by Goksu and Ilki (2016) [G1]

2.4.3 Research conducted by Meda *et al.* (2014) [M9]

Meda *et al.* (2014) [M9] carried out a test program on four columns with the same concrete strength, sectional geometry and reinforcement arrangement. The reinforcing bars of the first two columns were artificially corroded. Afterwards, they were extracted from the specimens and tested in tension in order to investigate the influence of corrosion on the mechanical properties deterioration of reinforcement. The aim of the test of the first two columns was also to obtain the necessary time to reach the required corrosion levels following Faraday's law. Based on the experimental results of the first two columns, the third column was

corroded up to a desired corrosion level in terms of mass loss of 20% and tested under cyclic loading. The last column was used as reference un-corroded specimen and also tested under cyclic loading to compare with the corroded column. The columns were tested as single curvature with an aspect ratio of approximately 5.3 which were normally dominated by flexural behavior. The details of test specimens are indicated in **Figure 2.8**. It is noted that in this experimental program, only longitudinal reinforcing bars were corroded while the stirrups were protected from corrosion by using suitable paint. The impressed current intensity of 0.5A was applied for each reinforcing bar for 47 days following Faraday's law to obtain a theoretical corrosion level of 20% in terms of mass loss. The test results revealed that a significant deterioration of mechanical properties of corroded reinforcement was observed, including yielding strength, ultimate strength, and ultimate strain. As a result of reinforcement corrosion, the seismic behavior of corroded column was strongly influenced. Particularly, in this research, with the corrosion level of 20% in terms of mass loss, a decrease of 30% of the ultimate lateral force and a decrease of ultimate horizontal displacement of about 50% were found in the corroded column compared to the un-corroded column. Furthermore, the significant degradation of stiffness of corroded column was clearly observed in the last cycles. Although the significant deterioration of strength and ductility was observed in the corroded column, its failure mode was not changed as compared to the un-corroded column.

Figure 2.8 Details of specimens tested by Meda *et al.* (2014) [M9]

2.4.4 Research conducted by Yang *et al.* (2016) [Y2]

Yang *et al.* (2016) [Y2] carried out an experimental program on five columns with various corrosion levels in terms of maximum corrosion level of longitudinal reinforcement which varied from 0% to 16.8%. The details of test specimens are indicated in **Figure 2.9**. The test results revealed that two critical parameters which affected the seismic behavior of corroded columns were corrosion level of longitudinal reinforcement and maximum cover concrete crack width induced by corrosion. The increase of corrosion level of longitudinal reinforcement resulted in the decrease of the flexural strength, ultimate displacement, ductility, and energy dissipation in corroded columns. In addition, two empirical equations to predict the deteriorations of ductility and energy dissipation capacity were also proposed in this study based on the regression analyses of the test data.

Figure 2.9 Details of specimens tested by Yang *et al.* (2016) [Y2]

2.5 Summary

Based on the literature review conducted in this chapter, the shortcomings of the previous studies on the field of corrosion and its effects on reinforced concrete structures can be summarized as follows:

1. Several stress-strain models for confined and unconfined concrete have been proposed in literature. In addition, the stress-strain relations for corroded

reinforcement have been well studied. However, so far there is no analytical stress-strain model for confined concrete with corroded transverse reinforcement. This shortcoming provides motivation for the current study.

2. Tests on corroded RC columns subjected to cyclic loading revealed that the corrosion level and axial load ratio were the main parameters strongly dictating their seismic behavior. Therefore, it is interesting to study whether the failure modes of corroded RC columns may be changed under severe corrosion of reinforcement and high axial force which have not been investigated in literature.
3. In all the tests on corroded RC columns in the literature, only longitudinal reinforcing bars were corroded. There are limited tests on columns with both corroded transverse and longitudinal reinforcing bars. In reality, both transverse and longitudinal reinforcing bars are corroded and the transverse reinforcement is corroded more severely due to its smaller diameter and thinner clear cover concrete. Therefore, the seismic behavior of such columns with various corrosion levels of both transverse reinforcement and longitudinal reinforcement needs to be further experimentally and analytically studied.
4. All tests on corroded RC columns in the literature were conducted with high aspect ratio and low axial load ratio where the flexural behavior is dominated. Consequently, the seismic behavior of such corroded columns with low aspect ratio and high axial load ratio still remains an open-question.

Chapter 3. EXPERIMENTAL PROGRAM AND CORROSION MEASUREMENT

3.1 Introduction

In this chapter, three series of experimental program are presented. The first test series is carried out on 36 small-scale square and circular columns to study the stress-strain relations of confined concrete with corroded transverse reinforcement. The main variables of this test series are the corrosion levels of transverse reinforcement, cross sectional shape of confined concrete, as well as arrangement and configuration of confining transverse reinforcing bars. The second test series is conducted to investigate the effects of corrosion on seismic behavior of RC columns which fail in flexural manners, including 08 large-scale un-corroded and corroded slender columns subjected to cyclic loading. In addition, to understand the seismic response of RC short columns with corroded reinforcing bars, the last test series is conducted on 08 large-scale specimens. The key parameters of the second and third test series include the corrosion levels of reinforcement and applied axial load ratios. The experimental program is presented in this chapter, including the details of test specimens, accelerated corrosion scheme, test setup, instrumentation and measurement, as well as corrosion measurement results.

3.2 Design of Test Specimens

3.2.1 Details of test specimens in Series 1

This experimental investigation included 36 reinforced concrete columns which were designed with 600 mm in height, either 200 mm square or 200 mm diameter circular sections, and cover concrete thickness of 10 mm. **Figure 3.1** shows the arrangements of longitudinal reinforcing bars, transverse hoops, square helices, and spiral reinforcement of the test specimens. As indicated, test specimens were divided into three groups: Group A (AS, AM, AL), Group B (BS, BM, BL), and Group C (CS, CM, CL) presenting different cross sectional shapes, various arrangements of longitudinal and transverse reinforcing bars. Afterward, the specimens in each series were corroded with different corrosion levels by controlling the accelerated corrosion time and the applied current intensity. The

experimental stress-strain relations of the original reinforcing bars are indicated in **Figure 3.2** and their mechanical properties are presented in **Table 3.1**. In order to make sure that test specimens fail in the middle regions, the spacing of transverse reinforcement was decreased to 25 mm within the regions of 100 mm from both ends of the specimens to provide more confinement effect in these regions. Furthermore, to prevent the spalling of cover concrete at both ends of the specimens because of the stress concentration and corrosion attacks, an external confinement using steel frames was also installed in two end regions of the specimens, as demonstrated in **Figure 3.1**. The target concrete strength of 30 MPa for test specimens was supplied by a local ready-mix plant and casted in five batches. Three 150 x 300 mm cylinder specimens and an unconfined concrete specimen were made for each batch. The unconfined concrete specimens have the same dimension as the other specimens, however, without transverse reinforcement, that is 600 mm in height and either 200 mm square or 200 mm circular sections, which were tested to estimate the maximum strength and the corresponding axial strain for unconfined concrete. The average compressive strengths of the cylinders at testing days, above 28 days, for the five batches of specimens were 30.5, 29.3, 25.9, 25.3, and 31.9 MPa while the corresponding strengths of the unconfined concrete specimens were 25.4, 24.9, 21.7, 18.0, and 24.4 MPa, respectively. The axial concrete strain of unconfined concrete at maximum stress for each batch of specimens was also recorded, as indicated in **Table 3.2**. As a result of the size effect and less effective consolidation, the maximum strength of unconfined concrete was less than expected and equal to 85% the strength of standard cylinder specimen. It is noted that to improve the electrical conductivity of concrete in the accelerated corrosion scheme, 5% sodium chloride (NaCl) by weight of cement was added into the concrete mixing ingredients. More details of test specimens in Series 1 can be found in **Appendix A**.

Table 3.1 Properties of steel reinforcement in Series 1

Steel type	Nominal diameter mm	Yield strength MPa	Ultimate strength MPa	Modulus of elasticity GPa
R6	6	360.0	525.4	210
T10	10	568.3	654.5	210

Table 3.2 Summary of test specimen in Series 1

Unit	Plain concrete data			Longitudinal reinforcement		Transverse reinforcement				
	f'_c MPa	f'_{co} MPa	ε_{co}	No. bars	Dia. mm	f_y MPa	Dia. mm	Spa. mm	f_{yh} MPa	ρ_s (%)
AL0	30.5	25.4	0.0016	4	10	568	6	65	360	0.97
AL1	30.5	25.4	0.0016	4	10	568	6	65	360	0.97
AL2	30.5	25.4	0.0016	4	10	568	6	65	360	0.97
AL3	30.5	25.4	0.0016	4	10	568	6	65	360	0.97
AM0	30.5	25.4	0.0016	4	10	568	6	40	360	1.57
AM1	30.5	25.4	0.0016	4	10	568	6	40	360	1.57
AM2	30.5	25.4	0.0016	4	10	568	6	40	360	1.57
AM3	30.5	25.4	0.0016	4	10	568	6	40	360	1.57
AS0	29.3	24.9	0.0015	4	10	568	6	25	360	2.51
AS1	29.3	24.9	0.0015	4	10	568	6	25	360	2.51
AS2	29.3	24.9	0.0015	4	10	568	6	25	360	2.51
AS3	29.3	24.9	0.0015	4	10	568	6	25	360	2.51
BL0	29.3	24.9	0.0015	8	10	568	6	65	360	1.65
BL1	29.3	24.9	0.0015	8	10	568	6	65	360	1.65
BL2	29.3	24.9	0.0015	8	10	568	6	65	360	1.65
BL3	29.3	24.9	0.0015	8	10	568	6	65	360	1.65
BM0	25.9	21.7	0.0014	8	10	568	6	40	360	2.68
BM1	25.9	21.7	0.0014	8	10	568	6	40	360	2.68
BM2	25.9	21.7	0.0014	8	10	568	6	40	360	2.68
BM3	25.9	21.7	0.0014	8	10	568	6	40	360	2.68
BS0	25.9	21.7	0.0014	8	10	568	6	25	360	4.29
BS1	25.9	21.7	0.0014	8	10	568	6	25	360	4.29
BS2	25.9	21.7	0.0014	8	10	568	6	25	360	4.29
BS3	25.9	21.7	0.0014	8	10	568	6	25	360	4.29
CL0	25.3	18.0	0.0016	8	10	568	6	55	360	1.14
CL1	25.3	18.0	0.0016	8	10	568	6	55	360	1.14
CL2	25.3	18.0	0.0016	8	10	568	6	55	360	1.14
CL3	25.3	18.0	0.0016	8	10	568	6	55	360	1.14
CM0	31.9	24.4	0.0017	8	10	568	6	40	360	1.57
CM1	31.9	24.4	0.0017	8	10	568	6	40	360	1.57
CM2	31.9	24.4	0.0017	8	10	568	6	40	360	1.57
CM3	31.9	24.4	0.0017	8	10	568	6	40	360	1.57
CS0	31.9	24.4	0.0017	8	10	568	6	25	360	2.51
CS1	31.9	24.4	0.0017	8	10	568	6	25	360	2.51
CS2	31.9	24.4	0.0017	8	10	568	6	25	360	2.51
CS3	31.9	24.4	0.0017	8	10	568	6	25	360	2.51

Figure 3.1 Details of test specimens in Series 1

Figure 3.2 Typical stress-strain curves of reinforcement for test Series 1

3.2.2 Details of test specimens in Series 2 and Series 3

Each test series includes eight full-scale un-corroded and corroded columns tested with combined axial force and cyclic loading. Of which, two columns of each test series acted as control specimens without corrosion of reinforcement which were tested with constant axial loads of $0.1f'_cA_g$ and $0.25f'_cA_g$ together with horizontal cyclic loading. The other six columns were subjected to accelerated corrosion for

different time periods, resulting in varying corrosion levels. For each test series, after finishing the corrosion process, three corroded columns were tested with axial load of $0.1f'_cA_g$ while the axial load of $0.25f'_cA_g$ was applied for the other three corroded columns. **Figure 3.3** and **Figure 3.4** show the arrangements of longitudinal reinforcing bars and transverse hoops of test specimens which were designed for seismic zones requirement in accordance with ACI 318-14 (2014) [A1]. It is noted that test specimens in Series 2 were designed to have a cross-section of 350 x 350 mm and clear height of 1780 mm, resulting in the shear span to depth ratio a/d of 3.18 while test specimens in Series 3 have a similar cross-section of 350 x 350 mm and clear height of 1080 mm, resulting in the shear span to depth ratio a/d of 1.93. It is noted that a is half of the clear height of the column due to double curvature test and d is the effective depth which can be assumed that $d = 0.8h$ [A6] (h is the depth of the column cross section). **Figure 3.5** indicates the experimental stress-strain relations of the original reinforcing and **Table 3.3** summaries their material properties. A target concrete strength of 40 MPa was used for test specimens. For each specimen, the actual compressive concrete strength was achieved based on the compression tests of three standard concrete cylinders (height of 300 mm and diameter of 150 mm) at the same days of testing. The geometry, reinforcement details, and actual compressive concrete strength of all test specimens are tabulated in **Table 3.4**. More details of test specimens in Series 2 and 3 can be found in **Appendix A**.

Table 3.3 Properties of steel reinforcement in Series 2 and 3

Steel type	Nominal diameter mm	Yield strength MPa	Ultimate strength MPa	Modulus of elasticity GPa
R8	7.8	300	415	210
T20	20	550	635	210

Table 3.4 Summary of test specimens in Series 2 and 3

Series	Specimen	b mm	h mm	L mm	A_s mm^2	A_v mm^2	s mm	f_{yl} MPa	f_{yt} MPa	f'_c MPa	$\frac{P}{f'_c A_g}$
2	U1	350	350	1780	2513.3	163.1	50/100	550	300	32.2	0.1
	C1	350	350	1780	2513.3	163.1	50/100	550	300	34.4	0.1
	C2	350	350	1780	2513.3	163.1	50/100	550	300	32.0	0.1
	C3	350	350	1780	2513.3	163.1	50/100	550	300	40.0	0.1
	U2	350	350	1780	2513.3	163.1	50/100	550	300	38.1	0.25
	C4	350	350	1780	2513.3	163.1	50/100	550	300	28.8	0.25
	C5	350	350	1780	2513.3	163.1	50/100	550	300	31.3	0.25
	C6	350	350	1780	2513.3	163.1	50/100	550	300	37.5	0.25
3	UC1	350	350	1080	2513.3	163.1	50	550	300	32.2	0.1
	CC1	350	350	1080	2513.3	163.1	50	550	300	28.8	0.1
	CC2	350	350	1080	2513.3	163.1	50	550	300	32.0	0.1
	CC3	350	350	1080	2513.3	163.1	50	550	300	27.8	0.1
	UC2	350	350	1080	2513.3	163.1	50	550	300	38.1	0.25
	CC4	350	350	1080	2513.3	163.1	50	550	300	34.4	0.25
	CC5	350	350	1080	2513.3	163.1	50	550	300	31.3	0.25
	CC6	350	350	1080	2513.3	163.1	50	550	300	40.0	0.25

Figure 3.3 Details of test specimens in Series 2

Figure 3.4 Details of test specimens in Series 3

Figure 3.5 Typical stress-strain curves of reinforcement for test Series 2 and 3

3.3 Accelerated Corrosion Scheme

In this study, the steel reinforcing bars were corroded using an electro-chemical method. A constant current density of approximately 0.5 mA/cm^2 was applied to the steel reinforcing bars which were connected to the anodes of DC power supplies

while the copper plates were used as the cathodes. For test specimens in Series 2 and Series 3, both longitudinal and transverse reinforcing bars were corroded to study the effects of corrosion on seismic behavior of columns in corrosive environments. On the other hand, the longitudinal reinforcing bars were not corroded for specimens in Series 1 and isolated from the transverse reinforcement by using the electrical tapes because the objective of this test series is to investigate the stress-strain relations of confined concrete with corroded transverse reinforcement. In addition, to simulate the corrosive environment, the specimens were immersed in the water tank with a 5% sodium chloride (NaCl) solution, as shown in **Figure 3.6** and **Figure 3.7**. In theory, the corrosion level in terms of mass loss can be estimated by using the Faraday's law and governed by the accelerated corrosion time. However, many researchers pointed out that the Faraday's law overestimates the corrosion level and this finding is also confirmed in this experimental program. Therefore, in this study, the corrosion levels are estimated based on the measured data of experiment as presented in the following section.

Figure 3.6 Accelerated corrosion scheme for test specimens in Series 1

Figure 3.7 Accelerated corrosion scheme for test specimens in Series 2 and Series 3

3.4 Test Setup and Deformation Measurement

3.4.1 Test setup of specimens in Series 1

A 5000 kN capacity hydraulic testing machine was utilized to provide the concentric axial load using displacement control with the loading rate of 0.5 mm/min. A preload of 50 kN was applied to the specimens and the readings from the linear variable displacement transducers (LVDTs) and concrete strain gauges were checked to ensure the specimens deform uniformly. **Figure 3.8** shows the typical test setup of the square and circular specimens.

3.4.2 Deformation measurement of test specimens in Series 1

Two different methods of recording axial deformations were used during testing of the specimens in this experimental program [L5]. The first method was to measure the overall axial deformation of the specimen between the platen and the crosshead, that is, the gauge length is the total height of the specimen, 600 mm, using the reading results of the hydraulic machine. The measured results of the first method will be used if the failure does not happen in the central part of the specimen, which is defined as the localized failure. The second method used two pairs of 25 mm LVDTs mounted on the opposite sides of the square specimens while three LVDTs were used for circular specimens, which were mounted on a pairs of aluminum hoops embedded in the mid-height of the specimens. The distance between two aluminum hoops is 250 mm that is the measured gauge length. It was observed that the failure regions of all test specimens were at the central part of the specimen

within the gauge length of 250 mm as predicted. The axial deformation of the specimens was then derived from the average readings of the LVDTs. A pair of concrete strain gauges was also attached to the surface of the specimens to measure the axial concrete strain in the elastic range of concrete. The experimental results revealed that the readings of the concrete strain gauges exactly coincided with the readings of the LVDTs in the elastic range of the specimens. In this study, it is also noted that strain gauges were not installed on the reinforcing bars because they are damaged by the accelerated corrosion process.

Figure 3.8 Typical test set-up of square and circular specimens in 5000 kN capacity hydraulic universal testing machine

3.4.3 Test setup of specimens in Series 2 and Series 3

Figure 3.9 and **Figure 3.10** demonstrate the test setup for cyclic loading which enables the test specimens to be tested under double-curvature bending. A constant axial force is applied using two vertical actuators with capacity of 1000 kN through the L-shaped steel frame. A horizontal actuator is used to produce the reversible horizontal displacement and its axis passes through the mid-height of the specimen to simulate the double-curvature bending condition. The quasi-static cyclic loading history for all test specimens is shown in **Figure 3.11**. During the test, several cycles of lateral displacements corresponding to drift ratio from 0.25% to 6.0% are applied through the horizontal actuator. The drift ratio (DR) is defined as the ratio

of inter-storey horizontal displacement over the storey height. In the current study, the column specimens are subjected to two cycles of loading with the displacement equal to storey drift ratio of 0.25%, 0.5%, 1%, 1.5%, 2%, 2.5%, 3%, 3.5%, 4%, 4.5%, 5%, 5.5% and 6% as shown in **Figure 3.11**.

Figure 3.9 3D schematic view of experimental setup

Figure 3.10 Photograph of experimental setup

Figure 3.11 Quasi-static cyclic loading history for test specimens

3.4.4 Deformation measurement in Series 2 and Series 3

Instrumentation is installed to measure the global response as well as local deformation of the specimens. Linear Variable Differential Transducers (LVDTs) are installed in critical regions of the column specimens to measure the deformation of different parts of the columns during the test, as indicated in **Figure 3.12**. In these test series, no strain gauges were installed on the reinforcing bars because they are damaged by the accelerated corrosion process.

Figure 3.12 Deformation measurement for test specimens

3.4.4.1 Measurement of horizontal displacement

Two LVDTs of 150mm gauge length attached to magnetic stands are used to measure the displacements at the top of columns during the test procedure. These LVDTs are also used to measure rotation as well as out of plane movement at the top of the column specimens.

3.4.4.2 Measurement of flexural deformation

The flexural deformations of the column specimens are estimated from the discrete rotations in each segment along the specimens using a pairs of LVDTs, as shown in **Figure 3.13**.

Figure 3.13 Calculation of the flexural deformations for test specimens

Based on Bernoulli hypothesis, that is, the plain section remains plane after deformation, the rotation of segment i θ_{fi} is estimated as following:

$$\theta_{fi} = \frac{\delta_{iR} - \delta_{iL}}{h_i} \quad (3.1)$$

where δ_{iR} and δ_{iL} are the displacements measured by the right and left LVDTs at segment i , respectively; h_i is the distance between the LVDTs at segment i . The horizontal displacement of the column specimen due to flexural deformation of this segment is then given by:

$$\delta_{fi} = \theta_{fi} * x_{fi} \quad (3.2)$$

where x_{fi} is the distance from the centre of segment i to the centre of the column specimen. By summing the deflections of the individual segment, the total horizontal displacement of the column specimen owing to flexural deformation is calculated as following:

$$\delta_f = \sum \delta_{fi} = \sum \frac{\delta_{iR} - \delta_{iL}}{h_i} x_{fi} \quad (3.3)$$

where subscript “*i*” represents the particular segment under consideration.

3.4.4.3 Measurement of shear deformation

A pair of Linear Potentiometers arranged in a cross-liked manner is used to measure the shear deformation of the columns as shown in **Figure 3.14**.

Figure 3.14 Calculation of the shear deformations for test specimens

With reference to **Figure 3.14**, the average shear deformation at segment *i* γ_{si} is calculated as follows:

$$\gamma_{si} = \frac{\delta_{si} - \delta'_{si}}{2L_{si}} (\tan \alpha_{si} + \frac{1}{\tan \alpha_{si}}) \quad (3.4)$$

where δ_{si} and δ'_{si} are the displacements of the LVDTs arranged in the diagonal directions; L_{si} is the initial length of the LVDTs and α_{si} is the angle between the diagonal and vertical directions as shown in **Figure 3.14**. The horizontal displacement of the column specimen due to the shear deformation of this particular segment is calculated as:

$$\delta_{si} = \gamma_{si} * x_{si} \quad (3.5)$$

where x_{si} is the vertical distance of the region used to estimate the average shear deformation. Thus, the total horizontal displacement of the column specimen due to shear deformation can be estimated by summing the displacement of the individual segment:

$$\delta_s = \sum \delta_{si} = \sum \gamma_{si} * x_{si} \quad (3.6)$$

where subscript “ i ” represents the particular segment under consideration.

3.5 Corrosion Measurement

3.5.1 Initial cracks induced by corrosion

After the accelerated corrosion, test specimens were taken out of the tank. Their surfaces were cleaned to remove all the rust. The width and length of cracks induced by corrosion were traced and measured at all sides of specimens using the crack width gauges. For test specimens in Series 1, it was observed that the corroded specimens subjected to low corrosion level, which is generally less than 10% in terms of mass loss, did not show any visible cracks. On the other hand, the cracks induced by corrosion were obvious for the specimens subjected to high corrosion level. These cracks primarily appeared and developed vertically along the direction of longitudinal reinforcement. For test specimens in Series 2 and Series 3, all corroded test specimens showed the visible cracks. **Figure 3.15** and **Figure 3.16** demonstrate the distribution of cracks induced by corrosion on the four sides of corroded columns. It is also observed that the main cracks induced by corrosion also developed vertically along the direction of longitudinal reinforcement. In this study, the total crack width of the specimen W_{cr} is measured, which is defined as the average value of crack width determined for the four sides of the test specimen:

$$W_{cr} = \frac{\sum w_{cri} l_i}{L} \quad (3.7)$$

where w_{cri} is the width of crack i ; l_i is the length of the crack i ; L is the clear height of test specimens. **Table 3.5** and **Table 3.6** indicate the total crack width of test specimens. As observed, the total crack width increases with the increase of

corrosion level of reinforcement. It is interesting to observe that there are good correlations between the total crack width and the corrosion levels of transverse reinforcement in terms of mass loss $X_{corr}^{(1)}$, average residual cross sectional area $X_{corr}^{(2)}$, and minimum residual cross sectional area $X_{corr}^{(3)}$, as shown in **Figure 3.15** to **Figure 3.17** and Eq. (3.8) to Eq. (3.10).

$$X_{corr}^{(1)} = 17.26W_{cr} + 7.44 \quad (3.8)$$

$$X_{corr}^{(2)} = 19.13W_{cr} + 14.46 \quad (3.9)$$

$$X_{corr}^{(3)} = 35.51W_{cr} + 34.17 \quad (3.10)$$

In general, the best approach to evaluate the behavior of real RC structures under corrosion is based on the measured data of corroded reinforcement which can be obtained using destructive testing. However, this method is impossible for the majority of existing structures. The good relationships proposed in Eq. (3.8) to Eq. (3.10) show the possibility to evaluate the corroded structures based on the total crack width which can be easily measured in real RC structures.

Table 3.5 Corrosion measurement of test specimens in Series 1

Specimens	Transverse Reinforcement			Total Crack width mm
	$X_{corr}^{(1)}$ %	$X_{corr}^{(2)}$ %	$X_{corr}^{(3)}$ %	
AL0	0	0	0	0
AL1	4.9	10.8	23.8	0
AL2	9.8	18.9	36.9	0.12
AL3	17.5	30.7	53.7	0.48
AM0	0	0	0	0
AM1	7.3	6.7	18.9	0
AM2	12.5	17.4	36.6	0.21
AM3	21.6	41.1	73.6	0.71
AS0	0	0	0	0
AS1	9.5	13.8	41.6	0.13
AS2	16.7	14.3	53.3	0.44
AS3	25	26.6	76.8	1.1
BL0	0	0	0	0
BL1	7.7	10.7	35	0
BL2	10.3	18.1	59.9	0.15
BL3	12.3	19.4	58.8	0.41
BM0	0	0	0	0
BM1	5.6	5.9	17.6	0
BM2	10	17.3	48.7	0.29
BM3	13.4	30.4	50.5	0.27
BS0	0	0	0	0
BS1	14.9	26.3	56.5	0.35
BS2	20.8	28.3	59.2	0.66
BS3	25	34.6	79.1	0.9
CL0	0	0	0	0
CL1	16.8	15.1	31.8	0.45
CL2	21.8	26.2	47.4	0.72
CL3	31.5	40.6	85.4	1.25
CM0	0	0	0	0
CM1	7.6	5.7	24.3	0
CM2	22.8	40	70.5	1
CM3	32.9	44.5	89.1	1.5
CS0	0	0	0	0
CS1	9.3	8.3	28	0.2
CS2	10	11.2	36	0.35
CS3	13.6	19	47.3	0.6

Table 3.6 Corrosion measurement of test specimens in Series 2 and Series 3

Specimens	Transverse Reinforcement			Longitudinal Reinforcement			Total Crack width mm
	$X_{corr}^{(1)}$ %	$X_{corr}^{(2)}$ %	$X_{corr}^{(3)}$ %	$X_{corr}^{(1)}$ %	$X_{corr}^{(2)}$ %	$X_{corr}^{(3)}$ %	
UC1	0	0	0	0	0	0	0
CC1	11.4	21.4	40.2	3.4	3.1	4.8	0.26
CC2	21.3	28.4	58.4	5.8	7.9	9.6	0.61
CC3	26.1	39.4	60.3	6.8	9	11.5	1
UC2	0	0	0	0	0	0	0
CC4	8.4	16.9	30.1	3.4	6.9	7.5	0.16
CC5	12.1	21.7	44.2	3.3	6.8	8.2	0.36
CC6	18.2	27.8	51.2	7.5	12.2	19.8	0.59
U1	0	0	0	0	0	0	0
C1	11.5	23.8	48.7	3.4	7.1	8	0.26
C2	14.4	21.3	51.9	6.1	10.4	13.1	0.18
C3	25	30.5	62.3	10.9	20.4	27.6	1.19
U2	0	0	0	0	0	0	0
C4	13.6	22.6	41.3	3.4	4.2	6.1	0.52
C5	15.5	29.5	59.2	3.9	8	10	0.48
C6	23.5	33.5	73.8	7.3	11.5	14.3	0.98

Figure 3.15 Relationship between total crack width of the specimen and corrosion level of transverse reinforcement in terms of mass loss

Figure 3.16 Relationship between total crack width of the specimen and corrosion level of transverse reinforcement in terms of average residual cross sectional area

Figure 3.17 Relationship between total crack width of the specimen and corrosion level of transverse reinforcement in terms of minimum residual cross sectional area

Note: The East-West is the lateral loading direction; Dimensions in mm.

Figure 3.19 Corrosion induced concrete cover crack in corroded short columns

3.5.2 Corrosion level measurement

It is well known that the corrosion degree of reinforcement can be evaluated in terms of either mass loss or residual cross-sectional area. In this study, three evaluation methods of corrosion degree of reinforcement based on experimental

measurement are proposed, including corrosion levels in terms of mass loss $X_{corr}^{(1)}$, average residual cross sectional area $X_{corr}^{(2)}$, and minimum residual cross sectional area, or pitting corrosion $X_{corr}^{(3)}$, defined as follows:

$$X_{corr}^{(1)} = \frac{W_0 - W_1}{W_0} \quad (3.11)$$

$$X_{corr}^{(2)} = \frac{D_0^2 - D_{re}^2}{D_0^2} \quad (3.12)$$

$$X_{corr}^{(3)} = \frac{D_0^2 - D_{min}^2}{D_0^2} \quad (3.13)$$

where W_0 and D_0 are the original weight and diameter of reinforcement before corrosion; W_1 , D_{re} , and D_{min} are the residual weight, average residual diameter, and minimum residual diameter of reinforcement after corrosion, respectively. The measurement procedure follows ASTM G1-03 (2003) [A7]. Particularly, after testing, all the reinforcing bars were taken out of the test specimens and then were cleaned by steel brushes. After that, they were immersed in 10% hydrochloric acid (HCl) for 20 minutes to remove all the rust. Finally, all the reinforcing bars were measured to estimate their weight loss and residual diameters. In order to measure the average and minimum residual diameters (or pitting corrosion) along the length of transverse reinforcing bars, the transverse reinforcement was equally divided into eight regions, four regions at the corners, and the other four regions at the middle of steel reinforcement, then the average and minimum residual diameters of each transverse reinforcement were recorded. It is noted that in Series 2 and Series 3, both transverse reinforcement and longitudinal reinforcing bars were corroded. Therefore, the average and minimum residual diameters of longitudinal reinforcing bars were also measured following a similar way by equally dividing each longitudinal reinforcing bar into 14 regions of approximately 125 mm length for each region. The experimental observation also exposed that the pitting corrosion of both transverse reinforcement and longitudinal reinforcement becomes more serious with the increase of severity of corrosion. Particularly, for the corroded columns subjected to low corrosion levels, the diameter of reinforcement reduced relatively

uniformly, generally defined as uniform corrosion, as demonstrated in **Figure 3.20** to **Figure 3.22**. On the other hand, with the highly corroded columns, the pitting corrosion of both transverse and longitudinal reinforcing bars was noticeable, even so the fracture of transverse reinforcing bars induced by corrosion can be observed, as indicated in **Figure 3.23** to **Figure 3.25**. In addition, in this experimental program, it is interesting to observe that there is relatively high correlation between corrosion level in terms of minimum residual cross sectional area and corrosion level in terms of mass loss of corroded specimens, as indicated in Eq. (3.14) and **Figure 3.26**. In addition, the correlation between corrosion level in terms of average residual cross sectional loss and corrosion level in terms of mass loss of corroded specimens is also demonstrated in Eq. (3.15) and **Figure 3.27**.

$$X_{corr}^{(3)} = 2.72X_{corr}^{(1)} + 5.13 \quad (3.14)$$

$$X_{corr}^{(2)} = 1.32X_{corr}^{(1)} + 2.18 \quad (3.15)$$

More details of corrosion measured results of all test specimens can be found in **Appendix D**.

Figure 3.20 Appearance of some typical corroded transverse reinforcing bars of test Specimen AS1 after testing and removing all the rust

Figure 3.21 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen C1 after testing and removing all the rust

Figure 3.22 Appearance of some typical corroded transverse reinforcing bars of test Specimen CC4 after testing and removing all the rust

Figure 3.23 Appearance of some typical corroded transverse reinforcing bars of test Specimen AS3 after testing and removing all the rust

Figure 3.24 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen C3 after testing and removing all the rust

Figure 3.25 Appearance of some typical corroded transverse reinforcing bars of test Specimen CC6 after testing and removing all the rust

Figure 3.26 Relationship between corrosion levels in terms of mass loss and minimum residual cross sectional area

Figure 3.27 Relationship between corrosion levels in terms of mass loss and average residual cross sectional area

3.6 Summary

This chapter describes the experimental preparation program carried out on corroded RC columns. Furthermore, the corrosion measurement of all test specimens is also presented. Several important conclusions can be summarized as follows:

1. The construction details of 36 small-scale square and circular columns in the first test series, 08 large-scale slender columns in the second test series, and 08 large-scale short columns in the last test series were described together with the scheme for accelerated corrosion process.
2. Special emphasis on the precision in the set-up of test specimens as well as the installation of instrumentations for measurement and thereafter evaluating the contribution of each factor on the performance of test specimens.
3. It is interesting to observe that there is a good correlation between the corrosion level in terms of mass loss and corrosion level in terms of average residual cross sectional area, as well as a high correlation between the corrosion level in terms of mass loss and corrosion level in terms of minimum residual cross sectional area for corroded test specimens.
4. The good correlations between the total crack width and corrosion levels of transverse reinforcement in terms of mass loss, average residual cross sectional area, and minimum residual cross sectional area are also proposed in this study which raises the possibility of seismic assessment for the existing RC structures without destructive testing.

Chapter 4. STRESS-STRAIN MODEL FOR CORRODED CONFINED CONCRETE

4.1 Introduction

Thirty six column specimens in Series 1 were tested under compression axial load and this chapter presents and discusses the test results of these specimens. The stress-strain relations of confined concrete with different corrosion levels of transverse reinforcement are experimentally investigated. Meanwhile, the influences of corrosion level of transverse reinforcement on the characteristic parameters of the stress-strain relations are also investigated. Finally, an analytical stress-strain model for confined concrete with corroded transverse reinforcement is proposed based on the experimental data by incorporating the corrosion effects into the model for un-corroded confined concrete suggested by Mander *et al.* (1988) [M5].

4.2 Experimental Results and Discussions of Test Specimens in Series 1

As mentioned in **Chapter 3**, in this experimental program, it is interesting to observe that there are relatively high correlations among different measured methods of corrosion levels; particularly, corrosion level in terms of mass loss, corrosion level in terms of average residual cross sectional area, and corrosion level in terms of minimum residual cross sectional area, as indicated in Eq. (3.14) and Eq. (3.15). In addition, although the test results show that the cross-sectional loss varies along the length of the transverse reinforcement, the measured mass loss and residual cross sectional area for different corroded transverse reinforcing bars are relatively comparable. This is due to the fact that all the transverse reinforcing bars were corroded with the same constant current density of 0.5 mA/cm^2 during the accelerated corrosion process. Hence, for convenience and simplification in demonstration and calculation, the corrosion level in terms of mass loss is adopted to describe the corrosion degree of transverse reinforcement as well as develop the stress-strain model for confined concrete with corroded transverse reinforcement in the following sections.

4.2.1 Measured stress-strain curves for corroded confined concrete

In this study, it is noted that the test result of the specimen from the hydraulic testing machine was the total load carried by the confined concrete with transverse reinforcement, unconfined cover concrete, and longitudinal reinforcing bars. Therefore, the longitudinal steel force and the cover concrete force contributions were subtracted to give the total load carried by the confined concrete which was divided by the core area to obtain the confined concrete stress [M4], [L5]. The longitudinal steel force was calculated based on the tensile test results. To convert the measured stress-strain relations of reinforcement in tension into the stress-strain relations in compression, the steel model proposed by Dodd and Cooke (1992) [D4] was adopted. On the other hand, for un-corroded specimens, the force contribution of the unconfined cover concrete was calculated by multiplying the concrete stress obtained from the unconfined concrete specimens f'_{co} (of the same size as the reinforced specimens) by the cover area of the reinforced concrete specimen. For the corroded specimens, the compressive concrete strength of cover concrete was reduced to $\zeta f'_{co}$ due to the cracks of cover concrete induced by corrosion and the softening coefficient ζ can be estimated as follows [H4]:

$$\zeta = \frac{0.9}{\sqrt{1 + 600\varepsilon_r}} \quad (4.1)$$

$$\varepsilon_r = \frac{W_{cr}}{p_0} \quad (4.2)$$

where ε_r is the tensile strain induced by the cracks of cover concrete; W_{cr} is the total crack width of the specimen which can be defined as Eq. (3. 7) and easily measured in the experiment and real engineering, as indicated in **Table 3.5** in **Chapter 3**; p_0 is the perimeter of the column section. **Figure 4.1** indicates the experimental results of test specimens, including measured axial load-longitudinal strain curves and measured stress-strain curves. In addition, the experimental result comparisons of stress-strain curves for confined concrete of test specimens subjected to various corrosion levels are also demonstrated in **Figure 4.2**.

Figure 4.1 (a) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (b) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (c) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (d) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (e) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (f) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (g) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (h) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (i) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (k) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (I) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.1 (m) Experimental results: (a) Measured axial load-longitudinal strain curves for test specimens; (b) Measured stress-strain curves for test specimens

Figure 4.2 Experimental stress-strain curves comparison for confined concrete of test specimens subjected to various corrosion levels

4.2.2 Behavior of test specimens

The failure modes of test specimens are characterized sequentially by the appearance and propagation of vertical cracks along the longitudinal reinforcing bars, the cover concrete spalling after the specimens exceeded the peak stress. Afterwards either the fracture of transverse reinforcement or the buckling of longitudinal reinforcing bars occurs first, depending on the spacing and corrosion levels of transverse reinforcement, and finally the crushing of core concrete. As observed in **Figure 4.2**, the volumetric ratio of transverse reinforcement and the corrosion level are the most important parameters that significantly affect the stress-strain relations of corroded specimens for all cross sectional shapes, including

maximum concrete strength and corresponding axial strain, ultimate concrete strain, and stress-strain curves after exceeding the maximum strength.

The experimental observation also revealed that the pitting corrosion becomes more significant with the increase of corrosion level. Particularly, for the corroded specimens with the corrosion level approximately less than 10%, it is observed that the diameter of transverse reinforcing bars of these specimens reduced relatively uniformly, generally defined as uniform corrosion. **Figure 4.3** demonstrates an example of some typical corroded transverse reinforcing bars of corroded Specimen AS1 with the corrosion level of 9.5% after testing and cleaning all the rust. In addition, the accelerated corrosion process of transverse reinforcement did not cause any visible cracks on the surface of these specimens. As a result of uniform corrosion and low corrosion level of transverse reinforcement, the overall stress-strain relations of these corroded specimens were not affected significantly when compared to the un-corroded specimens in the same series, as indicated in **Figure 4.2**, particularly for the corroded Specimens AS1, AM1, AL1, BM1, BL1, CS1, and CM1. Furthermore, in the well-confined Specimens AS1, BS1, and CS1, those with small spacing of transverse reinforcement and high volumetric ratio of confining reinforcement, the corroded specimens still showed the ductile behavior after the maximum stress exceeded even though they were corroded. Regarding the failure mode, these specimens failed when the longitudinal reinforcing bars were buckled and the core concrete was crushed. **Figure 4.4** shows typical failure of some low corroded specimens with the corrosion level less than 10% after testing and taking out all the instruments. On the other hand, for highly corroded specimens with corrosion levels greater than 15%, that is normally a corrosion level greater than 15%, the severe pitting corrosion or the fracture of transverse reinforcing bars induced by corrosion can be observed. **Figure 4.5** demonstrates an example of some typical corroded transverse reinforcing bars of Specimen AS3 with the corrosion level of 25.0% after testing. In addition, it is interesting to notice that the severe pitting corrosion and corrosion induced fracture of transverse reinforcing bars occurred near the cover concrete crack regions. This is because the cracks of the cover concrete due to corrosion facilitated the chemical reaction between the ferrous ions and hydroxyl ions to form the corrosion products. It is also observed

that the cracks induced by corrosion developed vertically along the direction of longitudinal reinforcement and occurred in the highly corroded specimens. Afterward, these cracks were further developed and widened with the increase of the applied compression axial force during the test. Finally, these specimens failed with the fracture of transverse reinforcing bars and then the following buckling of the longitudinal reinforcement. **Figure 4.6** indicates the typical failure of some highly corroded specimens with corrosion levels greater than 20%. Because of the severe pitting corrosion and the fracture of transverse reinforcing bars induced by corrosion, the stress-strain relations of these highly corroded specimens are significantly affected, as demonstrated in **Figure 4.2**. Particularly, more brittle behavior and steeper descending branches can be noticed in the complete stress-strain curves of these specimens. More details of experimental results of all test specimens in Series 1 can be found in **Appendix A**.

Figure 4.3 Appearance of some typical corroded transverse reinforcing bars of Specimen AS1 ($X_{corr} = 9.5\%$) after testing and removing all the rust

AS1 ($X_{corr} = 9.5\%$) BM1 ($X_{corr} = 5.6\%$) CM1 ($X_{corr} = 7.6\%$)

Figure 4.4 Appearance of specimens subjected to low corrosion levels after testing

Figure 4.5 Appearance of some typical corroded transverse reinforcing bars of Specimen AS3 ($X_{corr} = 25.0\%$) after testing and removing all the rust

AS3 ($X_{corr} = 25.0\%$) BS3 ($X_{corr} = 25.0\%$) CM3 ($X_{corr} = 32.9\%$)

Figure 4.6 Appearance of specimens subjected to high corrosion levels after testing

4.2.3 Discussion of test results

4.2.3.1 Effect of corrosion level

The effect of corrosion level on the stress-strain relation of test specimens is demonstrated in **Figure 4.2**. As observed, the initial stiffness was not significantly affected by the increase of corrosion level. However, the higher corrosion level resulted in the lower maximum concrete strength and axial concrete strain at maximum strength. Furthermore, significant deterioration of confined strength after reaching the maximum stress was more obvious with the increase of corrosion level for all cross sectional shapes, especially with the highly corroded specimens. For instance, comparing to the un-corroded Specimen AS0, an approximately 7.1%, 10.0%, 13.4% maximum confined strength reduction and 7.8%, 17.3%, 22.7% axial strain at maximum stress decrease for corroded Specimens AS1, AS2, and AS3 with

the same cross sectional shape and reinforcement details were observed corresponding to the increase of their corrosion levels from 0% to 9.5%, 16.7%, and 25.0%, respectively. Although similar trends were also noticed for the other corroded specimens belonging to Groups B and C, their deterioration rates of strength and ductility are significantly different, depending on the arrangements and spacing of confining reinforcement, as well as the cross sectional shapes of confined concrete. As predicted, the deterioration rate of strength and ductility after peak stress of corroded confined concrete constructed with large hoop spacing, low volumetric ratio, and highly corroded transverse reinforcement is much faster than that of corroded confined concrete with small hoop spacing, high volumetric ratio, and low corrosion level. It is also of interest to note that the corrosion effect was more detrimental on the axial strain at maximum stress and ultimate axial strain than that on confined concrete strength.

4.2.3.2 Effect of volumetric ratio of transverse reinforcement

In general, the volumetric ratio of transverse reinforcement is considered as one of the most significant parameters to improve the strength and ductility capacities of confined concrete. In this study, this effect on the stress-strain relations of corroded confined concrete under various corrosion levels can be observed in **Figure 4.2**. For tested Specimens AS2, AM2, and AL3 with the corrosion levels of 16.7%, 12.5% and 17.5%, respectively, comparing to the un-corroded Specimens with the same design AS0, AM0, and AL0, an approximately 10.0%, 7.8%, 22.3% peak stress decrease and 13.8%, 20.0%, 31.3% ultimate axial strain reduction were observed corresponding to the volumetric ratio of transverse reinforcement of these specimens reduces from 2.51% to 1.57% and 0.97%, respectively. Furthermore, the experimental observation of the descending branches of stress-strain curves also revealed that among the corroded specimens subjected to relatively similar corrosion levels, the lower volumetric transverse reinforcement ratio and larger hoop spacing resulted in more brittle behavior for corroded confined concrete. The similar trend can be also observed in **Figure 4.2** with corroded specimens belong to Groups B and C. In conclusion, the volumetric ratio of transverse reinforcement significantly affects the stress-strain relations of corroded confined concrete,

including the maximum strength, ultimate axial strain, as well as the descending branches of stress-strain curves after exceeding the maximum strength.

4.2.3.3 Effect of confinement reinforcement configuration

It is well known that the transverse reinforcement arrangement is one of the main factors affecting the performance of confined concrete because of its influence on the distribution of lateral confining pressure. However, this effect has not been well studied in cases of confined concrete undergoing severe corrosive environment. In this study, the effect of transverse reinforcement arrangement can be observed by comparing the stress-strain relations of two pairs of corroded Specimens AM1&BL1, AS2&BM3, of almost the same volumetric ratio of transverse reinforcement and subjected to similar corrosion levels. It is noted that Specimens AM1 and AS2 were constructed using single perimeter hoops while Specimens BL1 and BM3 designed with double hoops configuration. In addition, due to the compressive concrete strength varied among test specimens, the confined strength enhancement defined as ratio of confined concrete strength to unconfined concrete strength is used to compare the confinement effectiveness of test specimens. The experimental results showed that both Specimens BL1 and BM3 performed better than AM1 and AS2 in terms of strength and ductility, as well as the improvement of deterioration rate after exceeding the maximum stress, for details, the enhancement of peak stress and ultimate strain of Specimen BL1 were 3.3% and 14.2% higher than those of Specimen AM1 while 7.6% and 14.5% higher of peak stress enhancement and ultimate strain can be also observed in Specimen BM3 compared to Specimen AS2. Therefore, these comparisons confirmed the improvement of strength and ductility in corroded concrete confined with double hoops configuration.

4.2.3.4 Effect of cross sectional shape of confined concrete

Generally, normal concrete confined by circular spirals performs better than rectilinear ties because of its uniformly distributed confining pressure around the perimeter of the section. In this study, this effect was investigated and quantified for corroded circular and square specimens in terms of their strength and ductility. Comparing two pairs of the corroded Specimens CS1&AS1, CM1&AM1 which

were designed with a similar volumetric ratio of transverse reinforcement and under almost the same corrosion levels showed that the peak stress enhancements of circular corroded Specimens CS1 and CM2 were 15.0% and 10.6% higher than those of square corroded Specimens AS1 and AM1, respectively. In addition, these circular corroded specimens showed a ductile behavior after their peak stress attained. On the other hand, square corroded specimens exhibited a pronounced reduction in load carrying capacity after their maximum load reached. Therefore, in conclusion, the cross sectional shape significantly affects the confinement effectiveness of corroded confined concrete.

4.3 Stress-Strain Model for Confined Concrete with Corroded Transverse Reinforcement

4.3.1 Stress – strain relations of corroded confined concrete

In this study, to establish the new analytical model for corroded confined concrete, the stress-strain model for un-corroded confined concrete proposed by Mander *et al.* (1988) [M5] was adopted and modified to take into consideration the effects of corrosion because of some of its advantages, including the overall stress-strain curve can be represented by one single polynomial function and its application for various cross sectional shapes of confined concrete. More importantly, comparing the well-known stress-strain models in literature [S3], [M5], [S1], [H3] with the experimental results of un-corroded Specimens AL0, AM0, AS0, BL0, BM0, BS0, CL0, CM0, and CS0 in this study showed that the model proposed by Mander *et al.* (1988) [M5] has the best interpretation of these experimental data, as indicated in **Figure 4.10**. In the model for un-corroded confined concrete proposed by Mander *et al.* (1988) [M5], the longitudinal compressive concrete stress f_c is expressed as follows:

$$f_c = \frac{f'_{cc} x^r}{r - 1 + x^r} \quad (4.3)$$

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}} \quad (4.4)$$

$$r = \frac{E_c}{E_c - E_{sec}} \quad (4.5)$$

$$E_c = 5,000\sqrt{f'_{co}} \quad (4.6)$$

$$E_{sec} = \frac{f'_{cc}}{\varepsilon_{cc}} \quad (4.7)$$

where ε_c is the longitudinal compressive concrete strain; f'_{cc} and ε_{cc} are the maximum confined strength and corresponding axial strain, respectively, which will be modified later to take into consideration the effects of corroded transverse reinforcement; E_c and E_{sec} are the elasticity modulus of concrete and secant modulus of confined concrete at the maximum stress, respectively; f'_{co} is the maximum strength of unconfined concrete, which is estimated based on the experimental results, as shown in **Table 3.2** in **Chapter 3**. When the experimental data is unavailable, the unconfined concrete strength f'_{co} can be expected to be equal 85% strength of the standard cylinder test results.

4.3.2 Maximum strength of corroded confined concrete

Generally, corrosion of reinforcement reduces the mechanical properties and diameter of reinforcement, resulting in the reduction of total cross-sectional area A_v and yield strength of transverse reinforcement f_{yh} . Therefore, a modification of volumetric ratio ρ_{sc} Eq. (4.8) and yield strength f_{yh}^c Eq. (4.9) for transverse reinforcement was made in this proposed model, resulting in the reduction of effective lateral confining pressure f'_l Eq. (4.10). Finally, based on the test data of 36 specimens, a regression analysis was conducted to modify the maximum confined strength f'_{cc} Eq. (4.11).

$$\rho_{sc} = (1 - X_{corr})\rho_s \quad (4.8)$$

$$f_{yh}^c = (1 - \alpha_s X_{corr})f_{yh} \quad (4.9)$$

$$f'_l = \frac{1}{2}k_e \rho_{sc} f_{yh}^c \quad (4.10)$$

$$f'_{cc} = (1 - \alpha X_{corr})f'_{co} \left(-1.254 + 2.254 \sqrt{1 + \frac{7.94 f'_l}{f'_{co}}} - 2 \frac{f'_l}{f'_{co}} \right) \quad (4.11)$$

where X_{corr} is the corrosion level in terms of mass loss of transverse reinforcement; α_s is the yield strength reduction factor for corroded transverse reinforcement, taken as 0.005 [D2]. It is also noted that both the study conducted by Du *et al.* (2005) [D2] and current study used the electrochemical technique to accelerate the corrosion process with the same current intensity of 0.5 mA/cm². In addition, the types of steel reinforcement employed in these two studies are also similar. Therefore, it is reasonable to adopt the test results in [D2] for this study; α is stress correction coefficient derived from the regression analysis of the test data; $\alpha = 0.19$ for square confined section with single hoops configuration (Group A); $\alpha = 0.40$ for square confined section with double hoops configuration (Group B); $\alpha = 0.51$ for circular confined section with spiral hoops (Group C); k_e is the confinement effectiveness coefficient, more calculation details of this coefficient can be found in **Chapter 2** and Mander *et al.* (1988) [M5]. The average ratio of the measured maximum corroded confined strength of 36 specimens to their values calculated by using Eq. (4.11) is 0.997 and its standard deviation of 0.052, showing a good agreement between the experimental results and the proposed equation, as shown in **Table 4.1** and **Figure 4.7**.

Table 4.1 Experimental results and comparisons with proposed analytical model for test specimens

Unit	f_{cc}^{exp} MPa	f_{cc}^{pro} MPa	$\frac{f_{cc}^{exp}}{f_{cc}^{pro}}$	ϵ_{cc}^{exp} %	ϵ_{cc}^{pro} %	$\frac{\epsilon_{cc}^{exp}}{\epsilon_{cc}^{pro}}$	ϵ_{cu}^{exp} %	ϵ_{cu}^{pro} %	$\frac{\epsilon_{cu}^{exp}}{\epsilon_{cu}^{pro}}$	E_{stress} %
AL0	31.96	29.51	1.083	0.331	0.289	1.145	2.607	2.381	1.095	7.07
AL1	30.62	29.05	1.054	0.300	0.268	1.119	2.582	2.217	1.165	11.84
AL2	29.49	28.59	1.032	0.305	0.248	1.229	2.347	2.056	1.142	8.46
AL3	24.83	27.86	0.891	0.218	0.217	1.005	1.792	1.815	0.987	11.27
AM0	33.85	32.91	1.029	0.373	0.396	0.941	3.501	3.287	1.065	6.41
AM1	31.84	31.95	0.996	0.351	0.353	0.993	2.867	2.942	0.974	4.84
AM2	31.20	31.29	0.997	0.344	0.324	1.060	2.800	2.710	1.033	5.36
AM3	29.01	30.12	0.963	0.286	0.276	1.035	2.168	2.315	0.937	17.56
AS0	39.57	37.17	1.065	0.421	0.520	0.810	3.988	4.489	0.888	7.58
AS1	36.78	35.51	1.036	0.388	0.448	0.867	4.019	3.887	1.034	3.35
AS2	35.61	34.27	1.039	0.348	0.397	0.877	3.437	3.631	0.947	12.54
AS3	34.27	32.83	1.044	0.325	0.341	0.953	2.706	2.970	0.911	17.46
BL0	33.84	34.74	0.974	0.582	0.446	1.304	3.809	3.273	1.164	14.20
BL1	32.28	33.03	0.977	0.433	0.356	1.218	3.343	2.966	1.127	18.39
BL2	32.91	32.45	1.014	0.407	0.327	1.244	2.824	2.862	0.987	12.06
BL3	29.55	31.99	0.924	0.313	0.306	1.022	2.401	2.781	0.864	19.98
BM0	36.89	38.20	0.966	0.851	0.672	1.266	4.979	4.645	1.072	5.91
BM1	35.26	36.64	0.962	0.728	0.577	1.262	4.512	4.335	1.041	7.05
BM2	34.15	35.40	0.965	0.612	0.506	1.209	3.608	4.088	0.883	18.72
BM3	33.59	34.46	0.975	0.490	0.456	1.074	4.021	3.902	1.031	16.78
BS0	44.77	46.72	0.958	1.034	0.947	1.092	6.005	5.954	1.009	6.57
BS1	43.45	41.37	1.050	0.472	0.625	0.755	5.090	4.901	1.039	9.11
BS2	41.38	39.29	1.053	0.456	0.517	0.882	3.837	4.492	0.854	7.89
BS3	38.45	37.83	1.016	0.365	0.447	0.815	3.531	4.205	0.840	18.99
CL0	26.33	26.97	0.976	0.574	0.559	1.028	2.721	2.962	0.919	7.85
CL1	24.90	23.47	1.061	0.409	0.384	1.065	2.099	2.422	0.867	5.43
CL2	22.04	22.45	0.982	0.396	0.336	1.180	1.957	2.260	0.866	19.50
CL3	20.67	20.53	1.007	0.328	0.248	1.321	1.915	1.952	0.981	18.04
CM0	36.30	37.76	0.961	0.647	0.635	1.019	3.183	2.916	1.091	7.50
CM1	34.21	35.47	0.964	0.627	0.544	1.152	2.630	2.678	0.982	7.46
CM2	30.06	31.04	0.968	0.335	0.376	0.893	2.202	2.203	0.999	19.17
CM3	29.87	28.19	1.060	0.201	0.274	0.734	2.035	1.889	1.078	14.37
CS0	44.84	45.32	0.989	0.899	0.899	1.000	3.424	3.754	0.912	6.47
CS1	42.39	41.72	1.016	0.877	0.753	1.165	3.026	3.379	0.895	7.62
CS2	42.65	41.48	1.028	0.689	0.744	0.926	2.854	3.355	0.851	7.56
CS3	33.75	40.11	0.841	0.401	0.690	0.581	3.004	3.209	0.936	15.85
Mean			0.997			1.034			0.985	
Coefficient of variation			0.052			0.176			0.095	11.28

Figure 4.7 Comparisons of the corroded confined concrete strength of 36 specimens between experimental results and proposed analytical model

4.3.3 Axial corroded concrete strain at maximum strength

As mentioned previously, the axial strain of corroded confined concrete corresponding to its maximum strength reduces significantly due to reinforcement corrosion, even much more than the deterioration of maximum confined strength. Based on the experimental data of 36 specimens and regression analysis, the axial corroded concrete strain at the maximum stress ε_{cc} can be estimated for both circular and square confined sections with corroded transverse reinforcement, as follows:

$$\varepsilon_{cc} = (1 - \beta X_{corr}) \varepsilon_{co} \left[1 + 5 \left(\frac{f'_{cc}}{f'_{co}} - 1 \right) \right] \quad (4.12)$$

Basically, Eq. (4.12) was derived from modifying the original equation proposed by Mander *et al.* (1988) [M5] that takes into consideration the corrosion effect on the reduction of axial strain at peak stress. In this equation, β is strain correction coefficient; $\beta = 0.49$ for square confined section with single hoops configuration (Group A); $\beta = 1.29$ for square confined section with double hoops configuration

(Group B); $\beta = 0.28$ for circular confined section with spiral hoops (Group C); ε_{co} is the axial strain of unconfined concrete corresponding to maximum unconfined stress, which is estimated based on the experimental results of unconfined concrete specimens, as indicated in **Table 3.2** in **Chapter 3**. The value of $\varepsilon_{co} = 0.002$ can be assumed when the test data is not available. In this proposed equation, the strength of corroded confined concrete f'_{cc} is calculated following Eq. (4.11). The comparisons of axial corroded concrete strain between the experimental data and the proposed equation Eq. (4.12) produce a reasonably good agreement because the average ratio of measured axial corroded concrete strain at peak stress of 36 specimens to their values estimated by using Eq. (4.12) is 1.034 and its standard deviation of 0.176, as indicated in **Table 4.1** and **Figure 4.8**.

Figure 4.8 Comparisons of the axial corroded concrete strain at maximum strength of 36 specimens between experimental results and proposed analytical model

4.3.4 Ultimate strain of corroded confined concrete

It is well recognized that it is conservative to estimate the ultimate strain of confined concrete corresponding to the strain at which the fracture of the first confining reinforcement occurs [M5], [P1], causing longitudinal reinforcement to buckle and the crush of core concrete follows. In order to predict the ultimate strain

of corroded confined concrete ε_{cu} , the empirical equation proposed by Paulay and Priestley (1992) [P1], which based on the energy balance approach, was adopted and modified as following:

$$\varepsilon_{cu} = 0.004 + (1 - X_{corr}) \frac{1.4 \rho_{sc} f_{yh}^c \varepsilon_{sm}^c}{f_{cc}'} \quad (4.13)$$

$$\varepsilon_{sm}^c = (1 - \beta_s X_{corr}) \varepsilon_{sm} \quad (4.14)$$

where the modified volumetric ratio of transverse reinforcement ρ_{sc} and the strength of corroded confined concrete f_{cc}' are estimated following Eq. (4.8) and Eq. (4.11); f_{yh}^c is the yield strength of corroded transverse reinforcement calculated based on Eq. (4.9); ε_{sm}^c and ε_{sm} are the steel strains at the maximum tensile stress of corroded and un-corroded transverse reinforcement, respectively; $\varepsilon_{sm} = 0.12$ is adopted in this study based on the test result; β_s is the ultimate strain reduction factor for corroded transverse reinforcement, taken as 0.05 [D3]. **Table 4.1** and **Figure 4.9** show a good correlation between the measured ultimate strain of corroded concrete of 36 specimens and their predicted values using Eq. (4.13), particularly the average ratio of the test data to the predicted results is 0.985 and its standard deviation of 0.095.

Figure 4.9 Comparisons of ultimate corroded concrete strain of 36 specimens between experimental results and proposed analytical model

4.3.5 Comparison of experimental and analytical stress-strain curves for test specimens

Figure 4.10 demonstrates the comparisons of complete stress-strain curves of 36 specimens between the experimental data and the proposed analytical model that illustrated a reasonably good prediction of this proposed model. Furthermore, the normalized corroded concrete stress error E_{stress} was evaluated to quantify the accuracy of the proposed analytical model that is the error between measured and calculated corroded concrete stress error, as the following equation:

$$E_{stress} = \frac{1}{\max(|F_{mea}^i|)} \sqrt{\frac{1}{n} \sum_{i=1}^n (F_{mea}^i - F_{cal}^i)^2} \quad (4.15)$$

where F_{mea} and F_{cal} are the measured and calculated corroded concrete stresses at the i^{th} loading step. **Table 4.1** summarizes the values of normalized corroded concrete stress error of 36 specimens. As indicated in **Table 4.1**, the mean error in corroded concrete stress of 36 specimens is 11.28%, showing a reasonable estimation of the overall stress-strain curves for corroded confined concrete by adopting this proposed model.

Figure 4.10 (a) Comparison of experimental and analytical stress-strain curves for test specimens

Figure 4.10 (b) Comparison of experimental and analytical stress-strain curves for test specimens

Figure 4.10 (c) Comparison of experimental and analytical stress-strain curves for test specimens

Figure 4.10 (d) Comparison of experimental and analytical stress-strain curves for test specimens

Figure 4.10 (e) Comparison of experimental and analytical stress-strain curves for test specimens

4.4 Summary

In this chapter, the influences of the corroded transverse reinforcement on the stress-strain relation of confined concrete are experimentally and analytically investigated. The key parameters affecting the stress-strain relation of confined concrete with corroded transverse reinforcement are investigated and quantified, including corrosion level, volumetric ratio, arrangement and configuration of confining reinforcing bars, and cross sectional shape of confined concrete. Some important conclusions can be summarized from the experimental and analytical studies as followings:

1. A stress-strain model for confined concrete with corroded transverse reinforcement is proposed by incorporating the corrosion effects into the model for un-corroded confined concrete proposed by Mander *et al.* (1988) [M5]. The proposed model showed a reasonably good estimation of the experimental stress-

strain curves for both circular and square specimens with various corrosion levels of transverse reinforcement and subjected to compression axial loading.

2. The experimental results revealed that the corrosion level and the volumetric ratio of transverse reinforcement are the most important factors affecting the stress-strain relations of corroded confined concrete. As the corrosion level increases, both strength and ductility of the corroded confined concrete drastically decrease and the slope of the stress-strain curve after exceeding the maximum stress also becomes steeper. Furthermore, the corrosion effect on the corroded confined concrete is found to be more detrimental on the axial strain at the maximum stress and ultimate strain than that on the maximum strength.
3. The pitting corrosion is more obvious with the increase of corrosion level which significantly affects the overall stress-strain relations of corroded confined concrete. Particularly, when the corrosion level in terms of mass loss is less than approximately 10%, the uniform corrosion of transverse reinforcement was observed to slightly influence the global behavior of corroded confined concrete. In addition, neither the cover concrete crack induced corrosion nor the fracture of transverse reinforcing bars induced corrosion at the end of the test was observed. However, with the highly corroded specimens under corrosion levels from 15% to 30%, a severe pitting corrosion can be noticed which resulted in the significant deterioration of the strength and ductility of corroded confined concrete. This is because of the severe reduction of the confinement effectiveness caused by the fracture of confining transverse reinforcement due to severe pitting corrosion.
4. Regarding the effect of cross sectional shape of confined concrete, the experimental results showed that with the similar volumetric ratio of transverse reinforcement and under the same corrosion levels, the corroded concrete confined with circular spirals performed better than that confined with rectilinear ties in terms of both strength and ductility capacity. In addition, more ductile behavior was also observed for the corroded concrete confined with circular spirals even though subjected to relatively high corrosion levels.
5. The experimental results also confirmed that the corroded concrete confined with double hoops configuration, resulting in the uniform distribution of confinement

pressure, significantly improved the confinement effectiveness, particularly the increase of the maximum strength and ultimate concrete strain, as well as delay in the deterioration rate of the stress-strain curves after exceeding the maximum stress, comparing to the corroded concrete confined with single hoops configuration.

Chapter 5. EXPERIMENTAL STUDY ON REINFORCED CONCRETE SLENDER COLUMNS WITH CORRODED REINFORCEMENT

5.1 Introduction

Eight slender column specimens in Series 2 were tested under constant axial force and horizontal cyclic loading. The seismic performance of test specimens was assessed in terms of crack pattern, hysteretic response, yield displacement, lateral load resistance, drift capacity, and energy dissipation capacity. The experimental results highlighted that the corroded columns suffered a significant degradation of strength and deformation capacity compared to un-corroded columns. In addition, it is remarkable to observe that the failure mode of corroded columns switched from typical flexural failure to flexural-shear failure and sudden axial failure when they are highly corroded and subjected to high axial force. An empirical equation to predict the residual flexural strength of corroded columns was proposed which is based on the maximum pit depth of corroded longitudinal reinforcing bars.

5.2 Experimental Results and Discussion

This section presents and discusses the experimental results of eight un-corroded and corroded specimens tested with various corrosion levels and axial load ratios. The hysteretic responses of test specimens are demonstrated from **Figure 5.1** to **Figure 5.8**. Three performance levels were used to highlight the response of test specimens, particularly in terms of yielding level (PL1), maximum lateral force (PL2), and failure stage (PL3 which is defined corresponding to the maximum lateral force dropped by 20%). In general, the hysteretic responses showed the reduction of stiffness, deterioration of lateral load resistance, and the pinching effect during repeated cyclic loading that was more obvious with corroded columns due to the bonding reduction between reinforcement and surrounding concrete induced by corrosion. As expected in design for un-corroded Specimens U1 and U2 failed in typical flexure, these specimens did not reach the nominal shear strength estimated following the suggestion of ASCE/SEI 41-13 (2014) [A6]. However, their theoretical flexural strengths were attained, which were estimated using the test

results of materials and in accordance with ACI 318-14 (2014) [A1], as indicated in **Figure 5.1** and **Figure 5.2** for un-corroded Specimen U1 and U2. Seismic behavior assessment of all test specimens is presented in the following section. More details of test results of specimens in Series 2 can be found in **Appendix B**. It is also noted that from **Figure 5.1** to **Figure 5.8**, $X_{corr}^{(1t)}$ and $X_{corr}^{(1l)}$ are the corrosion levels in terms of mass loss of transverse reinforcement and longitudinal reinforcement, respectively; $P/f_c A_g$ is the applied axial force.

Figure 5.1 Hysteric response of test Specimen U1

Figure 5.2 Hysteric response of test Specimen U2

Figure 5.3 Hysteric response of test Specimen C1

Figure 5.4 Hysteric response of test Specimen C2

Figure 5.5 Hysteric response of test Specimen C3

Figure 5.6 Hysteric response of test Specimen C4

Figure 5.7 Hysteric response of test Specimen C5

Figure 5.8 Hysteric response of test Specimen C6

5.2.1 Crack patterns and failure modes

The appearance and propagation of cracks on the surface of test specimens were recorded at every maximum applied horizontal displacement during cyclic loading. **Figure 5.9** and **Figure 5.10** demonstrate the crack patterns of test specimens at maximum lateral force (PL2) and final stage (end of the test), respectively. As observed, three failure modes were identified in which the first failure mode is typical flexural failure which happened in un-corroded Specimens U1, U2 and corroded Specimens C1 and C2 subjected to low corrosion levels and axial force of $0.1f_c'A_g$. For these specimens, the horizontal flexural cracks perpendicular to column axis appeared first in the top and bottom regions of the specimens at the drift ratio of approximately 1.0% and 0.75% for un-corroded specimens and corroded specimens, respectively. When the applied drift ratio increased, these flexural cracks extended within the plastic hinge regions of specimens and the appearance of flexural-shear diagonal cracks was also observed. However, the flexural-shear cracks did not lead to the failure of these specimens. It was noted that compared to the un-corroded Specimen U1, the corroded Specimens C1 and C2

showed less flexural and flexural-shear cracks. In addition, for these corroded specimens, together with the flexural cracks, the vertical cracks along the longitudinal reinforcement were also obvious. This is because the initial cracks induced by corrosion developed vertically along the direction of longitudinal reinforcement, and afterward these cracks further developed and widened with the increase of the applied horizontal displacement and axial force. As commonly observed in the dominated flexural columns, the test specimens failed with extensive spalling of cover concrete and the crushing of core concrete within the plastic hinge regions of the specimens as well as buckling of longitudinal reinforcement. It is also noted that none of the stirrups fractured at the end of the test for corroded Specimens C1 and C2. The second failure mode defined as flexural-shear failure was observed in corroded Specimens C3, C4, and C5 which were subjected to either high corrosion levels or high axial load ratio. For these specimens, fewer flexural cracks were observed at the early stages of cyclic loading compared to those failed in typical flexure. On the other hand, the diagonal shear cracks were more obvious for these corroded specimens and right after the maximum force was attained, extensive diagonal cracks developed in the plastic hinge regions of the specimens with the angles of main diagonal cracks of around 40, 45, and 30 degrees for corroded Specimens C3, C4, and C5, respectively. These diagonal cracks directly resulted in the failure of the specimens. It is also noted that the development of vertical cracks along the longitudinal reinforcement was more obvious than that of corroded Specimens C1 and C2 because these corroded specimens were subjected to higher corrosion levels. This is the evidence of the bonding reduction between reinforcement and surrounding concrete induced by corrosion, which mainly caused the adverse pinching effect during repeated cyclic loading. This phenomenon was also more noticeable for corroded Specimens C4 and C5 subjected to high axial force of $0.25f_c'A_g$, as indicated in **Figure 5.6** and **Figure 5.7**. The fracture of stirrups at the end of the test was also prominent in these corroded specimens which significantly caused the change of failure mode from typical flexural failure to flexural-shear failure. The third failure mode was identified as sudden axial failure with the explosion of concrete and reinforcement which happened at the top end of corroded Specimen C6 under high corrosion level

of transverse reinforcement of 23.5% and high axial force of $0.25f'_cA_g$, as shown in **Figure 5.10**. It was also observed that after taking all reinforcement out of the test specimens, majority of transverse reinforcement fractured due to extremely severe corrosion, resulting in the loss of confinement effectiveness for confined concrete and buckling resistance of longitudinal reinforcement which mainly caused the sudden axial failure.

Figure 5.9 Crack patterns of test specimens at maximum lateral load

Figure 5.10 Crack patterns of test specimens at final stage (end of the test)

5.2.2 Hysteretic response comparisons

Figure 5.11 shows the comparisons of hysteretic responses between un-corroded specimens and corroded specimens which are subjected to the same axial force of $0.1f'_cA_g$ and $0.25f'_cA_g$. As observed, the un-corroded Specimens U1 and U2 failed in typical flexure which performed in a ductile manner while the corroded Specimens C3, C4, and C5 which failed in flexural-shear responded in a more brittle manner, that is, the lateral load resistance deteriorated right after the maximum lateral force was attained and the pinching effect was obvious during repeated cyclic loading. Comparisons of the backbone curves of test specimens with various corrosion levels and axial load ratios are also demonstrated in **Figure 5.12** and **Figure 5.13**. Of note, from henceforth, the values of yield displacement, lateral load capacity, displacement ductility, drift ratio, and energy dissipation are the average values of positive and negative loading directions, as indicated in **Table 5.1**. In addition, although the corrosion levels of both transverse reinforcement and longitudinal reinforcement affect the seismic behavior of test specimens, in current study, for simplicity in demonstration, the corrosion level in terms of mass loss of transverse reinforcement is chosen to present the effects of test parameters on the seismic performance of test specimens, as shown from **Figure 5.14** to **Figure 5.17**.

Table 5.1 Comparisons between un-corroded columns and corroded columns with various corrosion levels and axial load ratios

Spe.	Yield disp. Mm	Yield curv. 1/mm x 10 ⁻⁶	$V_{\max}$	$\frac{V_{\max}}{A_g \sqrt{f'_c}}$	δ_y %	δ_m %	δ_s %	μ_δ	Energy dissipation (kNm)			Failure modes
									PL1	PL2	PL3	
U1	25.0	9.02	232.1	0.33	1.4	3.3	5.8	4.1	3.6	15.5	40.9	1
C1	22.7	5.61	238.8	0.32	1.3	2.5	5.1	4.0	3.5	11.0	32.5	1
C2	24.8	4.92	193.2	0.28	1.4	2.5	4.7	3.3	2.7	7.0	20.6	1
C3	18.9	7.28	190.7	0.25	1.1	1.8	3.9	3.6	2.1	4.1	11.8	2
U2	25.4	8.42	302.5	0.40	1.4	2.7	6.0	4.2	4.5	14.2	51.9	1
C4	16.0	4.07	254.4	0.38	0.9	2.4	3.2	3.5	3.5	12.0	19.7	2
C5	13.3	5.14	237.1	0.35	0.7	2.0	2.7	3.6	3.3	7.9	12.4	2
C6	19.2	7.26	250.0	0.33	1.1	2.0	2.5	2.3	3.8	7.4	11.5	3

Notes: $\delta_y, \delta_m, \delta_s$ are the drift ratios at yielding level, maximum lateral force, and failure stage, respectively; μ_δ is the displacement ductility.

Figure 5.11 Comparisons of hysteretic responses of un-corroded specimens and corroded specimens

Figure 5.12 Comparisons of backbone curves of test specimens subjected to axial force of $0.1f'_c A_g$

Figure 5.13 Comparisons of backbone curves of test specimens subjected to axial force of $0.25f'_c A_g$

5.2.2.1 Yield displacement

In current study, the yield displacement of all test specimens is defined theoretically as suggested by Sezen and Moehle (2004) [S4]: at the point of 70% of the maximum lateral force on the lateral force-horizontal displacement curve, a secant is drawn and the other horizontal line corresponding to the maximum lateral force is also drawn. From the intersection of these two lines, taking the projection to the horizontal axis, then the yield displacement is obtained. **Table 5.1** indicates the average values of yield displacement for test specimens from positive and negative loading directions. As indicated, the yield displacement decreased with the increase of corrosion level of reinforcement and applied axial force. For instance, compared to un-corroded Specimen U2 and subjected to the same axial load of $0.25f'_cA_g$, the yield displacement reduced 37.1%, 47.9%, and 24.4% for the corroded Specimens C4, C5, and C6, respectively. The similar reduction trend can also be observed for those corroded specimens under axial load of $0.1f'_cA_g$.

5.2.2.2 Lateral load capacity

Figure 5.12 shows the effect of various corrosion levels and axial force ratios on the lateral load capacity of test specimens which was normalized as $V_{\max} / A_g \sqrt{f'_c}$ due to the compressive concrete strength varied among test specimens. It was observed that the lateral load capacity decreased corresponding to the increase of corrosion levels. For example, the test specimens with the axial load of $0.25f'_cA_g$, the normalized lateral load capacity of these specimens reduced 5.2%, 13.5%, and 16.7% from un-corroded Specimen U2 to the corroded Specimens C4, C5, and C6, respectively. The similar deterioration of normalized lateral load capacity for the test Specimens U1, C1, C2, and C3 with axial load of $0.1f'_cA_g$ can also be observed with the reduction of 4.7%, 17.3%, and 31.5%, respectively.

Figure 5.14 Effects of test parameters on lateral load capacity of test specimens

5.2.2.3 Drift capacity

The effects of corrosion levels and axial force ratios on the drift capacities at various performance levels of test specimens are demonstrated in **Figure 5.15**, including drift ratios at the yielding level, maximum lateral force, and failure stage. Overall, drift capacities decreased when the corrosion level and axial load ratio increased at all performance levels of test specimens. Regarding to the drift ratio at failure stage (PL3), the reduction of 11.5%, 19.6% and 33.4% was observed for corroded Specimens C1, C2 and C3 compared to the un-corroded Specimens U1. More significant reduction of the drift ratio at failure stage can be observed for highly corroded Specimens C4, C5 and C6 which were subjected to high axial force of $0.25f'_c A_g$, those are 47.4%, 55.4%, and 57.9% of reductions compared to un-corroded Specimen U2, respectively. This is due to the fracture of confining transverse reinforcement induced by severe corrosion occurred in these specimens, resulting in the significant deterioration of the drift capacity at failure stage.

Figure 5.15 Effect of test parameters on drift capacity of test specimens

5.2.2.4 Energy dissipation capacity

Energy dissipation capacity of the RC columns subjected to cyclic loading is defined as the area under the lateral force and horizontal displacement hysteretic curves. **Figure 5.16** indicates the cumulative energy dissipation capacity of test specimens. In addition, **Figure 5.17** also demonstrates the effects of test parameters on the energy dissipation capacity at different performance levels. As observed, the total energy dissipation capacity depends on not only corrosion level of test specimens but also the applied axial force. For example, with the increase of corrosion level, the total energy dissipation at failure stage decreased 20.6%, 49.7%, and 71.1% from un-corroded Specimen U1 to corroded Specimens C1, C2 and C3,

respectively. The similar reduction trend of energy dissipation capacity was also observed for corroded specimens subjected to axial force of $0.25f_c'A_g$. In addition, it was observed that the energy dissipation capacity among corroded specimens with similar corrosion levels of reinforcement was also reduced with the increase of applied axial force from $0.1f_c'A_g$ to $0.25f_c'A_g$.

Figure 5.16 Energy dissipation capacity of test specimens

Figure 5.17 Effects of test parameters on energy dissipation capacity of test specimens

5.2.2.5 Curvature distribution

In this study, the experimental curvatures of test specimens are estimated based on the test data of LVDT sets as follows:

$$\phi = \frac{\Delta_t - \Delta_c}{h_t l_t} \quad (5.1)$$

where Δ_t and Δ_c are the displacements of the LVDTs measured by the tension and compression sides of the column, respectively; l_t is the length of column segment where one set of two LVDTs is attached; h_t is the center-to-center distance between two LVDTs. **Figure 5.18** demonstrates the curvature distributions of test specimens at yield displacement (as defined in previous section) and maximum lateral force for both positive and negative loading directions. As observed, for both un-corroded and corroded columns, the curvatures at yield displacement and maximum lateral force distributed relatively linear along 5.6% to 94.4% column height. In addition, the main contribution to the flexural deformation of all test specimens was observed from their top and bottom ends. **Table 5.1** indicated the curvatures of test specimens at yield displacement (defined as yield curvature). As indicated, the increase of corrosion level resulted in the decrease of yield curvature for the test specimens subjected to both axial force ratio of $0.1f'_c A_g$ and $0.25f'_c A_g$. It is noted that these measured yield curvatures are due to flexural deformation at top and bottom ends of the columns by deducting the curvature due to bar slip from the total measured curvatures.

Figure 5.18 Curvature distributions of test specimens

5.2.2.6 Displacement composition

Contributions of the slip, shear, and flexural deformation to the total lateral displacement at the top of test specimens were estimated based on the reading results of the attached LVDTs. The slip and flexural deformation was estimated using the average curvatures which were indicated in the previous section while the change in length of the pairs of diagonal LVDTs attached to the side of the specimens was used to calculate the shear deformation. **Figure 5.19** shows the displacement composition for test specimens in which the contributions of the slip, shear and flexural deformation are presented from the upper part to the lower part, respectively. The experimental results showed that the contribution of flexural deformation to the total displacement was the most dominant for test specimens because they failed in flexure or flexural-shear. In addition, the slip deformation was also relatively large proportion to the total displacement for all test specimens. As observed, with the increase of the applied horizontal displacement, the contribution of flexural deformation to total displacement reduced while the contribution of slip deformation increased. This phenomenon was more obvious for corroded specimens because of the reduction of bond slip between longitudinal reinforcing bars and concrete at their top and bottom ends. On the other hand, for all test specimens, the contribution of shear deformation was found to be relatively constant corresponding to the increase of horizontal displacement with average

values from 10% to 25% of total displacement. In addition, it is remarkable to note that for the corroded Specimens C3, C4, and C5 in which the failure mode switched from flexure to flexural-shear, the increase of contribution of shear deformation can be observed after the maximum lateral force was attained, as shown in **Figure 5.19**. This observation is consistent with the appearance and propagation of diagonal shear cracks within the plastic hinge regions of these corroded specimens.

Figure 5.19 Displacement decomposition of test specimens

5.3 Proposed Residual Flexural Strength Estimation

Comparison of the theoretical flexural strength of two un-corroded specimens with the experimental result of the maximum lateral force shows a good correlation with the ratios of the test result to the theoretical flexural strength of un-corroded Specimens U1 and U2 estimated based on sectional analysis are 0.97 and 1.04, respectively, as indicated in **Figure 5.1** and **Figure 5.2**. Therefore, it is reasonable to set the flexural strength of test specimens equal to the experimental result of the maximum lateral force. It is noted that the flexural strength of corroded RC members mainly reduces because of the reduction of mechanical properties of corroded reinforcement, those are yield strength and cross sectional area, bonding

between reinforcement and concrete, and corrosion induced cover concrete crack. In order to consider the complicated effects of these parameters on the reduction of the flexural strength of corroded RC members, several studies in the literature suggested that the residual flexural strength of corroded beams can be predicted using the empirical expressions in which the ratio of the maximum pit depth to the original radius of longitudinal reinforcement can present a relatively good correlation with the reduction of their flexural strength [T2], [O5]. Therefore, a similar approach is utilized to predict the residual flexural strength of RC columns with corroded reinforcement in this study. Due to the compressive concrete strength variation among test specimens, the flexural strength of test specimens was normalized as $V_u / A_g \sqrt{f'_c}$. Based on a regression analysis, the residual flexural strength of corroded columns is estimated as follows:

$$FS_{corr} = -0.826(Pit_{max} / R_0) + 0.971 \quad (5.2)$$

where FS_{corr} is the residual flexural strength defined as the ratio of flexural strength of the corroded column to that of the un-corroded column; Pit_{max} is the maximum pit depth of corroded longitudinal reinforcing bars estimated based on the experiment; R_0 is the original radius of longitudinal reinforcement. **Table 5.2** indicates the values of these parameters to predict the residual flexural strength for corroded columns. **Figure 5.20** demonstrates a good result of the regression analysis with a R^2 value of 0.922.

Table 5.2 Proposed residual flexural strength for test specimens

Specimen	f'_c MPa	V_u MPa	$\frac{V_u}{f'_c A_g}$	FS_{corr}	Pit_{max} mm	$\frac{Pit_{max}}{R_0}$
UC1	32.2	232.1	0.33	1.00	0.00	0.00
CC1	37.5	238.8	0.32	0.95	0.40	0.04
CC2	32.0	193.2	0.28	0.84	1.36	0.14
CC3	40.0	190.7	0.25	0.74	3.05	0.31
UC2	38.1	302.5	0.40	1.00	0.00	0.00
CC4	30.0	254.4	0.38	0.95	0.62	0.06
CC5	31.3	237.1	0.35	0.86	1.03	0.10
CC6	37.5	250.0	0.33	0.83	1.49	0.15

Figure 5.20 Relationship between ratio of the maximum corrosion pit depth to original radius of longitudinal reinforcement and residual flexural strength

5.4 Summary

In this chapter, the influences of reinforcement corrosion on the seismic performance of RC slender columns are experimentally and analytically investigated. The key parameters are investigated and quantified, including the corrosion levels of reinforcement and axial load ratios. Some important findings can be concluded from the experimental and analytical studies as followings:

1. Reinforcement corrosion strongly affects the seismic performance of RC slender columns, including the hysteretic response, crack pattern, yield displacement, lateral load resistance, drift capacity, and energy dissipation capacity, even more so when they are highly corroded and subjected to high axial load.
2. Three failure modes are observed in which two un-corroded columns and two corroded columns subjected to low corrosion level and axial load fail in typical flexural manner. The second failure mode is flexural-shear failure which is directly caused by the formation and propagation of the diagonal shear cracks in the plastic hinge regions of the columns. This failure is found out in three corroded columns subjected to either high corrosion levels or high axial load.

The third failure mode is sudden axial failure which is occurred in a corroded column subjected to a high corrosion level combined with a high axial load, resulting in the explosion of concrete and reinforcement at the top end of the column. This failure is mainly caused by the loss of confinement effectiveness for confined concrete and buckling resistance of longitudinal reinforcement due to the fracture of transverse reinforcing bars induced by extremely severe corrosion.

3. The test results reveal that the increase of corrosion levels results in the significant deterioration of the lateral load and drift capacities of RC slender columns. In addition, the adverse effect of reinforcement corrosion on drift capacity at failure is more serious than that on the lateral load capacity. Furthermore, the displacement ductility of corroded columns is also found out to be decreased corresponding to the increase of axial force ratios and corrosion levels of reinforcement. The test results also show that the energy dissipation capacity of corroded columns strongly depends on the corrosion levels of reinforcement and applied axial load ratios. Particularly, the energy dissipation capacity decreases with the increase of corrosion levels and applied axial force ratios.
4. This study proposes an empirical equation to predict the residual flexural strength of corroded columns based on the experimental results which is a function of the maximum pit depth of corroded longitudinal reinforcing bars.

Chapter 6. EXPERIMENTAL STUDY ON REINFORCED CONCRETE SHORT COLUMNS WITH CORRODED REINFORCEMENT

6.1 Introduction

This chapter presents an experimental study carried out on eight full-scale un-corroded and corroded reinforced concrete short columns subjected to a simulated seismic loading to investigate effects of corrosion on the seismic performance of short columns which fail in shear. The main variables are the corrosion level of reinforcement and the applied axial force ratio. The seismic behavior of test specimens was evaluated in terms of crack pattern, hysteretic response, shear strength, drift capacity, and energy dissipation capacity. The experimental results highlighted that the corroded columns suffered a significant degradation of shear strength and deformation capacity compared to un-corroded columns, especially when they are highly corroded and under high axial load ratio. Furthermore, an assessment method is proposed to predict the shear strength of these columns, taking into consideration the reductions of transverse reinforcement and concrete contributions to the shear strength deterioration by incorporating the corrosion effects into the shear strength model proposed in ASCE/SEI 41-13 (2014) [A6].

6.2 Experimental Results and Discussion

This section presents and discusses the experimental results of eight un-corroded and corroded specimens tested with various corrosion levels and axial load ratios. The hysteretic responses of test specimens are demonstrated in **Figure 6.1** to **Figure 6.8**. Three performance levels were used to highlight the response of test specimens, particularly in terms of maximum shear force (PL2), shear failure (PL3 which is defined corresponding to the shear strength dropped by 20%), and axial failure (PL4: when columns were unable to sustain the axial force). In general, the hysteretic responses showed the deterioration of shear strength right after the maximum shear force was attained, and the pinching effect during repeated cyclic loading was more obvious with corroded columns due to the bonding reduction between reinforcement and surrounding concrete induced by corrosion. The

appearance and propagation of vertical cracks along the longitudinal reinforcing bars in corroded specimens showed the evidence of the bonding reduction due to corrosion that was not observed in un-corroded specimens. More details of test results of specimens in Series 3 can be found in **Appendix C**. It is also noted that from **Figure 6.1** to **Figure 6.8**, $X_{corr}^{(lt)}$ and $X_{corr}^{(lt)}$ are the corrosion levels in terms of mass loss of transverse reinforcement and longitudinal reinforcement, respectively; $P/f_c A_g$ is the applied axial force.

Figure 6.1 Hysteric response of test Specimen UC1

Figure 6.2 Hysteric response of test Specimen UC2

Figure 6.3 Hysteric response of test Specimen CC1

Figure 6.4 Hysteric response of test Specimen CC2

Figure 6.5 Hysteric response of test Specimen CC3

Figure 6.6 Hysteric response of test Specimen CC4

Figure 6.7 Hysteric response of test Specimen CC5

Figure 6.8 Hysteric response of test Specimen CC6

6.2.1 Crack patterns of test specimens

Figure 6.9 and **Figure 6.10** demonstrate the crack patterns of test specimens at maximum shear force (PL2) and axial failure (PL4), respectively. It is noted that all test specimens were designed to fail by shear in order to observe the effects of corrosion levels and axial load ratios on the seismic performance of RC short columns in corrosive environment. As observed in **Figure 6.9**, the primarily diagonal cracks were observed for all test specimens and more diagonal cracks occurred and developed in un-corroded specimens than in corroded specimens. For un-corroded Specimens UC1 and UC2, the flexural-shear cracks appeared at early drift ratio of 0.75%. After that, the shear cracks initially developed with average diagonal crack angles of approximately 39, and 29 degrees, respectively. Under a higher axial load ratio, the un-corroded Specimen UC2 reached the maximum shear force at a smaller drift ratio of 2.5% compared to the drift ratio of 3.4% for un-corroded Specimen UC1. These columns failed with a gradual increase of shear crack width and spalling and crushing of concrete. However, for corroded columns, there were little or no flexure-shear cracks which appeared at early drift ratios. In

addition, together with diagonal cracks, the vertical cracks along the longitudinal reinforcement were also obvious. This is because the initial cracks induced by corrosion developed vertically along the direction of longitudinal reinforcing bars, and afterward these cracks further developed and widened with the increase of the applied horizontal displacement and constant axial force. Furthermore, the corroded specimens were subjected to high axial load and under high corrosion level responded in a more brittle manner, that is, the shear cracks were major cracks from the top to bottom end of the specimens to form the inclined failure plan, resulting in the sudden loss of their shear capacity. More seriously, a sudden axial failure can be observed for corroded Specimen CC6 which was subjected to axial force of $0.25f'_cA_g$ and under high corrosion level of transverse reinforcement of 18.2%. Particularly, the shear capacity was immediately lost right after the maximum shear force was reached at a small drift ratio of 1.48% and there was no post-strength degradation. **Figure 6.11** illustrates the relationship between the diagonal crack angles at the maximum shear force with respect to the longitudinal axis of the specimen and the corrosion level in terms of mass loss of transverse reinforcement for all test specimens. As indicated, the diagonal crack angles depend not only on the applied axial force but also on the corrosion level of transverse reinforcement. The increase of axial force resulted in the decrease of diagonal crack angles. In addition, it was observed that when the corrosion level of transverse reinforcement increased, the diagonal crack angles also decreased. This observation is more obvious in corroded columns subjected to high axial force than those under low axial force, particularly, at the maximum shear force, the average diagonal crack angles of test specimens with axial force of $0.1f'_cA_g$ were 39, 39, 36, and 27 degrees for Specimens UC1, CC1, CC2, and CC3, respectively. They were 29, 20, 16, and 14 degrees for test Specimens UC2, CC4, CC5, and CC6 subjected to higher axial force ($0.25f'_cA_g$), respectively. These values are much smaller than the commonly used crack angle of 45 degrees assumed in strut-and-tie model.

Figure 6.9 Crack patterns of test specimens at maximum shear force

Figure 6.10 Crack patterns of test specimens at axial failure

Figure 6.11 Relationship between the corrosion level of transverse reinforcement and the crack angle at maximum shear force

6.2.2 Hysteretic response comparisons

Figure 6.12 shows the comparisons of hysteretic responses between un-corroded specimens and corroded specimens which are subjected to the same axial force ratios of $0.1f'_cA_g$ and $0.25f'_cA_g$. Comparisons of the backbone curves of test specimens with various corrosion levels and axial load ratios are also demonstrated in **Figure 6.13** and **Figure 6.14**. Of note, from henceforth, the values of shear strength, displacement ductility, drift capacity, and energy dissipation are the average values of positive and negative loading directions, as indicated in **Table 6.1**. In addition, for simplicity in demonstration, the corrosion level in terms of mass loss of transverse reinforcement is chosen to present the effects of test parameters on the seismic performance of test specimens, as shown from **Figure 6.15** to **Figure 6.18**.

Table 6.1 Comparisons between un-corroded columns and corroded columns with various corrosion levels and axial load ratios

Specimen	f'_c MPa	$V_{\max}$ kN	$\frac{V_{\max}}{A_g \sqrt{f'_c}}$	δ_y %	δ_m %	δ_s %	δ_a %	μ_δ	Energy dissipation (kNm) at		
									PL1	PL2	PL3
UC1	32.2	411.2	0.59	1.95	3.22	3.89	4.69	2.01	16.3	25.8	35.5
CC1	28.8	358.9	0.55	1.62	2.89	3.82	4.56	2.32	14.2	20.5	23.2
CC2	32.0	327.8	0.47	1.52	2.44	3.09	3.59	2.12	8.6	13.4	14.9
CC3	27.8	293.8	0.45	1.32	1.84	2.69	3.02	1.97	7.7	11.0	12.9
UC2	38.1	513.2	0.68	1.81	2.51	3.18	3.65	1.74	10.8	16.5	18.9
CC4	34.4	426.6	0.59	1.30	2.07	2.86	3.53	2.17	8.8	13.2	16.6
CC5	31.3	368.8	0.54	1.05	1.56	2.78	3.61	2.82	5.3	15.6	18.2
CC6	40.0	397.5	0.51	1.02	1.46	1.75	1.60	1.61	5.0	7.2	7.2

Note: μ_δ is displacement ductility; $\delta_y, \delta_m, \delta_s, \delta_a$ are the drift ratios at yielding level, maximum shear force, shear failure, and axial failure, respectively.

Figure 6.12 Comparisons of hysteric responses of un-corroded specimens and corroded specimens

Figure 6.13 Comparisons of backbone curves of test specimens subjected to axial force of $0.1f'_c A_g$

Figure 6.14 Comparisons of backbone curves of test specimens subjected to axial force of $0.25f'_c A_g$

6.2.2.1 Shear strength

Figure 6.15 shows the effect of various corrosion levels and applied axial force ratios on the shear strength of test specimens which was normalized as $V_{\max} / A_g \sqrt{f'_c}$ due to the compressive concrete strength variation among test specimens. It was observed that the increase of corrosion levels results in the decrease of shear strength and its significant reduction can be observed when the columns are highly corroded and subjected to high axial load. For example, the test Specimens UC1, CC1, CC2, and CC3 with the axial load of $0.1f'_c A_g$, when the corrosion level raised from 0% to 11.4%, 21.3%, and 26.1%, the normalized shear strength of these specimens reduced 7.7%, 20.0%, and 23.1%, respectively. More severe deterioration of normalized shear strength in the test Specimens UC2, CC4, CC5, and CC6 with the axial load of $0.25f'_c A_g$ can be observed with the increase of corrosion level from 0% to 8.4%, 12.1%, and 18.2%, respectively. Therefore, in conclusion the shear strength of short corroded columns significantly depends on the corrosion level of transverse reinforcement and the applied axial force.

Figure 6.15 Effects of test parameters on shear strength of test specimens

6.2.2.2 Drift capacity

The effects of corrosion levels and axial force ratios on the drift capacities at various performance levels of test specimens are demonstrated in **Figure 6.16**, including drift ratios at the maximum shear force, shear failure, and axial failure.

Overall, drift capacities decreased when the corrosion level and axial load ratio increased. For instance, when test specimens were subjected to axial load of $0.1f_c'A_g$, the drift ratio at maximum shear force reduced by 10.4%, 24.2%, and 42.9% from un-corroded Specimen UC1 to corroded Specimens CC1, CC2, and CC3, respectively. Regarding the drift ratio at axial failure, only a slight reduction of 2.8%, 3.2% and 1.1% was observed for the corroded Specimens CC1, CC4 and CC5 compared to the un-corroded Specimens UC1 and UC2. However, the drift ratios of highly corroded Specimens CC2, CC3 and CC6 significantly decreased, those are 23.5%, 35.7%, and 56.2% reductions compared to un-corroded Specimens UC1 and UC2, respectively. This is due to the fracture of confining transverse reinforcement induced by severe pitting corrosion which resulted in the significant deterioration of the drift capacity at axial failure.

Figure 6.16 Effect of test parameters on drift capacity of test specimens

6.2.2.3 Energy dissipation capacity

Figure 6.17 indicates the cumulative energy dissipation capacity of test specimens. In addition, **Figure 6.18** also demonstrates the effects of test parameters on the energy dissipation capacity at different performance levels. As observed, the total energy dissipation capacity depends not only on the corrosion level of test specimens but also on the applied axial force. For example, with the same axial force of $0.1f'_cA_g$, the total energy dissipation at axial failure decreased by 34.5%, 57.9%, and 63.5% from un-corroded Specimen UC1 to corroded Specimens CC1, CC2 and CC3 corresponding to the corrosion level increased from 0% to 11.4%, 21.3%, and 26.1%, respectively. A similar reduction trend of energy dissipation capacity was also observed for test specimens subjected to axial force of $0.25f'_cA_g$. As observed in **Figure 6.18**, the energy dissipation capacity of both un-corroded and corroded columns was also reduced with the increase of applied axial force from $0.1f'_cA_g$ to $0.25f'_cA_g$.

Figure 6.17 Energy dissipation capacity of test specimens

Figure 6.18 Effects of test parameters on energy dissipation capacity of test specimens

6.2.2.4 Displacement composition

Figure 6.19 shows the displacement composition for test specimens in which the contributions of the slip, shear and flexural deformation are presented from the upper part to the lower part, respectively. The experimental results showed that the shear deformation significantly contributed to the total displacement because the test specimens failed in shear. As observed the shear deformation increased rapidly right after the maximum shear force was attained which was consistent with the propagation and opening of the major diagonal shear cracks. At the maximum shear force (PL2), the contribution of shear deformation was accounted from 19% to 57% of the total displacement for all test specimens. This contribution increased by an average of 15% when loading to shear failure (PL3). In addition, the slip deformation was also relatively large in proportion to the total displacement for all test specimens which contributed from 27% to 68% of the total displacement at maximum shear force. However, this contribution reduced when loading to shear failure. It was observed that the contribution of slip to total displacement of corroded specimens was higher than that of un-corroded specimens because of the reduction of bond slip due to corrosion between longitudinal reinforcing bars and concrete at their top and bottom ends.

Figure 6.19 Displacement decomposition of test specimens

6.3 Proposed Shear Strength Assessment

Among various existing shear strength models in literature, the shear strength model proposed in ASCE/SEI 41-13 (2014) [A6] is being commonly used to estimate the shear strength of RC columns failed in shear. This model can incorporate the primary parameters of the column, including the shear span to depth ratio, axial force ratio, cross-sectional dimensions, compressive concrete strength, and displacement ductility demand. In this study, this shear strength model is adopted and modified to estimate the shear strength of corroded RC columns by considering the contribution reductions to shear strength of transverse reinforcement and concrete due to corrosion. This approach has been also employed to study the influences of corroded transverse reinforcing bars on the shear strength of RC beams in literature [O2], [E1]. The original shear strength equation proposed in ASCE/SEI 41-13 (2014) [A6] is given as:

$$V_n = kV_0 = k \left[\frac{A_v f_y d}{s} + \lambda \left(\frac{0.5 \sqrt{f'_c}}{a/d} \sqrt{1 + \frac{P}{0.5 \sqrt{f'_c} A_g}} \right) 0.8 A_g \right] \quad (6.1)$$

$$k = \begin{cases} 1, \mu_\delta \leq 2.0 \\ 1.15 - 0.075 \mu_\delta, 2.0 < \mu_\delta < 6.0 \\ 0.7, \mu_\delta \geq 6.0 \end{cases} \quad (6.2)$$

where k is a parameter to consider the reduction of shear strength with the increase of displacement ductility μ_δ ; a/d is the shear span to depth ratio; A_v is the total area of transverse reinforcement within the spacing s ; f_{yt} is the yield strength of transverse reinforcement; d is the effective depth which can be assumed that $d = 0.8h$ where h is the depth of the column cross section; A_g is the gross cross-sectional area of the column; $\lambda = 1$ for normal weight concrete; P is the applied axial force. The corrosion effects on the contributions of transverse reinforcement and concrete to the shear strength estimation of corroded columns are presented in the following section.

6.3.1 Transverse reinforcement contribution

Generally, corrosion of reinforcement reduces the mechanical properties and diameter of reinforcement, resulting in the reduction of total cross-sectional area A_v and yield strength of transverse reinforcement f_{yt} . Therefore, a modification of cross-sectional area A_{vc} and yield strength f_{yt}^c for transverse reinforcement was made in this proposed shear strength assessment as following equations

$$V_s^{pro} = \frac{A_{vc} f_{yt}^c d}{s} \quad (6.3)$$

$$A_{vc} = (1 - X_{corr}) A_v \quad (6.4)$$

$$f_{yt}^c = (1 - \alpha_s X_{corr}) f_{yt} \quad (6.5)$$

where X_{corr} is the corrosion level of transverse reinforcement. In this study, three considerations of cross-sectional area loss of transverse reinforcement were examined, including corrosion levels in terms of: mass loss $X_{corr}^{(1)}$, average residual cross-sectional area $X_{corr}^{(2)}$, and minimum residual cross-sectional area $X_{corr}^{(3)}$, as defined from Eq. (3.11) to Eq. (3.13) in **Chapter 3**, respectively; α_s is the yield strength reduction factor for corroded reinforcement, taken as 0.005 [D2]. It is also noted that both the study conducted by Du *et al.* (2005) [D2] and current study used the electrochemical technique to accelerate the corrosion process with the same current intensity of 0.5 mA/cm². In addition, the types of the steel reinforcement

employed in these two studies are also similar. Therefore, it is reasonable to adopt the test results in [D2] for this study. **Table 6.2** shows the calculation details of the contribution of transverse reinforcement to the shear strength for corroded specimens with three assessment methods of cross-sectional area loss of transverse reinforcement.

6.3.2 Concrete contribution

The volumetric expansion of corrosion products induces the tensile stresses at the interfacial regions between reinforcement and concrete, resulting in the cracks of cover concrete. These cracks reduce the contribution of cover concrete to the shear strength capacity of RC columns. This adverse effect can be simulated in this study by reducing the compressive concrete strength of cover concrete to $\zeta f'_c$ in which the softening coefficient ζ can be estimated as follows Hsu and Mo (2010) [H4]:

$$\zeta = \frac{0.9}{\sqrt{1 + 600\varepsilon_r}} \quad (6.6)$$

$$\varepsilon_r = \frac{W_{cr}}{p_0} \quad (6.7)$$

where ε_r is the tensile strain induced by the cracks of cover concrete; W_{cr} is the total crack width of the specimen which can be defined as Eq. (3. 7) and easily measured in the experiment and real engineering, as indicated in **Table 3.6** in **Chapter 3**; p_0 is the perimeter of the column section. As shown in Eq. (6.8) which is modified from shear strength equation proposed in ASCE/SEI 41-13 (2014) [A6], the contribution of concrete to the shear strength of corroded columns is estimated by remaining the compressive concrete strength f'_c for the core concrete area A_{core} and using the reduction of compressive concrete strength of $\zeta f'_c$ for the cover concrete area A_{cover} as well as taking the effective depth $d = 0.8h$. Finally, the shear strength of corroded columns is estimated as the summation of contributions to the shear strength of transverse reinforcement and concrete, as indicated in Eq. (6.9).

$$V_c^{pro} = \left(\frac{0.5\sqrt{f'_c}}{M/Vd} \sqrt{1 + \frac{P}{0.5\sqrt{f'_c}(A_{core} + \sqrt{\zeta}A_{cover})}} \right) 0.8(A_{core} + \sqrt{\zeta}A_{cover}) \quad (6.8)$$

$$V_n^{pro} = V_s^{pro} + V_c^{pro} \quad (6.9)$$

The calculation details of the shear strength provided by concrete for corroded columns are indicated in **Table 6.2**. It is noted that, as mentioned in **Chapter 5**, there were three corroded columns failed in flexural-shear and one column failed in sudden axial failure. Therefore, it is also reasonable to predict the shear strength for these corroded columns using this proposed shear strength assessment. Comparisons of the shear strength between the experimental results and proposed assessment for corroded columns are shown in **Table 6.3**. As indicated, compared to the experimental results, the shear strength prediction using the corrosion mass loss and average residual cross-sectional area was not conservative because the average ratios of the shear strength estimated based on the proposed shear strength assessment to the test results are 1.305, and 1.197 and their standard deviations of 0.104, and 0.099, respectively. However, the shear strength prediction using the minimum residual cross-sectional area of transverse reinforcement showed a good correlation with the test results with the average ratio of the shear strength calculated adopting the proposed shear strength assessment to the test results is 0.954 and its standard deviation of 0.071.

Table 6.2 Proposed shear strength assessment for test specimens

Specimen	b mm	d mm	a mm	A_{core} mm ²	A_{cover} mm ²	f'_c MPa	ζ	X_{corr} %	f_{yt}^c MPa	A_{vc} mm ²	s mm	P kN	μ_δ	k	V_s^{pro} kN	V_c^{pro} kN	V_n^{pro} kN
UC1	350	280	540	90000	32500	32.2	1.00	0.0	300.0	163.1	50	394.5	2.01	1.00	273.9	210.5	484.4
CC1	350	280	540	90000	32500	28.8	0.85	11.4	283.0	144.6	50	352.8	2.32	0.98	223.6	188.7	412.4
	350	280	540	90000	32500	28.8	0.85	21.4	267.9	128.2	50	352.8	2.32	0.98	187.8	188.7	376.5
	350	280	540	90000	32500	28.8	0.85	40.2	239.8	97.6	50	352.8	2.32	0.98	127.9	188.7	316.7
	350	280	540	90000	32500	28.8	0.85	21.4	267.9	128.2	50	352.8	2.32	0.98	187.8	188.7	376.5
CC2	350	280	540	90000	32500	32.0	0.84	21.3	268.1	128.4	50	392.0	2.12	0.99	191	204.5	395.5
	350	280	540	90000	32500	32.0	0.84	28.4	257.4	116.8	50	392.0	2.12	0.99	166.8	204.5	371.4
	350	280	540	90000	32500	32.0	0.84	58.4	212.4	67.9	50	392.0	2.12	0.99	80	204.5	284.6
	350	280	540	90000	32500	27.8	0.75	26.1	260.9	120.6	50	340.6	1.97	1.00	176.1	187	363.1
CC3	350	280	540	90000	32500	27.8	0.75	39.4	240.9	98.9	50	340.6	1.97	1.00	133.4	187	320.4
	350	280	540	90000	32500	27.8	0.75	60.3	209.6	64.8	50	340.6	1.97	1.00	76	187	263
	350	280	540	90000	32500	38.1	1.00	0.0	300.0	163.1	50	1166.8	1.74	1.00	274.1	317	591.1
	350	280	540	90000	32500	34.4	0.87	8.4	287.4	149.5	50	1053.5	2.17	0.99	237.5	288.5	526
CC4	350	280	540	90000	32500	34.4	0.87	16.9	274.6	135.5	50	1053.5	2.17	0.99	205.8	288.5	494.3
	350	280	540	90000	32500	34.4	0.87	30.1	254.9	114.1	50	1053.5	2.17	0.99	160.7	288.5	449.2
	350	280	540	90000	32500	31.3	0.84	12.1	281.8	143.4	50	958.6	2.82	0.94	212.3	256.3	468.6
	350	280	540	90000	32500	31.3	0.84	21.7	267.5	127.8	50	958.6	2.82	0.94	179.7	256.3	435.9
CC5	350	280	540	90000	32500	31.3	0.84	44.2	233.7	91.0	50	958.6	2.82	0.94	111.7	256.3	368
	350	280	540	90000	32500	40.0	0.80	18.2	272.7	133.5	50	1225.0	1.61	1.00	203.9	322.3	526.2
	350	280	540	90000	32500	40.0	0.80	27.8	258.3	117.8	50	1225.0	1.61	1.00	170.3	322.3	492.6
	350	280	540	90000	32500	40.0	0.80	51.2	223.1	79.5	50	1225.0	1.61	1.00	99.4	322.3	421.7

Specimen	b mm	d mm	a mm	A_{core} mm ²	A_{cover} mm ²	f'_c MPa	ζ	X_{corr} %	f_{yt}^c MPa	A_{vc} mm ²	s mm	P kN	μ_δ	k	V_s^{pro} kN	V_c^{pro} kN	V_n^{pro} kN
C3	350	280	890	90000	32500	40.0	0.73	25	262.5	122.4	50	490	3.81	0.86	155.41	123.28	278.7
	350	280	890	90000	32500	40.0	0.73	30.5	254.3	113.4	50	490	3.81	0.86	139.49	123.28	262.8
	350	280	890	90000	32500	40.0	0.73	62.3	206.6	61.5	50	490	3.81	0.86	61.47	123.28	184.7
C4	350	280	890	90000	32500	30.0	0.81	13.6	279.6	141	50	918.8	3.57	0.88	194.65	141.61	336.3
	350	280	890	90000	32500	30.0	0.81	22.6	266.1	126.3	50	918.8	3.57	0.88	165.95	141.61	307.6
	350	280	890	90000	32500	30.0	0.81	41.3	238.1	95.8	50	918.8	3.57	0.88	112.59	141.61	254.2
C5	350	280	890	90000	32500	31.3	0.82	15.5	276.8	137.9	50	958.6	3.61	0.88	187.85	145.42	333.3
	350	280	890	90000	32500	31.3	0.82	29.5	255.8	115	50	958.6	3.61	0.88	144.83	145.42	290.2
	350	280	890	90000	32500	31.3	0.82	59.2	211.2	66.6	50	958.6	3.61	0.88	69.22	145.42	214.6
C6	350	280	890	90000	32500	37.5	0.76	23.5	264.8	124.8	50	1148.4	2.39	0.97	179.57	180.63	360.2
	350	280	890	90000	32500	37.5	0.76	33.5	249.8	108.5	50	1148.4	2.39	0.97	147.26	180.63	327.9
	350	280	890	90000	32500	37.5	0.76	73.8	189.3	42.7	50	1148.4	2.39	0.97	43.97	180.63	224.6

Table 6.3 Comparisons of shear strength of corroded specimens using different assessment methods of corrosion level of transverse reinforcement

Specimen	V_n^{exp} kN	$X_{\text{corr}}^{(1)}$ %	$V_n^{\text{pro}(1)}$ kN	$\frac{V_n^{\text{pro}(1)}}{V_n^{\text{exp}}}$	$X_{\text{corr}}^{(2)}$ %	$V_n^{\text{pro}(1)}$ kN	$\frac{V_n^{\text{pro}(2)}}{V_n^{\text{exp}}}$	$X_{\text{corr}}^{(3)}$ %	$V_n^{\text{pro}(3)}$ kN	$\frac{V_n^{\text{pro}(3)}}{V_n^{\text{exp}}}$
CC1	358.9	11.4	412.4	1.15	21.4	376.5	1.05	40.2	316.7	0.88
CC2	327.8	21.3	395.5	1.21	28.4	371.4	1.13	58.4	284.6	0.87
CC3	293.8	26.1	363.1	1.24	39.4	320.4	1.09	60.3	263.0	0.90
CC4	426.6	8.4	526.0	1.23	16.9	494.3	1.16	30.1	449.2	1.05
CC5	368.8	12.1	468.6	1.27	21.7	435.9	1.18	44.2	368.0	1.00
CC6	397.5	18.2	526.2	1.32	27.8	492.6	1.24	51.2	421.7	1.06
C3	190.7	25	278.7	1.46	30.5	262.8	1.38	62.3	184.7	0.97
C4	254.4	13.6	336.3	1.32	22.6	307.6	1.21	41.3	254.2	1.00
C5	237.1	15.5	333.3	1.41	29.5	290.2	1.22	59.2	214.6	0.91
C6	250.0	23.5	360.2	1.44	33.5	327.9	1.31	73.8	224.6	0.90
Average				1.305			1.197			0.954
COV				0.104			0.099			0.071

6.4 Summary

In this study, the influences of corroded reinforcement on the seismic performance of RC short columns are experimentally and analytically investigated. The experimental program included eight full-scale un-corroded and corroded short columns subjected to cyclic loading. The key parameters affecting the seismic performance of RC short columns failed in shear with corroded reinforcement are investigated and quantified, including the corrosion levels of reinforcement and axial load ratios. Some important findings can be concluded from the experimental and analytical studies as followings:

1. Reinforcement corrosion strongly affects the performance of RC short columns subjected to cyclic loading, including the hysteretic response, crack pattern, shear strength, drift capacity, and energy dissipation capacity, even more so when they are highly corroded and subjected to high axial load.
2. The increase of corrosion levels resulted in the significant deterioration of the shear strength and drift capacity of RC short columns. Furthermore, the

experimental results revealed that the corrosion level effects on the shear strength and drift capacity deterioration is more significant when these columns are subjected to high axial force. However, compared to the un-corroded columns, the drift ratios at axial failure of corroded columns only slightly change when these columns are under low corrosion levels. Furthermore, the displacement ductility is also found to be irrelevant to the axial force and corrosion level of reinforcement for corroded short columns which failed in shear. On the other hand, the energy dissipation capacity of corroded columns strongly depends on the corrosion level of reinforcement and applied axial load. Particularly, the energy dissipation capacity decreases with the increase in corrosion level and applied axial force.

3. Although both un-corroded and corroded columns showed primarily diagonal cracks at the maximum shear force and failure stages, the appearance and propagation of diagonal cracks between un-corroded columns and corroded columns subjected to high axial force and high corrosion level are totally different. While the un-corroded columns showed a gradual development of flexure-shear and shear cracks together with the gentle degradation of shear strength after the maximum shear force attained, the corroded columns under high axial force and high corrosion level responded in a much more brittle manner with the sudden appearance of major diagonal cracks from the top to bottom end of the specimens to form the inclined failure plan when these columns reached maximum shear force and right after the sudden loss of their shear capacity can be observed.

4. The experimental observation also revealed that the diagonal crack angle at the maximum shear force significantly depends on the applied axial force and corrosion level of transverse reinforcement. The increase of axial force and corrosion level results in the decrease of diagonal crack angle. However, the decrease of diagonal crack angle due to the increase of corrosion level is more obvious in corroded columns subjected to high axial force than in those under low axial force. These diagonal crack angles are much smaller than 45 degrees assumed in strut-and-tie model.

5. The shear strength assessment for corroded columns is proposed based on modifying the shear strength model in ASCE/SEI 41-13 code. It is also

recommended that adopting this proposed shear strength assessment, the shear strength prediction based on the minimum residual cross-sectional area of transverse reinforcing bars showed good and reliable agreement with the test results in this study, including four corroded slender columns failed in flexural-shear failure and axial failure in Series 2 and six corroded short columns failed in shear in Series 3.

Chapter 7. FINITE ELEMENT MODELING OF REINFORCED CONCRETE COLUMNS WITH CORRODED REINFORCEMENT

7.1 Introduction

In this chapter, the behavior of corroded RC columns under seismic loading is studied using a three-dimensional (3D) non-linear Finite Element (FE) analysis, considering the material properties deterioration of reinforcement and concrete induced by corrosion. The experimental results of test specimens in the current study and literature are selected to verify the accuracy of the proposed 3D non-linear FE model. Thereafter, an extensive parametric investigation, including the FE models of 192 RC columns subjected to the simulated seismic loading is performed to study the influence of various crucial parameters on the seismic performance of corroded RC columns, particularly their lateral load resistance and ultimate drift capacity deteriorations. Finally, these key parameters are incorporated into three prediction equations of the lateral load resistance and ultimate drift capacity for both corroded slender columns and short columns.

7.2 Finite Element Simulation

7.2.1 Finite element software

In this chapter, a 3D non-linear FE analysis was carried out to simulate the seismic behavior of RC columns with corroded reinforcement using DIANA (9.4.4) [D1] – a commercial non-linear FE software package. The validity and reliability of this FE software to model the behavior of corroded RC structures have been confirmed in literature [K1], [H1], [O3]. In this proposed 3D non-linear FE model, concrete is modeled by adopting twenty-node isoparametric solid brick elements while a separate truss element which is connected to the concrete element using interface element is utilized to model the reinforcement. The local bond stress-slip law proposed in the CEB-FIP (1990) [C4] is employed and modified to incorporate the corrosion effect in this study. A combination of a horizontal cyclic displacement

and a vertical axial force is applied to simulate the seismic loading on the corroded RC columns.

7.2.2 Modeling of concrete

A constitutive model of concrete consists of the compression hardening and softening, as well as the tension behavior which is presented in the following sections.

7.2.2.1 Compression behavior of concrete

DIANA (9.4.4) [D1] suggested some predefined compressive stress-strain relationship as shown in **Figure 7.1**, including elastic, ideal, Thorenfeldt, linear, multi-linear, saturation type and parabolic function. In the current study, the parabolic curve based on fracture energy proposed by Feenstra (1993) [F2] is adopted to model the compressive behavior of concrete material, as shown in **Figure 7.2** where $\alpha_{c/3}$ is the compressive strain at one-third of the maximum compressive strength f_c ; α_c is the compressive strain at maximum compressive strength; α_u is the ultimate strain at which the material is totally softened in compression; h is the crack band width which is assumed to be related to the area of the finite element for 2D element $h = \sqrt{A}$ or the volume of the finite element for 3D element $h = \sqrt[3]{V}$ as suggested in DIANA (9.4.4) [D1]; G_c is the compressive fracture energy of concrete, $G_c = 8\sqrt{f'_c}$ is employed in this study as recommended by Nakamura and Higai (2001) [N1].

Figure 7.1 Predefined compressive behavior of concrete for total strain crack model [D1]

Figure 7.2 Parabolic compression curve of concrete [F2]

7.2.2.2 Tension behavior of concrete

Several pre-defined tension softening functions for total strain crack model are proposed in DIANA (9.4.4) [D1], as shown in **Figure 7.3**. In this FE modeling, the linear tension softening curve is adopted, as indicated in **Figure 7.4** where f_{ct} is the tensile strength of concrete. According to CEB-FIP (1990) [C4], in the absence of experimental data f_{ct} can be calculated as:

$$f_{ct} = 0.30(f_c)^{2/3} \quad (7.1)$$

The tensile softening curve proposed by Cornelissen *et al.* (1986) [C7] is mainly based on the tensile fracture energy of concrete G_f which is defined as the required energy to propagate a tensile crack per unit area and the crack bandwidth h . According to CEB-FIP (1990) [C4], in the absence of experimental data G_f can be estimated as follows:

$$G_f = G_{f0} \left(\frac{f_c}{10} \right)^{0.7} \quad (7.2)$$

where G_{f0} is the base value of fracture energy, depending on the maximum aggregate size $d_{\max}$ which is given in **Table 7.1**. CEB-FIP (1990) [C4] also proposed an alternative approach which is indicated in **Table 7.2** to estimate the tensile fracture energy G_f , depending on the concrete grade and maximum aggregate size.

Table 7.1 Base values of fracture energy G_{fo} (Nmm/mm²)

d_{max} (mm)	G_{fo} (Nmm/mm ²)
8	0.025
16	0.030
32	0.058

Table 7.2 Tensile fracture energy G_f (Nm/m²)

Max. Aggregate size d_{max} (mm)	G_f (Nm/m ²)							
	C12	C20	C30	C40	C50	C60	C70	C80
8	40	50	65	70	85	95	105	115
16	50	60	75	90	105	115	125	135
32	60	80	95	115	130	145	160	175

Figure 7.3 Predefined tension softening of concrete for total strain crack model [D1]

Figure 7.4 Linear tension softening curve for tension behavior of concrete [D1]

7.2.2.3 Modeling of crack cover concrete

Corrosion transforms steel into rust, resulting in the volumetric expansion that can develop the splitting stresses in concrete. The cracking and spalling of concrete induced by these stresses can be modeled by reducing the strength of concrete elements belonging this region to $\zeta f'_c$ in which the softening coefficient ζ can be estimated as follows [H4]:

$$f'_{cc} = \zeta f'_c \quad (7.3)$$

$$\zeta = \frac{0.9}{\sqrt{1 + 600\varepsilon_r}} \quad (7.4)$$

$$\varepsilon_r = \frac{W_{cr}}{p_0} \quad (7.5)$$

where ε_r is the tensile strain induced by the cracks of cover concrete; W_{cr} is the total crack width of the specimen which can be defined as Eq. (3. 7) and measured in experiment and real engineering, as indicated in **Chapter 3**. If the experimental data is not available, the total crack width of the specimen can be estimated based on corrosion levels of transverse reinforcement, as indicated in Eq. (3.8) to Eq. (3.10) in **Chapter 3**; p_0 is the perimeter of the column section. Furthermore, according to the recommendation of Hanjari *et al.* (2011) [H1], because of the cracked concrete around corroded reinforcement induced by corrosion, the tensile concrete strength should be also reduced proportionally to the reduction in compressive concrete strength as following expression:

$$f'_{tC} = \frac{f'_{cC}}{f'_c} f'_t \quad (7.6)$$

Figure 7.5(a) and **(b)** present the modeling of cover concrete under compression and tension.

Figure 7.5 Column FE model – Constitutive models for: (a) Cover concrete under compression and (b) Tension; (c) Steel reinforcement; (d) bond stress-slip relations

7.2.3 Modeling of corroded reinforcement

Generally, corrosion of reinforcement reduces the mechanical properties and diameter of reinforcement, resulting in the reduction of total cross-sectional area A_v , yield strength f_y , and ultimate strength of reinforcement f_u . Therefore, a modification of cross-sectional area A_{vc} and yield strength f_y^c for corroded reinforcement was made in this proposed FE model as following equations:

$$A_s(X_{corr}) = \frac{\pi D_0^2}{4} \left(1 - \frac{X_{corr}}{100}\right) \quad (7.7)$$

$$f_y^c = (1 - \alpha_s X_{corr}) f_y \quad (7.8)$$

$$f_u^c = (1 - \alpha_s X_{corr}) f_u \quad (7.9)$$

where $X_{corr}(\%)$ is the corrosion level of reinforcement. The value of the empirical coefficient $\alpha_s = 0.005$ suggested by Du *et al.* (2005) [D2] is utilized in this study.

Due to stress concentration at the pitting location, the ductility of corroded reinforcement reduces more drastically than its strength. In this study, the empirical equation developed by Du *et al.* (2005) [D3] to calculate the ultimate strain of corroded reinforcement is adopted:

$$\varepsilon_{uc} = (1 - \beta X_{corr}) \varepsilon_{u0} \quad (7.10)$$

where β is the empirical coefficient; $\beta = 0.03$ and $\beta = 0.05$ for a bare bar and a bar embedded in concrete, respectively. **Figure 7.5(c)** indicates an example of modeling of stress-strain relations for un-corroded and corroded reinforcing bars. The Monti-Nuti plasticity model proposed in DIANA (9.4.4) [D1] was also adopted to model the nonlinear cyclic behavior of steel reinforcement including buckling in RC columns under cyclic loading.

7.2.4 Bond-slip model

Three bond-slip models for interface elements between concrete and reinforcement are proposed in DIANA (9.4.4) [D1], namely, cubic model, power law model and multi-linear model which provide a nonlinear relationship between shear traction t_t and shear slip Δu_t , as shown in **Figure 7.6**. In this study, the multi-linear model is adopted to model the bond-slip of the interface elements. The advantage of this model is that it can be used to specify the bond strength at the corresponding slip value, thus rendering it flexible and accurate.

Figure 7.6 Bond shear traction slip curves [D1]

7.2.4.1 Bond strength of corroded reinforcement

Various bond strength deterioration models of corroded reinforcement induced by corrosion are available in literature, as mentioned in **Chapter 2**. In this study, the bond strength model developed by Maaddawy *et al.* (2005) [M2] is utilized to calculate the maximum bond strength of corroded reinforcement. As compared to other empirical bond strength models, some advantages of this model include its ability to take into account the contributions from concrete and stirrup independently and also consider the effect of impressed current density for accelerated corrosion on the bond strength deterioration. In this model, the maximum bond stress of corroded reinforcement $\tau_{\max C}$ can be expressed as follows:

$$\tau_{\max C} = R(0.55 + 0.24 \frac{c_c}{d_b}) \sqrt{f'_c} + 0.191 \frac{A_v f_{yh}}{S d_b} \quad (7.11)$$

$$R = (A_1 + A_2 X_{corr}) \quad (7.12)$$

where R is the empirical factor that predicts the change of bond strength induced by corrosion of reinforcement; A_1 and A_2 are the variables that depend on the current density used for accelerated corrosion, for details see **Chapter 2**.

7.2.4.2 Modified local bond stress-slip model

To take into consideration the influence of corrosion on the local bond behavior, the bond stress-slip model developed in the CEB-FIP (1990) [C4] is utilized and modified as follows:

$$\begin{aligned} \tau &= \tau_{\max C} \left(\frac{s}{s_1} \right)^\alpha && \text{For } 0 \leq s \leq s_1 \\ \tau &= \tau_{\max C} && \text{For } s_1 \leq s \leq s_2 \\ \tau &= \tau_{\max C} - (\tau_{\max C} - \tau_f) \left(\frac{s - s_2}{s_3 - s_2} \right) && \text{For } s_2 \leq s \leq s_3 \\ \tau &= \tau_f && \text{For } s_3 < s \end{aligned} \quad (7.13)$$

The maximum bond stress of corroded reinforcement $\tau_{\max C}$ can be estimated using Eq. (7.11). It is noted that with the generally designed cover concrete thickness and

transverse reinforcement amount, the bond failure in corroded reinforcement is mostly due to splitting [C8]. Therefore, the values of parameters of the modified bond stress-slip model can be chosen as:

$$\alpha = 0.4; s_1 = 0.6mm; s_2 = 0.6mm; s_3 = 2.5mm; \tau_f = 0.15\tau_{\max C} \quad (7.14)$$

Figure 7.5(d) shows an example of the modified bond model for un-corroded and corroded reinforcing bars.

7.3 Validation of Finite Element Models

To estimate the accuracy level of the proposed 3D non-linear FE model, several FE models are built according to experimental data in the current study and literature to compare the FE results with the experimental results. It is noted that the reduction in mechanical properties of corroded reinforcement is estimated based on the equations proposed in [D2], [D3]. The strength reduction of cover cracked concrete is calculated following the procedure presented in previous sections. The maximum bond strength of corroded reinforcement is estimated following the Eq. (7.11) proposed by Maaddawy *et al.* (2005) [M2]. The local bond stress-slip relation proposed by CEB-FIP (1990) [C4] is adopted and modified to take into account the corrosion effect by reducing the maximum bond strength of corroded reinforcement. The comparison of hysteresis loops between FE analyses and the experiment results will be done and the stress contour at the final loading stage will be also plotted to have deeper understanding about the stress distribution in concrete and reinforcement.

7.3.1 Validation of proposed 3D non-linear FE model using the current experimental study

In current experimental study, there are eight RC corroded slender columns in Series 2 and eight RC short columns in Series 3 were tested with various corrosion levels of reinforcement and axial force ratios. The details of all test specimens were presented in **Figure 3.3** and **Figure 3.4**. The summary of properties of test specimens was also tabulated in **Table 3.4** in **Chapter 3**. The material properties of test specimens using in the proposed FE model are indicated in **Table 7.3**. The

following section presents the comparisons between the FE analyses and the experimental results of the current study.

Table 7.3 Material properties of RC column specimens in FE analyses

Specimens	Core concrete		Cover concrete		Longitudinal reinforcement		Transverse reinforcement		$\tau_{\max}$ MPa
	f_c'	f_t'	f_c'	f_t'	f_y / f_u	ϵ_u	f_y / f_u	ϵ_u	
	MPa	MPa	MPa	MPa	MPa/MPa		MPa/MPa		
UC1	32.2	3.0	32.2	3.0	550/635	0.120	300/465	0.200	7.7
CC1	28.8	2.8	24.6	2.4	537/620	0.108	240/372	0.132	5.3
CC2	32.0	3.0	25.6	2.4	524/605	0.099	212/329	0.072	4.6
CC3	27.8	2.8	20.9	2.1	518/598	0.096	210/325	0.043	4.2
UC2	38.1	3.4	38.1	3.4	550/635	0.120	300/465	0.200	8.1
CC4	34.4	3.2	29.9	2.8	529/611	0.108	255/395	0.150	5.7
CC5	31.3	3.0	26.2	2.5	527/609	0.108	234/362	0.127	5.0
CC6	40.0	3.5	32.2	2.8	496/572	0.093	223/346	0.091	4.3
U1	32.2	3.0	32.2	3.0	550/635	0.120	300/465	0.200	7.7
C1	34.4	3.2	29.5	2.7	528/610	0.108	227/352	0.131	5.1
C2	32.0	3.0	27.7	2.6	514/593	0.098	222/344	0.114	4.5
C3	40.0	3.5	29.3	2.6	474/547	0.081	207/320	0.050	3.5
U2	38.1	3.4	38.1	3.4	550/635	0.120	300/465	0.200	8.1
C4	28.8	2.8	23.4	2.3	533/616	0.108	238/369	0.118	5.1
C5	31.3	3.0	25.7	2.4	523/603	0.106	211/327	0.107	4.5
C6	37.5	3.4	28.3	2.5	511/590	0.094	189/293	0.059	4.3

7.3.1.1 FE models of test specimens

Figure 7.7 shows the general meshing of FE models in DIANA (9.4.4) [D1] for both short and slender columns tested in this study while the reinforcement details of these FE models are demonstrated in **Figure 7.8**.

Figure 7.7 Meshing of the finite element models

Figure 7.8 Reinforcement details of the finite element models

7.3.1.2 Hysteretic behavior comparisons

Figure 7.9 and **Figure 7.10** indicate the comparison of hysteresis loops between the numerical analyses and the experimental data for both un-corroded and corroded columns in this current experimental study. It is noted that the experimental results are plotted in dotted lines while the FE results are shown in solid lines. As observed, there is a good correlation in the overall global behavior between the experimental and FE results in terms of the initial stiffness, energy dissipation capacity, lateral load resistance, and ultimate displacement.

Figure 7.9 Comparison of analyzed and experimental hysteresis loops of tested slender columns

Figure 7.10 Comparison of analyzed and experimental hysteresis loops of tested short columns

7.3.1.3 Reinforcement and concrete stress distribution

The stress distributions in concrete and reinforcement at the final stage of cyclic loading of several selected test specimens are presented in **Figure 7.11** through **Figure 7.17**.

Figure 7.11 FE analyses of the un-corroded column UC2 at the final stage of cyclic loading

Figure 7.12 FE analyses of the un-corroded column CC3 at the final stage of cyclic loading

Figure 7.13 FE analyses of corroded column CC4 at the final stage of cyclic loading

Figure 7.14 FE analyses of un-corroded column U2 at the final stage of cyclic loading

Figure 7.15 FE analyses of corroded column C1 at the final stage of cyclic loading

Figure 7.16 FE analyses of corroded column C3 at the final stage of cyclic loading

Figure 7.17 FE analyses of corroded column C5 at the final stage of cyclic loading

7.3.2 FE models validation of test specimens conducted in literature

In this FE validation section, the test specimens conducted by Meda *et al.* (2014) [M9] and Goksu and Ilki (2016) [G1] are also selected to validate the proposed FE

model. Two specimens tested by Meda *et al.* (2014) [M9] have concrete compressive strength of 20 MPa while the yield and ultimate strength of reinforcement are equal to 520 MPa and 620 MPa, respectively. On the other hand, the concrete compressive strength of three specimens conducted by Goksu and Ilki (2016) [G1], including one un-corroded column and two corroded columns, is equal to 25.5 MPa while the yield strength and ultimate strength of longitudinal reinforcement are equal to 460 MPa and 652 MPa, respectively. The yield strength and ultimate strength of 486 MPa and 681 MPa are designed for transverse reinforcement. The details of test specimens were indicated in **Figure 2.7** and **Figure 2.8** in **Chapter 2**. The description of test specimens is indicated in **Table 7.4** while their concrete and reinforcement material properties used in FE analyses are also mentioned in **Table 7.5**.

Table 7.4 Summary of test specimens to validate the proposed FE model in literature

Specimens	b _x h (mm)	L (mm)	Aspect ratio	Longitudinal reinforcement	Transverse reinforcement	Axial force ratio	Corrosion level (%)
UC [M9]	300x300	1800	5.33	4 ϕ 16 $\rho_l = 0.89\%$	ϕ 8@300 $\rho_v = 0.27\%$	0.22	0
CC [M9]							20
NS-X0 [G1]	200x300	1260	5.5	4 ϕ 14 $\rho_l = 1.03\%$	ϕ 8@100 $\rho_v = 1.08\%$	0.18	0
NS-X9 [G1]							9
NS-X16 [G1]							16

Table 7.5 Material properties of test specimens in FE analyses

Specimens	Core		Cover		Longitudinal		Transverse		$\tau_{\max}$ MPa
	concrete		concrete		reinforcement		reinforcement		
	f_c'	f_t'	f_c'	f_t'	f_y / f_u	ϵ_u	f_y / f_u	ϵ_u	
	MPa	MPa	MPa	MPa	MPa/MPa		MPa/MPa		
UC [M9]	20.0	2.21	20.0	2.21	520/620	0.18	520/620	0.18	5.85
CC [M9]	20.0	2.21	10.61	1.17	260/434	0.045			2.30
NS-X0 [G1]	25.5	2.6	25.5	2.6	460/652	0.115	486/681	0.134	9.14
NS-X9 [G1]	25.5	2.6	18.15	1.85	452/640	0.084			7.22
NS-X16 [G1]	25.5	2.6	14.70	1.50	434/615	0.060			5.72

7.3.2.1 FE models of test specimens

Figure 7.18 and **Figure 7.19** demonstrate the numerical modeling of specimens tested by Meda *et al.* (2014) [M9] and Goksu and Ilki (2016) [G1] as single curvature, including the meshing of FE models and steel reinforcement details.

Figure 7.18 FE modeling of specimens conducted by Meda *et al.* (2014) [M9]

Figure 7.19 FE modeling of specimens conducted by Goksu and Ilki (2016) [G1]

7.3.2.2 Hysteretic behavior comparisons

Figure 7.20 and **Figure 7.21** show the comparisons of the hysteresis loop of lateral load versus displacement of un-corroded and corroded RC columns conducted by Meda *et al.* (2014) [M9] and Goksu and Ilki (2016) [G1] in which the FE analyses are shown in the solid lines while the experimental results are indicated in the dotted lines. As observed, the FE results show a relatively good prediction of the seismic behavior of both un-corroded and corroded columns compared with the experimental results.

Figure 7.20 Comparison of analyzed and experimental hysteretic loops of specimens tested by Meda *et al.* (2014) [M9]

Figure 7.21 Comparison of analyzed and experimental hysteresis loops of specimens tested by Goksu and Ilki (2016) [G1]

7.3.2.3 Reinforcement and concrete stress distribution

Figure 7.22 to **Figure 7.26** present the stress contour in reinforcement and concrete of un-corroded and corroded columns tested by Meda *et al.* (2014) [M9] and Goksu and Ilki (2016) [G1] using FE analyses. As illustrated, all the longitudinal reinforcing bars at the critical region, that is plastic hinge region, reached their yield strength and ultimate strength at failure stages. Regarding to the concrete stress contour, as observed, the columns were highly stressed at the end of the simulation after the peak lateral load. Furthermore, the high tension and compression stress have been formed at the regions near the bottom of the column which is in agreement with the observation in the experiment.

Figure 7.22 FE analyses of un-corroded column UC tested by Meda *et al.* (2014) [M9] at the final stage of cyclic loading

Figure 7.23 FE analyses of corroded column CC tested by Meda *et al.* (2014) [M9] at the final stage of cyclic loading

Figure 7.24 FE analyses of un-corroded column X00 tested by Goksu and Ilki (2016) [G1] at the final stage of cyclic loading

Figure 7.25 FE analyses of corroded column X09 tested by Goksu and Ilki (2016) [G1] at the final stage of cyclic loading

Figure 7.26 FE analyses of corroded column X16 tested by Goksu and Ilki (2016) [G1] at the final stage of cyclic loading

7.4 Parametric Studies on Seismic Behavior of RC Columns with Corroded Reinforcement

Adopting the proposed 3D non-linear FE model discussed above, numerical simulations were performed to study the influence of various parameters on the seismic behavior of corroded RC columns, and to further estimate the reduction of their lateral load resistance and ultimate drift ratio capacity. As shown in **Figure 7.27**, the lateral load resistance is corresponding to the maximum lateral load. On the other hand, as common practice in the literature, the ultimate lateral displacement capacity of a RC column can be defined as a displacement value corresponding to the maximum lateral load carrying capacity deteriorates 20% [S5], [S1]. In this study, an extensive parametric study was carried out, including corrosion level, column aspect ratio, axial force ratio, transverse reinforcement ratio, and longitudinal reinforcement ratio. **Table 7.6** tabulates the range of studied parameters. As observed in the experimental results of corrosion measurement, the corrosion level of outer transverse reinforcement is much higher than that of inner transverse reinforcement and longitudinal reinforcement because its distance to the outside environment is smaller and its diameter is also smaller than that of longitudinal reinforcement. For example, the average corrosion level in terms of mass loss of outer transverse reinforcement is higher approximately 2.2, and 4.5 times than that of inner transverse reinforcement and longitudinal reinforcement, respectively. In addition, as mentioned in **Chapter 3**, there is a good correlation between the corrosion level of reinforcement in terms of mass loss and corrosion level in terms of average residual cross sectional area, as well as a high correlation between the corrosion level in terms of mass loss and corrosion level in terms of minimum residual cross sectional area. Hence in this study, for convenience and simplification in demonstration, the corrosion level in terms of mass loss of outer transverse reinforcement is chosen to describe the effect of corrosion level on the seismic behavior of corroded columns. In addition, it is noted that as commonly defined in literature, a short column is dominated by shear failure when its aspect ratio is less than 2.0. On the other hand, a slender column is governed by flexural failure if its aspect ratio is equal or greater than 2.0. The parametric investigation is conducted by analyzing the FE models of 12 RC columns, labeled from Type A to

Type Q, as indicated in **Figure 7.28** to **Figure 7.31**. The specimen configurations in the parametric study are also summarized in **Table 7.7**.

Table 7.6 Parameters study

No.	Notation	Description	Range investigated
1	$X_{corr}(\%)$	Corrosion level of transverse reinforcement in terms of mass loss	0, 10, 20, 30
2	a/d	Aspect ratio	1.25, 1.93, 3.18, 4.38
3	$N/f'_c A_g$	Axial force ratio	0.1, 0.25, 0.35
4	$\rho_v (\%)$	Volumetric transverse reinforcement ratio	1.14, 2.29
5	$\rho_l (\%)$	Longitudinal reinforcement ratio	1.31, 2.05

Table 7.7 Characteristics of the specimens in the parametric study

Series column	Width & depth $b \times h$ mm	Column height L mm	Aspect ratio a/d	Longitudinal reinforcement		Transverse reinforcement	
				ρ_l %	f_{yo} / f_{uo} MPa/MPa	ρ_v %	f_{yo} / f_{uo} MPa/MPa
A	350x350	2450	4.38	2.05	550/635	2.29	300/465
B				1.31		2.29	
C				2.05		1.14	
D				1.31		1.14	
E	350x350	1780	3.18	2.05		2.29	
F				1.31		2.29	
G				2.05		1.14	
H				1.31		1.14	
I	350x350	1080	1.93	2.05		2.29	
J				1.31		2.29	
K				2.05		1.14	
L				1.31		1.14	
M	350x350	700	1.25	2.05		2.29	
N				1.31		2.29	
P				2.05		1.14	
Q				1.31		1.14

Figure 7.27 Lateral load-displacement of RC columns

Figure 7.28 Details of specimens in the parametric study from Type A to Type D

Figure 7.29 Details of specimens in the parametric study from Type E to Type H

Figure 7.30 Details of specimens in the parametric study from Type I to Type L

Figure 7.31 Details of specimens in the parametric study from Type M to Type Q

7.4.1.1 Effect of corrosion level

The 3D non-linear FE analyses for the simulated models subjected to different corrosion levels are presented in this section. **Figure 7.32** and **Figure 7.33** demonstrate the effect of corrosion level on the backbone curve of lateral force-drift ratio relations of corroded short and slender columns in which the corrosion level varies from 0% to 30%. As observed, the higher corrosion level results in the lower lateral load resistance for both short and slender columns and its significant reduction can be seen when the columns are highly corroded. In addition, it is noticed that the corrosion effect on the lateral load resistance deterioration is more critical when the columns are subjected to higher axial force. With regard to the ultimate drift capacity, it appears that higher corrosion level results in the lower

ultimate drift capacity for both short and slender columns. However, this adverse effect is more serious for short columns than slender columns.

Figure 7.32 Influence of corrosion level on the backbone curve of corroded short columns

Figure 7.33 Influence of corrosion level on the backbone curve of corroded slender columns

7.4.1.2 Effect of axial load ratio

It is well-known that the axial force is considered as one of the key parameters in the studies of seismic behavior of RC columns. However, its effect on the corroded columns is still scarcely treated in the literature in terms of both experimental and

analytical studies. In this parametric study program, the axial force ratio varies from 0.1 to 0.35. **Figure 7.34** and **Figure 7.35** indicate that for both short and slender columns, the lateral load resistance of corroded columns rises with an increase in axial force. In contract, the higher axial force causes a more brittle behavior in corroded columns which is more critical for short columns subjected to high corrosion levels.

Figure 7.34 Influence of axial force ratio on the backbone curve of corroded short columns

Figure 7.35 Influence of axial force ratio on the backbone curve of corroded short columns

7.4.1.3 Effect of aspect ratio

In this parametric study scheme, the width and depth of the RC column section are kept constant for all the 3D non-linear FE models. Therefore, an increase in the

aspect ratio refers to an increase of total column height. The influence of aspect ratio on the backbone curves of corroded columns is demonstrated in **Figure 7.36** in which the aspect ratio varies from 1.25 to 1.93, 3.18 and 4.38 to simulate both shear-critical and flexural columns. It is observed that among the 3D non-linear FE models with the same corrosion level, the higher aspect ratio results in the higher ultimate drift capacity. However, the lower lateral load resistance is obtained in those FE models with the higher aspect ratio.

Figure 7.36 Influence of aspect ratio on the backbone curve of corroded RC columns

7.4.1.4 Effect of volumetric transverse reinforcement ratio

Generally, the stirrup amount and distribution play a vital role in improving the strength and ductility capacity of RC columns because of its confinement effect [L6]. **Figure 7.37** and **Figure 7.38** demonstrate the effect of stirrup amount on the performance of corroded RC columns. As observed in short columns subjected to

the same corrosion levels, the volumetric transverse reinforcement ratio significantly influences both the lateral load resistance and ultimate drift capacity of these corroded columns. On the other hand, for the slender columns under the similar corrosion levels, the decrease of volumetric transverse reinforcement ratio only affects the ultimate drift capacity while the lateral load resistance of these slender columns is not affected with the change of volumetric transverse reinforcement ratio.

Figure 7.37 Influence of volumetric transverse reinforcement ratio on the backbone curve of corroded short columns

Figure 7.38 Influence of volumetric transverse reinforcement ratio on the backbone curve of corroded slender columns

7.4.1.5 Effect of longitudinal reinforcement ratio

Figure 7.39 and Figure 7.40 indicate the influence of longitudinal reinforcement ratio on the seismic behavior of corroded short and slender columns. As observed, the increase of longitudinal reinforcement ratio insignificantly affects the lateral load resistance of corroded short columns which are subjected to the similar

corrosion levels. In contrast, for the corroded slender columns with the same corrosion levels, the increase of longitudinal reinforcement ratio results in the increase of lateral load resistance and slightly decrease of ultimate drift capacity of these corroded slender columns.

Figure 7.39 Influence of longitudinal reinforcement ratio on the backbone curve of corroded short columns

Figure 7.40 Influence of longitudinal reinforcement ratio on the backbone curve of corroded slender columns

7.5 Prediction of Lateral Load Resistance and Ultimate Drift Capacity for Corroded RC Columns

7.5.1 Prediction equation of lateral load resistance

The parametric study on 192 FE models was carried out to reveal the significance of several key parameters that influence the lateral load resistance deterioration of corroded RC columns under cyclic loading, particularly corrosion level, column aspect ratio, axial force ratio, volumetric transverse reinforcement ratio, and longitudinal reinforcement ratio. By conducting the regression analysis of the numerical results of 192 FE models, two prediction equations of the lateral load resistance for corroded short columns and slender columns are derived as follows:

$$V_{nC}^{sh} = (1 - 0.7X_{corr}) \left(12.2 + \frac{9.4}{a/d} \right) \left(12.1 + 22.7 \frac{N}{f_c' A_g} + 4.6\rho_v \right) \quad (7.15)$$

$$V_{nC}^{sl} = (1 - 0.5X_{corr}) \left(0.3 + \frac{32.5}{a/d} \right) \left(6.5 + 28.9 \frac{N}{f_c' A_g} + 6.3\rho_l \right) \quad (7.16)$$

where V_{nC}^{sh} , V_{nC}^{sl} are the lateral load resistance of the corroded short column and slender column, respectively; X_{corr} is the corrosion level of transverse reinforcement in terms of mass loss which can be measured based on experiment and real engineering, or predicted using the available corrosion rate models in literature, as mentioned in **Chapter 2**; a/d is aspect ratio of the column; $\frac{N}{f_c' A_g}$ is the applied axial force; ρ_v is the volumetric transverse reinforcement ratio of the column; ρ_l is the longitudinal reinforcement ratio of the column. The average ratio of the lateral load resistance of 192 FE models calculated by FE analyses to their lateral load resistance predicted by adopting Eq. (7.15) and Eq. (7.16) is 0.997 and its standard deviation of 0.062, showing a good correlation between the FE analyses and these prediction equations, as illustrated in **Figure 7.41**.

Figure 7.41 Comparisons of the lateral load resistance of 192 FE models calculated by FE analyses and proposed equations

7.5.2 Prediction equation of ultimate drift capacity

Several studies have proposed drift-based design equations for RC columns in which the effect of the confinement coefficient mainly due to the stirrup amount and distribution, aspect ratio and axial force has been incorporated into these equations [S1], [B4], [T1]. However, the influence of reinforcement corrosion on the ultimate drift capacity deterioration of corroded RC columns has not been well studied. The numerical results mentioned above revealed the significance of several key factors that influence the ultimate drift capacity of corroded RC columns, such as corrosion level, aspect ratio, axial force ratio, transverse reinforcement ratio, and longitudinal reinforcement ratio. Therefore, based on the multivariable regression analysis of numerical results of 192 FE models, the prediction equation of the ultimate drift capacity of corroded RC columns subjected to the simulated seismic loading is proposed as follows:

$$DR_{ultC} = (1 - 0.5X_{corr}) \left(0.2 + 0.6 \frac{a}{d} + 0.2\rho_v - 0.1\rho_l \right) \left(1.4 + \frac{0.1}{\frac{N}{f'_c A_g}} \right) \quad (7.17)$$

where DR_{ultC} is the ultimate drift capacity of the corroded RC column; X_{corr} is the corrosion level of transverse reinforcement in terms of mass loss. The comparison between the FE analyses and the proposed equation produces a good correlation because the average ratio of ultimate drift ratio of 192 FE models calculated by FE analyses to their ultimate drift ratio predicted by adopting Eq. (7.17) is 1.012 and its standard deviation of 0.127, as demonstrated in **Figure 7.42**.

Figure 7.42 Comparisons of the ultimate drift ratio capacity of 192 FE models calculated by FE analyses and proposed equation

7.6 Summary

In this chapter, the influences of reinforcement corrosion on the seismic behavior of RC columns are studied using a 3D non-linear FE approach. The critical parameters influencing the performance of corroded RC columns are investigated and their effects as well as interaction on the lateral load resistance and ultimate drift capacity

of corroded RC columns are quantified, including corrosion level, aspect ratio, axial force ratio, transverse reinforcement ratio, and longitudinal reinforcement ratio. According to the numerical results, some important conclusions can be summarized:

1. A 3D non-linear FE model for corroded RC columns subjected to seismic loading was proposed considering the degradation of corroded materials, including reduction in strength and ductility of unconfined cover concrete, decrease of cross-sectional area, strength and ultimate strain of corroded reinforcement, and bond strength deterioration of corroded reinforcement as well as modification of its local bond behavior.
2. The numerical analyses revealed that the lateral load resistance and ultimate drift capacity of both corroded short columns and slender columns deteriorate when the corrosion level increases. The deterioration is more significant in RC columns subjected to higher corrosion levels and higher axial force.
3. The FE results showed that the lateral load resistance of corroded short columns increases with the increase of axial force ratio and transverse reinforcement ratio. However, it is not significant with the increase of longitudinal reinforcement ratio. In contrast, the lateral load resistance of corroded slender columns significantly increases with the increase of longitudinal reinforcement ratio and axial force ratio. In addition, the change of transverse reinforcement ratio does not affect the lateral load resistance of corroded slender columns when they are subjected to the same corrosion levels. Regarding to the ultimate drift capacity, for both corroded short and slender columns, the ultimate drift capacity decreases with the reduction of aspect ratio, increase of axial force ratio, and decrease in transverse reinforcement ratio. On the other hand, it slightly decreases with the increase of longitudinal reinforcement ratio.
4. Based on an extensive parametric investigation of various key parameters, three prediction equations of the lateral load resistance and ultimate drift capacity of corroded RC columns under the seismic loading were derived from the multivariable regression analysis of the numerical results of 192 FE models.

Chapter 8. CONCLUSIONS AND OUTLOOK FOR FUTURE STUDIES

8.1 Conclusions

Deterioration of reinforced concrete structures in corrosive environments has attracted great attentions in the research community, especially when they are subjected to seismic loading. In this study, the stress-strain relation of confined concrete with different corrosion levels of transverse reinforcement was experimentally investigated. Furthermore, this study contributed to the comprehensive understanding of the seismic response of RC slender columns in corrosive environments, especially the possibility of change of their failure modes due to severe corrosion and high axial forces. In addition, the effect of corrosion on the behavior of corroded short columns which failed in shear was also experimentally investigated in this study. Based on the corrosion measurement results of all test specimens in this study, the good correlations between the total crack width and corrosion levels of transverse reinforcement in terms of mass loss, average residual cross sectional area, and minimum residual cross sectional area were proposed which raises the possibility of seismic assessment for the existing RC structures without destructive testing. Finally, a 3D non-linear FE approach was developed to further study the effects of corrosion on the seismic behavior of corroded columns. The accuracy of the proposed FE model was verified with the experimental results of the specimens in current study and literature. Thereafter, an extensive parametric investigation, consisting of the FE models of 192 RC columns subjected to simulated seismic loading was carried out to study the influence of various crucial parameters on the seismic performance of both corroded slender and short columns, particularly their lateral load resistance and ultimate drift capacity deterioration.

The conclusions are categorized as follows:

8.1.1 Stress-strain relations for corroded confined concrete

The stress-strain relations for confined concrete with corroded transverse reinforcement were investigated through the experimental and analytical studies. The important conclusions can be summarized as follows:

1. Four key parameters of the complete stress-strain relation are significantly affected due to the corrosion of transverse reinforcement, including the maximum concrete strength and corresponding axial concrete strain, maximum concrete strain at the fracture of the first hoops, and descending branch of the stress-strain curve after exceeding the maximum strength.
2. The experimental results showed that the corrosion level and the volumetric ratio of transverse reinforcement were the most important parameters which affected the stress-strain relations of corroded confined concrete. Both strength and ductility of the corroded confined concrete drastically decreased when the corrosion level increased and the volumetric ratio of transverse reinforcement decreased.
3. An analytical stress-strain model for confined concrete with corroded transverse reinforcement was proposed which showed a reasonably good agreement with the experimental data for both circular and square columns subjected to various corrosion levels and compression axial loading.

8.1.2 Reinforced concrete slender columns with corroded reinforcement

The seismic performance of RC slender columns with corroded reinforcement was evaluated through the experimental approach in this study. The following conclusions were determined:

1. Reinforcement corrosion strongly affects the seismic performance of RC slender columns, including the hysteretic response, crack pattern, lateral load resistance, drift capacity, and energy dissipation capacity.
2. It is remarkable to observe the failure mode of corroded columns switched from flexural failure to flexural-shear failure and sudden axial failure when they were highly corroded and subjected to high axial force.
3. An empirical equation to predict the residual flexural strength of corroded columns was proposed which is a function of the maximum pit depth of corroded longitudinal reinforcing bars.

8.1.3 Reinforced concrete short columns with corroded reinforcement

The seismic performance of RC short columns with corroded reinforcement was investigated through the experimental approach in this study. The conclusions were determined as follows:

1. Corroded short columns suffered a significant degradation of shear strength and deformation capacity as compared to un-corroded columns, especially when they are highly corroded and under high axial load ratio.
2. A shear strength assessment for corroded columns was proposed in this study based on the shear strength model suggested in ASCE/SEI 41-13 standard which considered the contribution reductions to the shear strength of transverse reinforcement and concrete due to corrosion.
3. Adopting the proposed shear strength assessment in this study, the shear strength prediction based on the minimum cross-sectional area of transverse reinforcing bars showed good and reliable agreement with the test results, including four corroded slender columns failed in flexural-shear and axial failures in test Series 2 and six corroded short columns failed in shear in test Series 3.

8.1.4 Finite element modeling of reinforced concrete columns with corroded reinforcement

1. A three-dimensional (3D) non-linear finite element for RC columns with corroded reinforcement subjected to seismic loading was proposed in this study, considering the material properties deterioration of reinforcement and concrete induced by corrosion.
2. The numerical analyses revealed that the lateral load resistance and ultimate drift capacity of both corroded short columns and slender columns deteriorate when the corrosion level increases. The deterioration is more significant in RC columns subjected to higher corrosion levels and higher axial force.
3. Three prediction equations of the lateral load resistance and ultimate drift capacity for both corroded slender columns and short columns were proposed based on the multivariable regression analysis of the numerical results of 192 FE models. These simple equations will help the engineers to assess the safety of existing corroded RC columns in earthquake prone regions.

8.2 Recommendation for Future Studies

The research data on RC structure deteriorations due to corrosion of reinforcement is inadequate and comprehensive experimental and analytical investigation are needed to provide better understanding of the behavior of RC structures with corroded reinforcement. Several ideas for further research are summarized as follows:

1. The stress-strain model for confined concrete with corroded transverse reinforcement proposed in current study is applicable for square and circular column sections. On the other hand, the rectangular wall-type and hollow columns section are also commonly used in building and bridge structures. Generally, the confinement effectiveness of these cross-shapes is relatively different from that of square and circular column sections. Therefore, further experimental and analytical studies would be very useful to propose the stress-strain relations of confined concrete for rectangular wall-type and hollow columns section with corroded transverse reinforcement.
2. The experimental program in this study focused on the RC columns in which the transverse reinforcement were designed for seismic zones requirement in accordance with ACI 318-14 standard that is sufficient confining transverse reinforcement in the plastic hinge regions of the columns. In addition, the RC columns were designed to have a concrete compressive strength of 40 MPa which is commonly used in current design. However, there are a number of buildings and bridges in the past which were constructed with low-strength concrete and insufficient transverse reinforcement. These existing structures are vulnerable to damage from corrosion and seismic actions. In the literature, the experimental research about the effects of reinforcement corrosion on the seismic response of these structures is still minimal. Hence, it is noteworthy to conduct further experimental studies about the RC columns with corroded reinforcement which are designed with low-strength and insufficient transverse reinforcement. The experimental data will also provide additional data to further verify the accuracy of the proposed shear strength assessment, the predicted equations of strength and ductility capacity, as well as the 3D on-linear FE model for corroded columns proposed in current study.

3. The axial load values for corroded columns subjected to the simulated seismic loading in the current study were set to be $0.1f'_cA_g$ and $0.25f'_cA_g$. Based on the experimental results, it was concluded that the adverse effects of corrosion on seismic behavior of RC columns were more serious when the columns were subjected to high axial force. Hence, future experimental studies are expected to be carried out with corroded columns subjected to higher axial force levels, those are $0.35f'_cA_g$ and $0.45f'_cA_g$. In addition, all corroded columns in this study were conducted under constant axial force and uniaxial cyclic loading. It would be valuable to conduct the experimental studies on corroded columns subjected to variable axial forces and biaxial cyclic loading.
4. The experimental results of corroded columns in current study can be used as reference data for the future study which should focus on the repair and strengthening methods of corrosion damaged columns to restore the strength and ductility of corroded columns, even more so to increase the seismic performance of these damaged columns due to corrosion.
5. The seismic behavior of RC columns with corroded reinforcement was well investigated in this study and the corroded beams subjected to the seismic loading have been also well studied in literature. In order to have a full understanding of seismic assessment of the whole buildings in corrosive environments, further experimental and analytical studies should be conducted on other structural members under corrosion such as, beam-column joints, shear walls, and reinforced concrete slabs.

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APPENDIX A

A.1 Details of Test Specimens

Test specimens in Series 1

1. Specimens AS, AM and AL: Drawing S1.01
2. Specimens BS, BM and BL: Drawing S1.02
3. Specimens CS, CM and CL: Drawing S1.03

Test specimens in Series 2

4. Specimens U1, U2, C1, C2, C3, C4, C5, C6: Drawing S2.01

Test specimens Series 3

5. Specimens UC1, UC2, CC1, CC2, CC3, CC4, CC5, CC6: Drawing S3.01

A.2 Test Results of Specimens in Series 1

Test Results of Specimens in Series 1

Figure A.1 Observation of Specimen AL0 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.2 Observation of Specimen AL1 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.3 Appearance of some typical corroded transverse reinforcing bars of Specimen AL1 after testing and removing all the rust

Figure A.4 Observation of Specimen AL2 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.5 Appearance of some typical corroded transverse reinforcing bars of Specimen AL2 after testing and removing all the rust

Figure A.6 Observation of Specimen AL3 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.7 Appearance of some typical corroded transverse reinforcing bars of Specimen AL3 after testing and removing all the rust

Figure A.8 Observation of Specimen AM0 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.9 Observation of Specimen AM1 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.10 Appearance of some typical corroded transverse reinforcing bars of specimen AM1 after testing and removing all the rust

Figure A.11 Observation of Specimen AM2 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.12 Appearance of some typical corroded transverse reinforcing bars of Specimen AM2 after testing and removing all the rust

Figure A.13 Observation of Specimen AM3 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.14 Appearance of some typical corroded transverse reinforcing bars of Specimen AM3 after testing and removing all the rust

Figure A.15 Observation of Specimen AS0 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.16 Observation of Specimen AS1 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.17 Appearance of some typical corroded transverse reinforcing bars of Specimen AS1 after testing and removing all the rust

Figure A.18 Observation of Specimen AS2 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.19 Appearance of some typical corroded transverse reinforcing bars of Specimen AS2 after testing and removing all the rust

Figure A.20 Observation of Specimen AS3 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.21 Appearance of some typical corroded transverse reinforcing bars of Specimen AS3 after testing and removing all the rust

Figure A.22 Observation of Specimen BL0 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.23 Observation of Specimen BL1 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Outer Stirrups

Inner Stirrups

Figure A.24 Appearance of some typical corroded transverse reinforcing bars of Specimen BL1 after testing and removing all the rust

Figure A.25 Observation of Specimen BL2 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Outer Stirrups

Inner Stirrups

Figure A.26 Appearance of some typical corroded transverse reinforcing bars of Specimen BL2 after testing and removing all the rust

Figure A.27 Observation of Specimen BL3 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Outer Stirrups

Inner Stirrups

Figure A.28 Appearance of some typical corroded transverse reinforcing bars of Specimen BL3 after testing and removing all the rust

Figure A.29 Observation of Specimen BM0 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.30 Observation of Specimen BM1 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Outer Stirrups

Inner Stirrups

Figure A.31 Appearance of some typical corroded transverse reinforcing bars of Specimen BM1 after testing and removing all the rust

Figure A.32 Observation of Specimen BM2 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Outer Stirrups

Inner Stirrups

Figure A.33 Appearance of some typical corroded transverse reinforcing bars of Specimen BM2 after testing and removing all the rust

Figure A.34 Observation of Specimen BM3 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Outer Stirrups

Inner Stirrups

Figure A.35 Appearance of some typical corroded transverse reinforcing bars of Specimen BM3 after testing and removing all the rust

Figure A.36 Observation of Specimen BS0 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.37 Observation of Specimen BS1 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Outer Stirrups

Inner Stirrups

Figure A.38 Appearance of some typical corroded transverse reinforcing bars of Specimen BS1 after testing and removing all the rust

Figure A.39 Observation of Specimen BS2 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Outer Stirrups

Inner Stirrups

Figure A.40 Appearance of some typical corroded transverse reinforcing bars of Specimen BS2 after testing and removing all the rust

Figure A.41 Observation of Specimen BS3 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Outer Stirrups

Inner Stirrups

Figure A.42 Appearance of some typical corroded transverse reinforcing bars of Specimen BS3 after testing and removing all the rust

Figure A.43 Observation of Specimen CL0 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.44 Observation of Specimen CL1 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.45 Appearance of some typical corroded transverse reinforcing bars of Specimen CL1 after testing and removing all the rust

Figure A.46 Observation of Specimen CL2 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.47 Appearance of some typical corroded transverse reinforcing bars of Specimen CL2 after testing and removing all the rust

Figure A.48 Observation of Specimen CL3 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.49 Appearance of some typical corroded transverse reinforcing bars of Specimen CL3 after testing and removing all the rust

Figure A.50 Observation of Specimen CM0 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.51 Observation of Specimen CM1 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.52 Appearance of some typical corroded transverse reinforcing bars of Specimen CM1 after testing and removing all the rust

Figure A.53 Observation of Specimen CM2 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.54 Appearance of some typical corroded transverse reinforcing bars of Specimen CM2 after testing and removing all the rust

Figure A.55 Observation of Specimen CM3 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.56 Appearance of some typical corroded transverse reinforcing bars of Specimen CM3 after testing and removing all the rust

Figure A.57 Observation of Specimen CS0 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.58 Observation of Specimen CS1 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.59 Appearance of some typical corroded transverse reinforcing bars of Specimen CS1 after testing and removing all the rust

Figure A.60 Observation of Specimen CS2 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.61 Appearance of some typical corroded transverse reinforcing bars of Specimen CS2 after testing and removing all the rust

Figure A.62 Observation of Specimen CS3 at: initial stage, maximum axial load, end of test, and after taking out instrumentation, respectively (from left to right)

Figure A.63 Appearance of some typical corroded transverse reinforcing bars of Specimen CS3 after testing and removing all the rust

APPENDIX B

Test results of specimens in Series 2

Figure B.1 Crack patterns of test Specimen U1 at different drift ratios

Figure B.2 Crack patterns of test Specimen U1 at different drift ratios (Redraw using Autocad software)

Appendix B

Figure B.3 Crack patterns of test Specimen U2 at different drift ratios

Figure B.4 Crack patterns of test Specimen U2 at different drift ratios (Redraw using Autocad software)

Figure B.5 Corrosion induced concrete cover crack of test Specimen C1

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure B.6 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen C1 after testing and removing all the rust

Appendix B

Figure B.7 Crack patterns of test Specimen C1 at different drift ratios

Figure B.8 Crack patterns of test Specimen C1 at different drift ratios (Redraw using Autocad software)

Figure B.9 Corrosion induced concrete cover crack of test specimen C2

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure B.10 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen C2 after testing and removing all the rust

Figure B.11 Crack patterns of test Specimen C2 at different drift ratios

Figure B.12 Crack patterns of test Specimen C2 at different drift ratios (Redraw using Autocad software)

Figure B.13 Corrosion induced concrete cover crack of test Specimen C3

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure B.14 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen C3 after testing and removing all the rust

Figure B.15 Crack patterns of test Specimen C3 at different drift ratios

Figure B.16 Crack patterns of test Specimen C3 at different drift ratios (Redraw using Autocad software)

Figure B.17 Corrosion induced concrete cover crack of test Specimen C4

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure B.18 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen C4 after testing and removing all the rust

Figure B.19 Crack patterns of test Specimen C4 at different drift ratios

Figure B.20 Crack patterns of test Specimen C4 at different drift ratios (Redraw using Autocad software)

Figure B.21 Corrosion induced concrete cover crack of test Specimen C5

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure B.22 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen C5 after testing and removing all the rust

Figure B.23 Crack patterns of test Specimen C5 at different drift ratios

Figure B.24 Crack patterns of test Specimen C5 at different drift ratios (Redraw using Autocad software)

Figure B.25 Corrosion induced concrete cover crack of test Specimen C6

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure B.26 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen C6 after testing and removing all the rust

Figure B.27 Crack patterns of test Specimen C6 at different drift ratios

Figure B.28 Crack patterns of test Specimen C6 at different drift ratios (Redraw using Autocad software)

APPENDIX C

Test results of specimens in Series 3

Figure C.1 Crack patterns of test Specimen UC1 at different drift ratios

Figure C.2 Crack patterns of test Specimen UC1 at different drift ratios (Redraw using Autocad software)

Figure C.3 Crack patterns of test Specimen UC2 at different drift ratios

Figure C.4 Crack patterns of test Specimen UC2 at different drift ratios (Redraw using Autocad software)

Figure C.5 Corrosion induced concrete cover crack of test Specimen CC1

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure C.6 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen CC1 after testing and removing all the rust

Figure C.7 Crack patterns of test Specimen CC1 at different drift ratios

Figure C.8 Crack patterns of test Specimen CC1 at different drift ratios (Redraw using Autocad software)

Figure C.9 Corrosion induced concrete cover crack of test Specimen CC2

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure C.10 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen CC2 after testing and removing all the rust

Figure C.11 Crack patterns of test Specimen CC2 at different drift ratios

Figure C.12 Crack patterns of test Specimen CC2 at different drift ratios (Redraw using Autocad software)

Figure C.13 Corrosion induced concrete cover crack of test Specimen CC3

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure C.14 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen CC3 after testing and removing all the rust

Figure C.15 Crack patterns of test Specimen CC3 at different drift ratios

Figure C.16 Crack patterns of test Specimen CC3 at different drift ratios (Redraw using Autocad software)

Figure C.17 Corrosion induced concrete cover crack of test Specimen CC4

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure C.18 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen CC4 after testing and removing all the rust

Figure C.19 Crack patterns of test Specimen CC4 at different drift ratios

Figure C.20 Crack patterns of test Specimen CC4 at different drift ratios (Redraw using Autocad software)

Figure C.21 Corrosion induced concrete cover crack of test Specimen CC5

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure C.22 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen CC5 after testing and removing all the rust

Figure C.23 Crack patterns of test Specimen CC5 at different drift ratios

Figure C.24 Crack patterns of test Specimen CC5 at different drift ratios (Redraw using Autocad software)

Figure C.25 Corrosion induced concrete cover crack of test Specimen CC6

Notes: The East-West is the lateral loading direction; Dimensions in mm.

Figure C.26 Appearance of some typical corroded transverse and longitudinal reinforcing bars of test Specimen CC6 after testing and removing all the rust

Figure C.27 Crack patterns of test Specimen CC6 at different drift ratios

Figure C.28 Crack patterns of test Specimen CC6 at different drift ratios (Redraw using Autocad software)

APPENDIX D

Figure D.1 Labelling and Measurement of corrosion levels for test specimens in Series 1

Table D.1 Corrosion measurement of transverse reinforcing bars for test specimens in Series 1

Specimen	No.	W0	W1	R1	R2	R3	R4	R5	R6	R7	R8	$X_{corr}^{(1)}$	$X_{corr}^{(2)}$	$X_{corr}^{(3)}$
		g	g	mm	mm	mm	mm	mm	mm	mm	mm	%	%	%
AL1	D4	174.00	164.85	5.31	5.68	5.85	5.54	5.79	5.77	5.73	5.90	5.26	9.87	21.68
	D5	174.00	165.12	5.27	5.94	5.69	5.54	5.02	5.94	5.78	5.97	5.10	11.52	30.00
	D6	174.00	164.37	5.11	5.36	5.75	5.15	5.57	5.43	5.90	5.57	5.54	16.58	27.47
	D7	174.00	166.37	5.89	5.85	5.57	5.90	5.81	5.83	5.74	5.78	4.39	6.68	13.82
	D8	174.00	165.51	5.67	5.56	5.80	4.98	5.78	5.93	5.37	5.84	4.88	12.38	31.11
	D9	174.00	167.24	5.80	5.60	5.91	5.55	5.91	5.00	5.59	5.91	3.88	11.05	30.56
	D10	174.00	165.42	5.86	5.64	5.90	5.62	5.96	5.78	5.75	5.71	4.93	7.28	12.27
Average												4.85	10.77	23.84
AL2	D4	174.00	155.10	5.17	5.85	4.92	5.80	5.59	5.94	5.00	4.73	10.86	19.75	37.85
	D5	174.00	156.47	5.50	5.95	4.84	4.87	5.22	5.85	5.07	5.82	10.07	19.30	34.93
	D6	174.00	156.44	5.15	5.44	4.82	5.51	5.88	5.52	4.99	5.63	10.09	19.97	35.47
	D7	174.00	158.86	4.71	5.60	5.72	5.80	5.56	5.86	4.91	5.73	8.70	16.39	38.38
	D8	174.00	158.31	5.15	5.82	5.25	5.71	5.10	5.87	5.56	4.92	9.02	18.32	32.76
	D9	174.00	158.14	4.51	6.00	5.32	5.71	5.55	5.90	5.20	4.54	9.12	20.75	43.50
	D10	174.00	155.58	5.40	5.69	4.81	5.71	5.75	5.06	5.43	5.58	10.59	18.14	35.73
Average												9.78	18.95	36.95
AL3	D4	174.00	147.29	5.05	5.71	4.54	5.02	5.23	5.65	5.67	5.15	15.35	23.36	42.75
	D5	174.00	141.29	5.20	5.67	5.59	5.04	4.56	5.50	5.60	3.49	18.80	28.28	66.17
	D6	174.00	142.91	*	4.12	5.34	5.10	4.71	5.49	4.36	5.39	17.87	32.49	52.85
	D7	174.00	147.26	5.05	5.55	5.20	5.63	4.46	4.67	4.30	5.64	15.37	28.81	48.64
	D8	174.00	142.80	4.29	5.45	4.87	5.42	4.91	5.02	3.41	5.97	17.93	32.83	67.70
	D9	174.00	141.69	4.44	4.84	4.63	5.28	4.98	4.50	4.42	4.62	18.57	38.28	45.73

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AL3	D10	174.00	141.68	5.45	4.95	5.80	5.45	4.85	4.15	4.45	4.75	18.57	31.08	52.16
	Average											17.49	30.73	53.71
AM1	D4	179.34	166.79	6.00	5.67	5.98	5.83	5.75	5.93	5.87	5.94	7.00	4.25	10.70
	D5	180.00	165.98	5.99	5.79	5.95	5.93	5.68	6.00	5.71	5.89	7.79	4.37	10.38
	D6	179.34	165.54	5.95	5.78	6.00	5.44	5.79	5.89	5.92	5.98	7.69	5.14	17.80
	D7	179.12	164.49	5.95	5.62	5.89	5.97	5.99	5.67	5.99	5.88	8.17	4.29	12.27
	D8	180.67	167.12	5.71	5.87	5.81	5.68	5.90	5.83	5.66	5.86	7.50	6.88	11.01
	D9	180.23	169.58	5.83	5.91	5.90	5.86	5.74	5.98	5.14	5.69	5.91	7.96	26.61
	D10	179.12	166.55	5.98	5.45	5.96	5.60	5.88	6.00	5.70	5.22	7.02	9.00	24.31
	D11	179.56	166.00	5.92	5.97	5.48	5.89	5.80	5.96	5.93	5.98	7.55	4.41	16.58
	D12	179.56	163.11	5.15	5.83	6.00	5.71	5.66	5.94	5.90	6.00	9.16	7.40	26.33
	D13	178.89	159.98	6.00	5.84	6.00	5.00	5.80	5.83	5.41	5.43	10.57	10.89	30.56
	D14	179.34	161.92	5.87	5.73	5.49	5.96	5.33	5.96	6.00	5.51	9.71	8.76	21.09
Average											8.01	6.67	18.88	
AM2	D4	179.34	162.96	6.00	5.82	5.95	5.53	5.66	5.76	5.51	5.72	9.13	8.36	15.67
	D5	178.89	161.11	6.00	5.40	5.68	5.71	4.90	4.65	5.94	4.82	9.94	19.37	39.94
	D6	179.34	153.09	5.99	5.69	4.61	5.53	5.69	5.68	5.12	3.54	14.64	23.98	65.19
	D7	178.89	153.81	5.88	5.25	5.57	4.81	4.26	5.81	6.00	5.15	14.02	20.75	49.59
	D8	179.12	155.09	5.77	5.21	5.35	4.96	5.58	4.60	5.50	5.97	13.41	19.97	41.22
	D9	179.78	157.98	5.87	4.92	5.48	5.44	5.65	5.26	5.18	5.71	12.13	17.83	32.76
	D10	179.12	159.73	6.00	5.79	5.34	5.61	5.38	5.61	5.91	5.62	10.82	11.09	20.79
	D11	179.34	154.68	5.75	5.31	4.84	5.78	5.76	5.44	5.62	5.58	13.75	15.67	34.93
	D12	179.34	154.41	5.53	4.92	5.62	5.37	5.71	4.81	5.49	5.48	13.90	20.01	35.73
	D13	179.56	156.18	5.90	5.54	5.82	5.89	5.54	5.10	5.00	5.04	13.02	16.62	30.56

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AM2												Average	12.48	17.37	36.64
AM3	D4	166.91	137.27	4.40	5.90	2.94	3.80	5.65	3.89	4.95	*	17.76	43.64	75.99	
	D5	175.34	136.20	5.94	4.83	3.06	5.67	4.70	4.32	1.97	5.31	22.32	44.37	89.22	
	D6	179.78	143.62	2.52	4.91	4.27	5.98	2.57	2.71	4.95	6.00	20.11	50.09	82.36	
	D7	181.34	136.07	5.10	3.39	3.45	5.99	4.57	2.79	3.96	5.18	24.96	48.55	78.38	
	D8	182.67	121.53	6.00	5.04	4.02	3.55	5.67	2.07	2.83	1.57	33.47	58.96	93.15	
	D9	177.12	146.69	3.08	5.15	5.78	5.59	6.00	4.52	4.95	3.34	17.18	35.97	73.65	
	D10	176.90	145.01	5.51	4.94	4.86	5.85	4.67	5.34	5.47	5.97	18.03	21.20	39.42	
	D11	180.23	140.75	5.48	5.55	5.22	4.00	4.41	5.75	3.94	3.44	21.90	38.02	67.13	
	D12	156.26	126.91	5.98	3.64	4.08	5.84	5.72	4.31	5.75	*	18.78	29.28	63.20	
Average												21.61	41.12	73.61	
AS1	D4	175.34	154.83	5.99	5.42	4.88	3.85	5.81	5.74	6.00	5.58	11.70	18.74	58.83	
	D5	175.79	159.72	5.77	5.55	5.92	6.00	5.90	5.96	5.83	5.12	9.14	7.96	27.18	
	D6	174.23	157.23	5.77	5.76	5.82	4.47	4.79	5.40	5.68	5.95	9.76	17.34	44.50	
	D7	175.79	161.57	5.79	5.85	5.96	6.00	5.97	5.42	5.85	4.87	8.09	9.31	34.12	
	D8	174.68	160.95	6.00	5.89	5.71	5.60	5.69	5.82	5.86	5.92	7.86	6.19	12.89	
	D9	175.79	160.40	5.72	5.75	5.82	5.81	5.88	5.73	5.60	4.46	8.76	13.01	44.75	
	D10	176.01	160.85	5.93	5.65	5.71	5.96	4.82	6.00	5.80	5.87	8.61	9.19	35.47	
	D11	177.56	160.87	5.71	4.90	5.58	5.29	5.89	5.90	5.60	5.89	9.40	13.04	33.31	
	D12	179.34	161.61	4.55	5.96	5.72	5.89	5.48	3.73	5.25	5.56	9.89	22.93	61.35	
	D13	176.68	160.12	5.87	5.85	5.77	5.82	5.79	5.59	5.03	5.58	9.37	10.93	29.72	
	D14	179.56	162.44	5.88	5.72	5.36	4.67	5.46	5.83	5.89	5.96	9.54	13.01	39.42	
	D15	175.12	161.88	5.84	5.87	5.89	5.85	5.89	5.59	5.64	4.45	7.56	12.03	44.99	

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AS1	D16	180.23	163.13	5.90	5.63	5.57	5.26	5.45	4.78	5.71	5.98	9.48	14.90	36.53
	D17	176.45	160.67	5.77	5.44	5.69	5.85	5.44	5.87	5.50	5.91	8.95	10.26	17.80
	D18	176.45	161.04	5.75	5.69	3.68	5.30	5.49	5.56	5.82	5.86	8.74	19.19	62.38
	D19	176.23	157.44	5.83	5.67	5.82	5.87	5.40	5.76	5.65	3.84	10.66	16.58	59.04
	D20	174.68	150.10	5.83	5.92	5.14	5.76	5.46	3.51	5.56	5.65	14.07	20.38	65.78
Average											9.50	13.82	41.65	
AS2	D4	176.45	151.67	6.00	6.00	5.29	6.00	5.66	4.75	6.00	5.85	14.05	9.95	37.33
	D5	176.45	146.32	6.00	3.97	6.00	6.00	6.00	6.00	6.00	4.67	17.08	13.51	56.22
	D6	176.45	145.53	6.00	5.58	6.00	5.05	5.99	5.87	5.47	6.00	17.52	8.32	29.16
	D7	141.61	118.95	6.00	5.94	6.00	5.74	6.00	6.00	6.00	3.60	16.00	11.01	64.00
	D8	177.56	146.31	5.95	6.00	6.00	5.16	5.44	3.89	3.78	6.00	17.60	22.63	60.31
	D9	174.46	144.01	5.23	2.40	5.47	4.98	6.00	6.00	2.97	5.34	17.45	36.03	84.00
	D10	175.34	144.82	6.00	6.00	6.00	5.55	5.78	*	5.91	5.58	17.41	5.54	14.44
	D11	148.71	121.95	6.00	5.87	4.36	6.00	6.00	6.00	6.00	4.40	17.99	13.55	47.20
	D12	110.09	90.35	5.83	6.00	5.56	3.69	5.90	4.24	*	*	17.93	24.79	62.18
	D13	175.34	150.47	5.97	3.83	6.00	6.00	6.00	6.00	5.65	6.00	14.19	10.34	59.25
	D14	176.45	144.19	6.00	5.76	5.38	5.86	6.00	3.29	5.57	6.00	18.28	16.51	69.93
	D15	176.45	147.59	6.00	6.00	5.99	6.00	6.00	6.00	6.00	3.76	16.36	9.16	60.73
	D16	176.45	148.14	6.00	6.00	6.00	4.37	5.93	5.30	5.02	6.00	16.05	13.59	46.95
	D17	176.45	148.90	6.00	6.00	5.80	6.00	5.95	5.94	6.00	3.16	15.61	12.69	72.26
	D18	175.34	145.67	6.00	6.00	6.00	5.61	5.82	3.27	6.00	6.00	16.92	13.28	70.30
	D19	176.45	147.38	6.00	5.81	4.84	6.00	6.00	5.97	6.00	4.86	16.48	10.22	34.93
	D20	176.45	147.36	6.00	5.73	5.79	4.77	5.75	5.87	5.22	6.00	16.49	11.60	36.80
Average											16.67	14.28	53.29	
AS3	D4	75.02	57.96	5.89	5.48	4.91	1.54	*	*	*	*	31.61	44.87	93.41

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AS3	D5	94.55	80.71	5.75	5.93	5.86	6.00	5.94	3.28	*	*	20.35	17.19	70.12
	D6	65.70	53.98	5.98	5.29	5.87	1.70	*	*	*	*	24.79	38.38	91.97
	D7	149.82	119.04	5.29	2.22	5.13	6.00	6.00	5.92	5.79	2.63	28.56	34.05	86.31
	D8	71.47	56.64	6.00	5.27	5.72	2.56	*	*	*	*	28.84	33.65	81.80
	D9	111.64	90.66	*	1.85	5.82	6.00	5.92	5.74	5.99	2.71	26.12	34.35	90.49
	D10	133.84	112.67	6.00	5.73	5.99	4.04	*	2.58	6.00	6.00	21.98	25.14	81.51
	D11	142.05	116.39	5.69	4.13	5.93	5.86	6.00	6.00	5.76	3.75	25.11	19.30	60.94
	D12	172.90	143.59	6.00	5.73	5.99	2.93	5.67	5.83	5.31	6.00	23.56	18.02	76.15
	D13	174.68	143.83	5.87	4.42	5.97	5.73	6.00	5.74	6.00	5.26	24.55	12.15	45.73
	D14	175.34	145.27	6.00	4.70	5.34	3.81	5.42	3.52	6.00	5.76	23.84	28.63	65.58
	D15	174.68	145.18	2.58	3.78	5.49	5.07	6.08	5.77	6.00	5.53	23.47	29.51	81.51
	D16	176.45	145.87	5.99	5.82	5.82	2.46	5.48	4.77	6.00	5.90	24.26	22.56	83.19
	D17	139.39	115.72	4.97	5.26	4.61	6.00	6.00	5.36	6.00	3.17	23.77	25.72	72.09
BL1	D18	175.12	146.59	5.95	4.58	6.00	2.83	5.08	4.86	5.97	5.88	22.81	26.51	77.75
	D19	176.01	145.13	6.00	5.57	5.36	6.00	6.00	5.37	6.00	1.97	24.56	22.45	89.22
	D20	176.45	143.18	5.99	5.84	6.00	3.86	5.27	5.42	4.77	5.90	26.40	19.56	58.61
	Average											24.98	26.59	76.85
	D4	177.34	159.67	5.00	4.81	5.39	5.30	5.91	5.64	5.98	6.00	9.97	15.86	35.73
	D5	174.90	158.12	5.43	5.91	4.52	4.16	6.00	6.00	6.00	4.65	9.59	20.98	51.93
	D6	175.79	159.85	5.41	5.97	5.83	5.53	5.92	5.94	5.86	4.53	9.07	12.15	43.00
	D7	176.45	161.83	6.00	5.10	5.85	5.42	5.95	4.74	5.88	5.45	8.29	14.48	37.59
	D8	176.01	164.42	5.81	6.00	6.00	5.74	5.70	5.81	6.00	6.00	6.58	3.88	9.75
	D9	175.79	162.79	5.85	6.00	5.43	5.39	5.74	6.00	5.98	5.53	7.39	8.48	19.30
	D10	176.45	157.70	5.97	3.47	4.40	5.76	5.68	5.79	6.00	6.00	10.63	19.49	66.55
	V4	148.04	138.46	6.00	5.96	6.00	6.00	5.93	6.00	5.48	5.61	6.47	4.20	16.58
	V5	138.28	128.40	5.44	5.95	4.52	6.00	6.00	6.00	5.12	6.00	7.14	11.99	43.25

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BL1	V6	138.72	130.22	5.98	5.90	5.82	5.99	6.00	5.98	5.04	6.00	6.13	5.30	29.44
	V7	138.06	129.85	5.97	5.96	5.55	5.92	6.00	5.95	5.93	5.98	5.94	3.06	14.44
	V8	137.83	129.45	5.98	5.92	4.98	5.98	6.00	6.00	5.68	5.97	6.08	6.11	31.11
	V9	138.50	128.14	5.92	5.94	4.10	6.00	6.00	5.88	3.81	5.92	7.48	17.61	59.68
	V10	138.72	129.98	6.00	5.92	4.94	5.93	5.83	5.98	5.88	6.00	6.30	6.23	32.21
Average												7.65	10.70	35.04
BL2	D4	176.23	149.45	5.94	5.85	5.94	5.98	3.95	4.94	5.60	3.75	15.19	23.62	60.94
	D5	170.90	146.20	5.87	4.32	5.96	6.00	3.87	4.25	5.53	5.01	14.45	27.71	58.40
	D6	93.89	84.85	6.00	5.30	5.77	5.88	4.47	*	*	*	9.62	16.46	44.50
	D7	155.81	131.60	2.58	5.91	5.90	5.75	5.81	5.42	5.22	4.29	15.54	27.47	81.51
	D8	175.34	151.56	5.40	3.75	5.38	5.09	5.61	5.56	5.71	5.84	13.56	22.19	60.94
	D9	105.65	93.71	5.56	5.81	5.88	5.90	4.94	3.37	*	*	11.30	23.63	68.45
	D10	175.79	154.30	5.65	3.84	5.53	5.79	5.71	5.61	5.88	5.89	12.22	16.35	59.04
	V4	139.16	128.70	5.97	6.00	5.95	6.00	4.86	6.00	3.47	6.00	7.52	15.01	66.55
	V5	138.06	126.68	6.00	5.97	2.30	6.00	3.17	6.00	5.88	5.34	8.24	28.24	85.31
	V6	137.61	128.36	5.91	5.96	4.65	5.95	5.53	6.00	5.69	5.91	6.72	9.75	39.94
	V7	135.17	118.50	4.86	5.85	6.00	5.91	5.91	5.85	2.42	5.88	12.33	20.94	83.73
	V8	137.83	129.90	5.90	5.96	6.00	6.00	5.95	5.96	4.79	5.96	5.76	6.07	36.27
	V9	138.94	131.21	6.00	6.00	5.85	6.00	6.00	5.95	4.19	6.00	5.57	8.20	51.23
	V10	138.50	130.23	5.65	6.00	4.59	5.98	6.00	6.00	5.79	6.00	5.97	8.12	41.48
Average												10.29	18.13	59.88
BL3	D4	175.34	150.22	5.68	5.60	5.60	5.78	5.77	5.65	5.60	4.03	14.33	17.08	54.89
	D5	175.57	147.51	5.79	3.55	5.68	5.06	5.69	5.96	5.60	5.80	15.98	19.26	64.99
	D6	176.45	146.15	5.80	4.47	5.92	3.98	5.27	5.71	5.94	5.91	17.17	19.75	56.00
	D7	158.03	127.05	2.89	5.76	5.87	5.76	5.70	5.29	5.13	4.61	19.61	27.00	76.80
	D8	177.34	144.76	5.73	5.64	5.66	3.44	2.01	5.74	5.81	5.93	18.37	30.69	88.78

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BL3	D9	150.93	125.30	2.64	5.91	5.60	5.99	5.93	5.65	5.60	3.57	16.98	27.43	80.64
	D10	174.68	141.27	5.60	5.98	5.65	2.76	2.36	4.96	5.98	5.62	19.12	34.29	84.53
	V4	142.05	133.49	5.60	5.86	5.23	5.90	5.72	5.60	5.60	5.60	6.03	11.68	24.02
	V5	137.83	129.16	5.92	5.98	4.32	5.97	5.96	5.89	5.99	5.60	6.29	9.63	48.16
	V6	139.61	127.94	5.60	5.98	5.84	5.60	2.57	5.90	5.13	5.87	8.36	21.64	81.65
	V7	139.39	129.75	4.83	5.83	5.04	5.60	5.88	5.96	5.60	5.60	6.91	14.67	35.20
	V8	141.16	128.81	5.91	5.92	5.78	5.98	3.71	5.95	5.49	5.86	8.75	13.66	61.77
	V9	137.39	125.65	4.57	5.98	5.51	5.60	5.60	5.90	5.29	5.93	8.54	14.51	41.99
	V10	138.28	129.58	5.60	5.60	5.60	5.95	5.22	5.60	5.96	5.93	6.29	10.30	24.31
	Average											12.34	19.40	58.84
BM1	D4	178.67	170.78	6.00	5.99	5.98	5.91	5.84	5.94	5.93	5.90	4.42	2.11	5.26
	D5	179.12	169.29	5.88	6.00	5.98	5.99	6.00	5.92	5.77	6.00	5.49	1.91	7.52
	D6	179.56	171.92	6.00	5.99	5.93	5.84	5.76	6.00	5.96	5.71	4.26	3.35	9.43
	D7	179.12	171.36	6.00	6.00	5.71	5.82	5.87	6.00	5.83	6.00	4.33	3.18	9.43
	D8	179.56	169.94	5.88	5.91	5.98	5.63	5.74	5.96	5.93	5.84	5.36	4.65	11.95
	D9	179.12	169.13	5.98	5.84	5.95	5.99	5.29	4.87	5.79	5.97	5.58	9.43	34.12
	D10	178.89	168.86	5.95	5.86	6.00	5.92	5.91	6.00	5.62	5.74	5.61	4.12	12.27
	D11	178.67	167.85	5.85	5.74	4.62	5.91	5.72	5.87	5.84	5.80	6.06	10.74	40.71
	D12	179.78	168.68	5.87	5.94	5.82	5.97	5.88	5.96	5.94	5.53	6.18	4.49	15.05
	D13	179.78	165.55	5.81	5.09	5.71	5.94	5.77	5.62	5.21	5.78	7.92	12.38	28.03
	D14	180.23	169.15	6.00	5.70	6.00	5.92	5.94	5.88	5.94	5.89	6.15	3.02	9.75
	V4	139.61	132.56	5.94	5.93	5.96	5.86	5.87	5.92	5.98	5.91	5.05	2.61	4.61
	V5	139.16	131.29	5.68	5.92	6.00	5.91	5.58	5.95	5.97	5.88	5.66	4.57	13.51
	V6	139.39	131.32	5.87	5.96	5.88	5.88	5.71	5.92	5.93	5.86	5.79	4.08	9.43
	V7	139.16	131.32	5.71	5.91	5.87	5.90	5.59	5.92	5.86	5.93	5.64	5.38	13.20
	V8	138.94	131.29	5.76	5.88	5.85	5.85	5.88	5.92	5.87	5.89	5.51	4.53	7.84

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BM1	V9	139.83	132.56	5.36	5.91	5.76	5.90	5.08	5.91	5.62	5.89	5.20	10.42	28.32
	V10	139.83	131.30	5.71	5.91	5.97	5.88	4.75	5.87	5.44	5.81	6.10	10.78	37.33
	V11	140.27	133.39	5.83	5.89	5.88	5.91	5.44	5.90	5.80	5.91	4.91	5.91	17.80
	V12	140.05	131.83	5.48	5.92	5.93	5.88	5.27	5.86	6.00	5.91	5.87	7.16	22.85
	V13	140.50	133.79	4.96	6.00	5.88	6.00	5.58	6.00	5.97	5.94	4.77	6.84	31.66
Average											5.57	5.90	17.56	
BM2	D4	179.78	164.96	5.89	5.92	5.93	5.86	5.85	5.31	5.87	5.85	8.24	6.23	21.68
	D5	179.34	160.79	4.75	4.16	5.75	5.82	5.95	5.05	5.12	5.56	10.34	22.85	51.93
	D6	179.56	160.37	6.00	4.45	5.37	5.72	5.82	5.81	5.79	6.00	10.69	12.27	44.99
	D7	180.00	158.68	6.00	5.82	5.83	5.50	5.72	5.63	5.74	4.77	11.85	12.07	36.80
	D8	179.56	158.73	5.86	5.62	5.78	5.34	5.27	5.92	5.03	4.17	11.60	19.79	51.70
	D9	180.45	153.16	6.00	3.28	5.09	5.81	3.44	3.33	5.97	6.00	15.12	34.25	70.12
	D10	179.78	157.59	5.70	5.34	4.28	4.80	5.93	5.87	5.98	5.12	12.34	19.67	49.12
	D11	179.34	156.66	5.49	5.91	5.72	4.37	4.34	5.44	5.03	4.37	12.65	28.21	47.68
	D12	122.96	104.39	3.16	5.56	6.00	5.34	5.69	4.07	3.05	*	15.10	38.75	74.16
	D13	202.87	173.39	5.44	5.87	5.98	2.93	5.92	5.86	5.78	4.20	14.53	23.51	76.15
	D14	179.34	146.78	6.00	5.62	3.55	2.21	4.50	5.61	3.18	5.82	18.15	42.21	86.43
	V4	138.28	128.59	5.66	6.00	5.81	6.00	5.49	5.92	5.84	5.77	7.01	6.19	16.28
	V5	138.72	129.53	5.29	5.84	4.56	6.00	6.00	5.91	3.07	5.98	6.63	21.05	73.82
	V6	138.06	129.79	5.25	6.00	6.00	6.00	5.73	5.96	6.00	5.94	5.99	4.61	23.44
	V7	139.39	126.65	5.71	5.94	5.84	5.87	6.00	5.87	5.97	5.96	9.14	3.47	9.43
	V8	138.50	129.71	6.00	5.90	4.80	5.80	5.77	5.82	4.23	5.93	6.35	15.01	50.30
	V9	137.61	128.65	6.00	5.93	6.00	5.91	5.89	6.00	6.00	0.05	6.51	24.24	99.99
	V10	138.06	129.45	5.49	5.89	5.92	5.94	5.54	5.86	6.00	5.85	6.23	6.19	16.28
	V11	139.16	128.84	6.00	5.98	5.21	6.00	6.00	6.00	4.99	5.84	7.42	8.08	30.83
	V12	139.16	134.96	4.71	6.00	5.83	5.89	4.15	5.93	5.97	5.91	3.02	14.48	52.16

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BM2	V13	142.27	130.60	6.00	5.89	5.96	5.99	4.34	6.00	6.00	5.93	8.20	7.72	47.68
	V14	140.27	124.18	5.64	5.98	5.91	6.00	*	5.94	5.87	5.17	11.47	6.97	25.75
	Average											10.03	17.33	48.68
BM3	D4	179.12	147.82	5.38	5.85	5.76	4.56	5.91	5.68	5.84	5.62	17.47	13.66	42.24
	D5	134.73	111.58	2.34	4.37	4.82	2.74	5.65	5.67	5.20	3.43	17.18	49.17	84.79
	D6	151.37	121.84	1.39	4.85	5.53	3.32	5.91	6.00	5.93	2.74	19.51	44.79	94.63
	D7	179.78	133.03	2.18	4.51	5.72	5.87	5.48	1.86	3.78	2.42	26.00	56.05	90.39
	D8	141.38	120.79	5.94	5.67	5.95	3.72	5.68	5.35	5.33	*	14.57	19.68	61.56
	D9	179.34	147.16	5.39	6.00	5.73	3.38	4.55	5.02	2.14	2.12	17.94	48.85	87.52
	D10	147.60	120.67	4.78	5.00	4.23	4.27	5.89	5.38	5.28	3.48	18.24	36.30	66.36
	D11	152.04	125.76	5.20	5.74	5.81	4.66	5.67	5.89	5.36	2.58	17.28	27.36	81.51
	D12	143.60	121.15	4.89	5.75	5.34	2.39	5.10	5.46	5.77	1.58	15.64	42.87	93.07
	D13	180.00	141.49	5.40	1.23	3.28	5.77	2.88	2.01	5.68	6.00	21.40	54.86	95.80
	V4	140.72	129.56	2.80	5.81	5.05	5.66	4.59	6.00	6.00	5.84	7.93	24.35	78.22
	V5	139.61	127.18	4.36	5.70	5.21	6.00	3.39	6.00	5.52	6.00	8.90	22.78	68.08
	V6	138.28	125.42	2.64	5.52	5.27	5.93	3.17	5.95	5.56	5.76	9.30	31.25	80.64
	V7	139.39	129.40	2.95	5.83	6.00	5.95	5.84	6.00	5.54	5.99	7.16	15.59	75.83
	V8	139.83	127.80	4.37	5.94	5.80	5.60	2.80	5.90	5.99	5.41	8.60	24.13	78.22
	V9	138.28	126.37	4.57	5.92	5.86	5.97	3.72	5.64	5.41	5.95	8.61	19.60	61.56
	V10	140.05	129.61	5.72	5.83	5.74	5.76	5.86	5.88	5.74	6.00	7.46	6.03	9.12
	V11	126.96	116.18	2.98	5.83	5.47	6.00	4.38	5.83	5.91	5.99	8.49	22.01	75.33
	V12	139.61	129.19	3.95	5.88	5.78	5.91	3.25	5.96	5.88	5.62	7.46	22.60	70.66
	V13	137.61	124.93	4.59	6.00	5.95	5.93	1.33	6.00	5.81	5.65	9.22	26.11	95.09
	Average											13.42	30.40	74.53
BS1	D4	142.05	114.90	5.64	5.45	5.59	5.23	5.67	3.36	2.44	*	19.11	36.84	83.46

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BS1	D5	174.01	134.24	5.40	3.65	5.40	5.23	5.65	3.20	4.84	1.77	22.85	46.41	91.30
	D6	111.64	91.91	5.60	5.45	5.54	5.37	4.78	2.80	*	*	17.67	32.67	78.22
	D7	174.01	145.31	5.58	5.65	5.46	5.67	5.67	4.61	5.58	2.74	16.50	27.18	79.15
	D8	96.55	82.05	5.47	5.38	5.64	5.50	1.77	*	*	*	15.02	37.27	91.30
	D9	144.27	121.01	5.40	5.77	5.61	5.53	5.45	5.78	5.19	3.38	16.12	23.04	68.27
	D10	144.27	117.78	5.71	2.46	*	2.04	5.34	5.20	5.48	4.60	18.36	46.12	88.44
	D11	145.16	122.54	5.58	5.44	5.40	5.10	5.41	5.61	5.02	2.63	15.58	29.89	80.79
	D12	177.78	148.97	5.46	5.36	5.25	3.90	5.48	5.43	5.33	5.36	16.21	25.00	57.75
	D13	178.01	147.88	5.59	5.44	5.36	5.42	5.09	5.51	4.63	3.83	16.93	27.50	59.25
	D14	175.79	144.89	5.61	5.36	5.53	4.94	5.51	3.37	5.57	4.90	17.58	27.79	68.45
	D15	177.56	148.08	5.13	3.59	5.67	5.65	5.54	5.13	5.23	5.28	16.60	26.25	64.20
	D16	157.59	148.08	5.52	5.33	4.80	3.88	5.17	5.39	5.47	4.78	6.03	29.37	58.18
	D17	174.01	144.38	5.58	3.17	4.83	5.44	5.08	4.53	5.38	5.52	17.03	32.18	72.09
	D18	176.23	145.23	5.53	4.41	5.50	5.32	5.38	4.36	5.08	5.58	17.59	26.47	47.20
	D19	175.34	148.67	5.57	5.54	5.60	4.90	5.48	5.21	5.52	5.39	15.21	18.96	33.31
	D20	175.57	148.42	5.55	5.29	5.59	5.65	4.86	4.85	5.65	5.42	15.46	20.27	34.66
	V4	135.84	115.50	5.71	5.49	1.92	5.55	4.28	5.48	5.67	5.48	14.97	32.01	89.76
	V5	135.17	114.93	3.36	5.49	3.58	5.43	5.50	5.52	5.48	5.40	14.98	31.39	68.64
	V6	135.17	118.33	4.92	5.40	5.48	5.36	5.51	5.50	5.38	5.47	12.46	19.67	32.76
	V7	135.39	117.91	5.58	5.53	5.13	5.46	3.37	5.47	5.50	5.62	12.91	24.67	68.45
	V8	135.84	116.82	5.47	5.45	4.35	5.46	3.59	5.26	5.58	5.59	14.00	27.93	64.20
	V9	135.61	115.97	4.26	5.49	5.60	5.47	5.55	5.46	4.99	5.39	14.49	22.67	49.59
	V10	135.17	117.66	5.39	5.31	5.54	5.61	4.38	5.61	4.80	5.46	12.95	23.07	46.71
	V11	137.61	118.81	3.75	5.40	5.20	5.43	5.80	5.26	5.48	5.56	13.66	23.87	60.94
	V12	135.17	117.69	5.43	5.38	5.35	5.40	5.52	5.53	5.55	5.54	12.93	17.11	20.49
	V13	135.39	117.35	5.27	4.91	5.33	5.36	5.47	5.51	4.96	5.60	13.32	21.94	33.03

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BS1	V14	135.39	116.90	5.16	5.43	5.59	5.52	4.75	5.44	5.52	5.45	13.66	20.27	37.33
	V15	135.17	117.30	4.52	5.41	4.39	5.49	5.43	5.49	5.60	5.61	13.22	23.66	46.47
	V16	134.95	116.45	5.53	5.39	5.65	5.59	4.98	5.60	4.87	5.52	13.70	19.26	34.12
	V17	135.61	117.87	5.15	5.52	4.70	5.47	5.08	5.60	5.44	5.59	13.08	21.42	38.64
	V18	135.61	117.88	5.27	5.61	5.47	5.54	5.62	5.61	5.20	5.08	13.08	18.25	28.32
	V19	134.95	118.82	5.64	5.57	5.48	5.48	5.27	5.45	5.30	5.48	11.95	17.23	22.85
	V20	135.39	118.28	5.25	5.27	5.52	5.47	5.66	5.57	5.46	5.47	12.64	17.23	23.44
	Average											14.94	26.32	56.52
BS2	D4	177.56	138.00	5.65	5.63	5.69	5.33	4.65	5.60	5.39	3.68	22.28	24.82	62.38
	D5	177.12	135.78	5.76	4.78	5.55	5.43	5.42	4.99	4.25	3.23	23.34	32.59	71.02
	D6	177.78	137.85	5.69	3.38	4.89	4.19	5.90	5.70	5.71	5.13	22.46	28.49	68.27
	D7	177.56	137.56	5.77	5.38	4.83	3.86	4.85	5.11	3.37	4.95	22.53	36.93	68.45
	D8	178.01	131.30	5.70	3.03	4.51	5.27	5.59	4.97	5.39	2.44	26.24	40.90	83.46
	D9	178.01	134.79	5.56	4.88	4.60	3.84	5.47	5.09	5.54	5.48	24.28	28.95	59.04
	D10	147.38	116.05	5.89	4.88	4.62	5.63	5.76	5.09	5.58	2.58	21.26	30.45	81.51
	D11	175.57	134.53	5.76	5.11	4.77	4.79	5.53	3.71	4.39	5.05	23.37	33.61	61.77
	D12	177.12	138.60	5.44	5.04	5.67	4.92	5.66	5.34	5.06	4.84	21.75	23.55	34.93
	D13	177.56	138.28	5.24	4.92	5.15	3.96	5.40	4.52	4.82	5.37	22.13	32.69	56.44
	D14	173.79	137.06	5.91	4.95	4.98	5.30	5.50	4.92	5.42	4.24	21.14	26.25	50.06
	D15	176.90	137.36	5.40	4.99	5.58	3.78	5.71	5.09	5.62	5.71	22.35	23.87	60.31
	D16	149.37	114.70	5.29	4.82	5.26	5.73	5.65	5.00	5.26	2.87	23.21	30.97	77.12
	D17	177.78	135.23	5.87	4.46	5.49	3.95	4.70	4.64	3.38	5.53	23.94	37.26	68.27
	D18	105.43	77.11	5.63	3.52	5.62	5.58	5.40	3.69	*	*	26.86	33.12	65.58
	D19	177.56	129.92	5.53	4.68	5.36	3.67	4.32	3.86	5.27	5.44	26.83	36.90	62.59
	D20	151.82	114.10	5.55	4.73	5.33	5.09	5.39	4.89	4.57	2.51	24.84	37.13	82.50
	V4	139.16	112.91	5.52	5.65	5.52	5.49	5.49	5.53	5.16	5.57	18.87	16.24	26.04

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BS2	V5	138.72	136.78	5.45	6.00	5.96	6.00	6.00	6.00	5.87	6.00	1.40	2.98	17.49
	V6	138.72	110.69	5.75	5.51	5.04	5.45	3.81	5.59	5.38	5.59	20.21	23.00	59.68
	V7	138.72	112.92	5.47	5.51	5.50	5.65	4.60	5.83	5.39	5.51	18.60	18.02	41.22
	V8	138.50	110.75	5.15	5.43	4.62	5.41	5.53	5.52	4.26	5.67	20.03	24.92	49.59
	V9	138.94	111.94	5.53	4.93	5.64	4.92	5.58	4.23	5.44	5.89	19.44	22.85	50.30
	V10	138.72	111.02	4.69	5.60	4.26	5.45	5.52	5.46	4.77	5.47	19.97	26.25	49.59
	V11	138.50	112.97	5.51	5.45	5.27	5.53	3.55	5.39	5.31	5.49	18.43	25.25	64.99
	V12	138.94	111.30	2.83	5.54	5.26	5.52	5.12	5.58	4.82	4.49	19.89	33.44	77.75
	V13	138.50	112.36	5.53	5.14	5.44	5.42	4.26	5.42	5.06	5.46	18.88	24.42	49.59
	V14	138.72	111.80	5.93	5.18	3.83	5.05	3.54	5.01	5.07	5.67	19.41	33.03	65.19
	V15	136.72	113.41	5.11	5.63	4.86	4.97	5.76	5.44	5.50	4.72	17.05	23.47	38.12
	V16	137.83	111.76	4.73	5.41	3.20	5.28	4.33	5.64	4.96	5.77	18.91	32.90	71.56
	V17	138.28	112.54	5.51	5.50	4.99	5.74	4.67	5.37	4.13	5.39	18.61	25.97	52.62
	V18	138.50	110.67	4.93	5.58	2.40	5.27	5.42	5.45	3.48	5.56	20.09	37.03	84.00
	V19	138.28	111.25	5.49	5.29	5.12	5.73	5.05	5.63	4.12	5.55	19.54	23.51	52.85
	V20	138.94	111.13	5.52	5.08	5.02	4.30	4.40	5.47	4.64	5.47	20.02	30.90	48.64
	Average											20.83	28.31	59.20
BS3	D4	175.57	124.04	5.61	4.11	5.49	3.67	5.56	5.19	5.35	4.34	29.35	32.90	62.59
	D5	175.79	121.81	5.50	5.17	4.83	4.48	5.28	4.68	5.57	2.56	30.71	37.10	81.80
	D6	177.56	123.20	5.46	3.90	5.45	5.51	3.98	2.00	5.31	5.17	30.61	41.29	88.89
	D7	175.34	126.96	5.02	3.89	5.58	5.15	5.23	3.38	5.40	5.50	27.59	33.48	68.27
	D8	175.34	126.42	5.54	5.03	5.61	3.31	4.66	4.13	5.37	3.83	27.90	39.03	69.57
	D9	176.45	128.84	5.71	4.97	5.69	3.94	5.46	5.15	5.58	4.39	26.99	27.43	56.88
	D10	176.90	129.27	5.36	5.26	5.30	3.96	5.61	3.42	5.06	3.96	26.92	37.56	67.51
	D11	176.90	128.83	4.54	4.41	5.10	3.98	5.00	5.45	5.41	3.99	27.17	37.72	56.00
	D12	179.56	129.34	5.48	3.65	5.44	4.62	4.60	3.41	3.96	5.47	27.97	41.76	67.70

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BS3	D13	150.26	108.09	4.74	5.62	5.33	3.76	5.20	4.37	5.37	2.88	28.07	39.71	76.96
	D14	174.90	120.76	5.51	2.85	4.44	5.61	3.48	4.96	3.02	5.38	30.95	46.07	77.44
	D15	150.04	107.39	4.52	4.55	5.62	2.96	5.16	5.53	5.70	4.39	28.43	35.90	75.66
	D16	175.57	122.14	4.55	3.25	4.69	2.55	4.99	4.54	5.41	5.38	30.43	45.73	81.94
	D17	143.16	98.77	3.33	3.45	5.57	5.54	3.85	2.58	5.56	*	31.01	49.39	81.51
	D18	172.01	135.59	5.51	4.48	5.46	5.48	5.24	5.31	5.49	5.30	21.18	22.45	44.25
	D19	175.79	123.54	3.28	4.06	5.65	5.52	5.61	*	3.25	3.73	29.72	45.17	70.66
	V4	137.83	128.53	6.00	5.91	4.36	6.00	6.00	6.00	4.73	6.00	6.75	12.11	47.20
	V5	134.95	105.59	4.19	5.52	3.72	5.45	5.33	5.48	3.66	5.51	21.75	34.46	62.79
	V6	135.61	106.18	5.08	5.49	5.45	5.59	4.68	5.51	4.65	5.52	21.70	23.55	39.94
	V7	134.06	105.96	4.46	5.50	4.17	5.41	5.55	5.42	3.66	5.67	20.96	31.11	62.79
	V8	134.73	105.00	5.48	5.41	3.49	5.39	4.09	5.51	4.67	5.41	22.06	32.45	66.17
	V9	134.50	104.23	4.22	5.58	4.14	5.34	5.51	5.47	3.41	5.49	22.51	33.44	67.70
	V10	134.28	103.99	5.49	5.48	3.63	5.44	3.60	5.52	2.57	5.54	22.56	39.71	81.65
	V11	134.06	105.11	4.18	5.51	5.15	5.37	5.55	5.54	4.25	5.55	21.60	26.68	51.47
	V12	134.28	105.70	5.48	5.46	4.40	5.63	4.48	5.49	4.17	5.28	21.28	29.19	51.70
	V13	135.84	104.53	5.14	5.59	4.33	5.44	4.88	5.41	4.08	5.48	23.05	29.33	53.76
	V14	132.06	101.88	5.34	5.32	4.15	5.37	4.16	5.42	2.76	5.40	22.85	37.59	78.84
	V15	136.72	103.92	5.39	5.44	5.22	5.33	4.17	5.42	2.88	5.40	23.99	33.14	76.96
	V16	98.99	75.14	5.44	5.33	5.58	5.42	1.66	5.52	3.86	*	24.09	38.97	92.35
	V17	134.95	104.55	5.33	5.56	5.32	5.48	4.01	5.45	2.76	5.45	22.53	32.76	78.84
	V18	133.84	100.99	3.50	5.81	2.82	5.46	5.43	5.42	5.36	5.51	24.55	32.93	77.91
	V19	135.84	105.08	3.79	5.45	5.19	5.48	5.43	5.54	4.99	5.48	22.64	25.79	60.10
Average												25.00	34.56	68.05
CL1	D4	130.51	101.73	5.65	5.51	5.54	5.24	4.72	5.08	5.17	4.96	22.05	23.91	38.12
	D5	98.99	79.30	5.77	5.25	5.91	5.61	5.32	5.36	5.85	*	19.89	13.47	23.44

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CL1	D6	127.85	108.53	5.57	5.53	5.53	5.67	5.43	5.46	5.74	5.25	15.11	15.28	23.44
	D7	121.41	102.92	5.66	5.71	5.53	5.79	5.52	5.71	5.58	5.42	15.23	12.42	18.40
	D8	121.85	103.32	5.88	5.57	5.53	5.82	4.79	5.48	5.83	5.67	15.21	13.78	36.27
	D9	124.29	108.12	5.98	5.76	5.83	5.82	4.20	5.70	5.93	5.85	13.01	11.84	51.00
Average												16.75	15.12	31.78
CL2	D4	122.52	91.78	5.02	5.14	5.19	5.69	5.18	3.90	5.25	5.52	25.09	27.43	57.75
	D5	128.73	100.76	5.00	3.72	5.55	4.52	5.26	5.16	5.40	5.69	21.73	29.51	61.56
	D6	124.96	95.78	4.09	5.22	4.53	4.73	5.31	5.53	5.63	5.32	23.35	29.30	53.53
	D7	122.07	98.08	4.80	4.92	5.24	5.10	5.35	5.67	5.68	4.88	19.66	24.74	36.00
	D8	128.29	103.76	5.72	5.53	5.57	5.16	5.08	5.10	5.54	5.18	19.12	20.20	28.32
Average												21.79	26.24	47.43
CL3	D4	127.85	85.00	5.41	5.12	4.50	4.20	2.61	4.97	4.98	5.45	33.51	39.81	81.08
	D5	87.01	57.21	4.68	4.42	4.21	4.64	5.08	4.42	4.47	*	34.25	42.24	50.77
	D6	124.07	84.93	3.74	3.83	4.19	4.44	4.28	4.50	5.02	*	31.55	48.98	61.15
	D7	121.63	85.50	3.50	4.31	5.49	5.38	5.14	5.29	4.84	5.04	29.71	34.02	65.97
	D8	124.07	89.66	4.69	4.81	5.31	5.13	5.07	4.17	5.00	*	27.74	33.77	51.70
	D9	65.48	44.40	2.57	4.55	4.95	5.47	4.73	*	*	*	32.19	44.89	81.65
Average												31.49	40.62	65.39
CM1	D4	126.96	116.21	6.00	5.96	4.48	5.87	5.75	5.75	6.00	5.99	8.47	8.96	44.25
	D5	127.18	116.59	6.00	6.00	6.00	5.84	4.58	5.81	5.87	5.97	8.33	7.88	41.73
	D6	136.50	125.74	6.00	5.86	5.92	5.87	5.34	5.81	5.94	5.91	7.88	5.55	20.79
	D7	104.76	95.26	5.87	6.00	5.57	5.89	5.92	5.91	5.85	*	9.07	4.66	13.82
	D8	122.74	113.36	6.00	5.93	5.82	5.49	5.72	5.81	5.85	5.91	7.64	6.03	16.28
	D9	121.63	113.04	5.99	5.90	6.00	5.89	4.82	6.00	5.73	5.79	7.06	7.68	35.47
	D10	122.07	113.84	5.96	5.95	5.93	5.71	5.79	5.93	5.99	5.86	6.75	3.63	9.43
	D11	121.85	113.72	5.99	5.96	6.00	5.88	5.99	5.98	5.90	5.96	6.67	1.41	3.96

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CM1	D12	122.74	114.97	6.00	5.96	5.98	5.93	4.92	5.88	5.96	5.95	6.33	5.83	32.76
	Average											7.58	5.74	24.28
CM2	D4	131.40	98.56	3.35	3.61	4.90	5.19	5.12	4.96	5.69	3.33	24.99	43.28	69.20
	D5	99.88	77.33	3.71	4.68	5.42	5.86	5.29	5.77	5.78	3.67	22.58	29.93	62.59
	D6	126.07	100.56	4.64	4.04	4.57	5.38	5.43	4.63	5.58	5.12	20.23	32.66	54.66
	D7	91.22	86.39	2.89	3.87	5.09	5.37	3.92	5.19	5.27	5.30	5.30	40.90	76.80
	D8	84.12	65.15	4.41	4.94	5.83	5.14	5.04	*	*	*	22.55	28.54	45.98
	D9	81.01	59.04	3.20	4.26	4.61	5.32	4.59	*	*	*	27.12	46.32	71.56
	D10	139.39	102.96	2.27	4.02	3.88	5.48	5.12	5.28	5.16	3.92	26.13	46.44	85.69
	D11	106.32	75.90	2.31	5.08	3.35	5.68	4.51	5.39	3.61	*	28.61	49.22	85.18
	D12	95.44	69.25	2.69	2.88	5.70	5.26	5.58	5.32	4.77	*	27.44	41.22	79.90
Average												22.77	39.97	70.47
CM3	D4	77.46	50.06	5.16	5.33	3.53	4.93	3.61	*	*	*	35.37	43.45	65.39
	D5	125.85	77.17	2.42	5.32	4.75	3.14	4.28	5.67	3.29	3.73	38.68	53.87	83.73
	D6	60.59	41.38	5.24	5.06	4.96	4.68	*	*	*	*	31.71	30.97	39.16
	D7	122.52	83.97	3.13	5.19	5.35	5.21	4.29	5.46	4.77	3.33	31.46	41.45	72.79
	D8	103.43	66.86	3.83	4.45	4.48	5.21	4.26	3.98	4.35	*	35.36	47.06	59.25
	D9	156.92	106.08	3.30	4.96	3.67	4.92	5.17	4.07	4.58	4.81	32.40	45.36	69.75
	D10	122.30	82.59	1.57	2.58	4.72	3.77	5.65	4.71	5.65	4.06	32.47	53.56	93.15
	D11	88.12	61.85	4.14	3.82	5.22	4.63	5.10	*	*	*	29.81	41.68	59.47
	D12	151.59	107.52	5.19	5.21	2.72	4.11	5.37	3.58	4.82	5.07	29.07	43.53	79.45
Average												32.93	44.55	69.13
CS1	D4	121.41	110.24	5.93	5.84	5.86	5.98	5.30	5.76	5.97	5.89	9.20	6.03	21.97
	D5	121.63	110.52	5.94	5.44	5.94	5.51	5.85	4.60	5.84	5.91	9.13	11.99	41.22
	D6	122.07	110.20	5.84	5.68	5.88	5.57	5.86	6.00	5.74	5.95	9.73	6.07	13.82

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CS1	D7	121.41	109.27	5.91	5.94	5.83	5.82	4.65	5.70	5.98	6.00	10.00	8.84	39.94
	D8	122.07	111.46	5.87	5.97	5.92	5.75	5.86	5.87	5.95	5.92	8.70	3.67	8.16
	D9	121.41	111.59	5.86	5.95	5.88	5.38	5.63	5.80	5.93	5.44	8.09	8.68	19.60
	D10	122.74	111.95	5.94	5.94	5.86	5.75	5.82	6.00	5.87	5.98	8.79	3.47	8.16
	D11	121.63	111.73	5.95	5.92	5.89	5.69	5.99	5.82	5.75	5.83	8.14	4.77	10.07
	D12	121.85	111.61	4.75	5.95	5.85	5.92	5.69	5.37	5.91	5.95	8.41	10.58	37.33
	D13	122.52	111.14	5.83	5.87	5.96	5.76	5.91	5.65	5.68	5.62	9.29	7.04	12.27
	D14	122.07	111.04	4.02	5.79	5.80	5.88	5.61	5.89	5.93	5.87	9.04	12.93	55.11
	D15	126.74	113.07	4.36	5.96	5.84	6.00	5.82	5.45	5.97	5.95	10.78	10.74	47.20
	D16	122.96	110.01	5.85	5.90	6.00	5.87	5.82	5.77	5.42	3.95	10.53	13.74	56.66
	D17	124.52	111.38	5.90	5.81	5.82	5.89	5.62	5.83	5.80	5.19	10.55	8.72	25.18
	D18	120.30	108.56	5.70	5.25	5.97	5.98	5.80	5.91	5.86	5.93	9.76	6.56	23.44
Average											9.34	8.26	28.01	
CS2	D4	118.30	106.28	4.98	5.62	5.79	5.73	5.88	5.85	6.00	5.73	10.16	9.83	31.11
	D5	124.29	107.02	5.79	5.74	5.90	4.49	5.91	3.76	5.87	5.99	13.90	18.06	60.73
	D6	123.18	110.43	5.95	5.91	5.82	5.56	5.83	5.95	5.87	5.78	10.35	5.46	14.13
	D7	121.19	110.59	5.77	6.00	5.97	5.85	6.00	5.71	5.63	3.67	8.74	13.66	62.59
	D8	121.63	108.34	5.87	5.85	5.96	5.66	5.37	5.23	5.77	4.30	10.93	15.93	48.64
	D9	119.41	108.01	5.73	5.60	6.00	5.39	5.45	5.85	5.82	*	9.55	10.02	19.30
	D10	119.63	108.03	5.93	5.91	5.25	5.63	5.58	5.69	5.86	6.00	9.70	8.76	23.44
	D11	120.52	109.35	5.84	5.86	6.00	5.70	5.93	5.68	4.20	5.91	9.27	11.64	51.00
	D12	119.19	108.14	5.89	5.58	5.92	5.47	5.85	5.91	5.11	5.54	9.27	11.05	27.47
	D13	119.41	108.88	5.93	5.92	5.91	5.74	5.66	5.81	5.94	5.84	8.82	5.14	11.01
	D14	118.75	108.23	5.88	5.94	5.48	5.43	5.66	5.81	5.83	5.87	8.86	8.56	18.10
	D15	118.97	107.16	5.81	5.77	5.86	5.98	5.68	5.20	5.47	5.90	9.92	9.47	24.89
	D16	71.91	65.34	5.34	5.90	5.85	5.98	5.95	*	*	*	9.14	6.43	20.79

Appendix D

CS2	D17	118.52	106.61	5.92	4.61	5.87	5.89	5.86	4.03	5.77	5.40	10.05	18.44	54.89
	D18	122.30	109.83	6.00	5.87	6.00	5.97	4.83	4.53	5.19	5.98	10.19	14.55	43.00
	D19	120.30	107.80	6.00	5.93	5.84	5.98	5.94	3.54	5.75	5.86	10.39	12.73	65.19
	Average											9.95	11.23	36.02
CS3	D4	110.31	96.03	5.72	6.00	5.24	5.26	5.88	5.25	5.31	*	12.95	15.27	23.73
	D5	109.87	96.42	5.96	5.72	5.78	5.69	5.63	5.79	4.96	5.07	12.24	13.66	31.66
	D6	120.74	109.04	5.94	6.00	5.68	5.37	5.83	5.40	5.29	5.87	9.69	10.62	22.27
	D7	122.30	108.96	6.00	5.66	6.00	6.00	5.30	5.87	5.99	5.96	10.90	5.02	21.97
	D8	119.19	103.92	5.97	5.60	5.42	5.75	5.60	4.96	5.53	6.00	12.81	12.77	31.66
	D9	122.74	106.92	5.79	4.65	5.71	5.59	3.68	5.48	4.17	5.18	12.89	29.68	62.38
	D10	121.63	105.62	5.92	4.79	5.52	5.72	5.66	5.87	6.00	2.38	13.16	23.95	84.27
	D11	122.07	105.38	5.75	5.93	6.00	6.00	3.87	6.00	6.00	5.82	13.68	10.66	58.40
	D12	123.85	104.56	5.92	6.00	5.02	5.63	5.50	5.55	5.78	5.91	15.58	10.89	30.00
	D13	124.29	107.75	6.00	5.74	5.87	5.86	3.77	5.46	5.17	6.00	13.31	16.47	60.52
	D14	123.85	107.02	6.00	4.23	5.73	5.17	5.68	5.08	5.22	6.00	13.59	19.34	50.30
	D15	125.18	107.12	6.00	5.83	5.47	5.76	5.81	5.01	5.64	5.67	14.43	11.37	30.28
	D16	124.74	105.40	6.00	5.88	4.68	4.71	5.30	4.47	4.75	4.44	15.50	29.75	45.24
	D17	124.29	104.32	6.00	5.80	6.00	6.00	3.09	2.76	3.49	5.76	16.07	34.32	78.84
	D18	124.74	107.02	4.95	5.86	4.00	4.56	5.50	5.38	5.35	5.89	14.20	25.29	55.56
	D19	117.86	98.66	6.00	6.00	5.97	5.99	3.34	4.25	3.38	3.68	16.29	35.30	69.01
	Average											13.58	19.02	47.25

SLENDER COLUMNS

Labelling and Measurement of "D" Stirrups

Labelling and Measurement of "V" Stirrups

SHORT COLUMNS

Figure D.2 Labelling and measurement of corrosion levels for test specimens in Series 2 and Series 3

Table D.2 Corrosion measurement of transverse reinforcing bars for test specimens in Series 2

Specimen	No.	W0	W1	R1	R2	R3	R4	R5	R6	R7	R8	$X_{corr}^{(1)}$	$X_{corr}^{(2)}$	$X_{corr}^{(3)}$
		g	g	mm	mm	mm	mm	mm	mm	mm	mm	%	%	%
C1	D1	485.38	417.20	4.89	4.96	7.10	6.65	7.24	7.34	6.03	5.95	14.05	35.38	60.70
	D2	488.01	416.00	6.11	6.48	7.18	5.45	2.95	6.90	7.36	7.26	14.76	36.59	85.70
	D3	486.88	419.80	3.73	7.15	7.34	5.95	7.24	7.14	6.89	6.49	13.78	30.74	77.13
	D4	488.76	406.00	6.88	7.20	6.45	6.40	5.35	7.18	6.58	7.27	16.93	27.01	52.95
	D5	488.01	398.40	5.41	4.75	4.98	7.12	6.85	7.12	7.13	6.76	18.36	35.49	62.92
	D6	486.88	409.20	5.98	7.15	6.65	6.87	0.00	4.71	5.90	6.95	15.95	49.80	100.00
	D7	486.51	394.70	4.89	4.95	5.20	5.93	7.10	5.40	6.61	7.14	18.87	42.74	60.70
	D8	490.26	407.10	7.11	6.88	5.40	5.73	4.65	6.44	6.48	7.29	16.96	35.85	64.46
	D9	488.76	427.90	6.24	7.41	6.87	7.10	7.34	7.37	7.24	6.35	12.45	19.69	36.00
	D10	489.13	424.10	7.09	7.80	6.90	7.41	5.60	6.98	6.40	6.99	13.30	21.83	48.45
	D11	490.26	427.60	6.54	7.20	0.00	7.31	6.37	7.20	6.95	7.31	12.78	38.64	100.00
	D12	488.01	420.80	6.63	7.30	6.13	6.37	4.46	6.09	4.24	7.10	13.77	40.04	70.45
	D13	489.13	420.90	5.19	7.33	0.00	6.95	6.90	6.75	6.10	7.28	13.95	44.47	100.00
	D14	491.38	420.10	7.17	6.23	5.54	5.71	4.88	6.78	6.50	7.18	14.51	35.82	60.86
	D15	481.63	385.00	0.00	4.29	4.26	7.02	5.48	7.39	4.87	7.47	20.06	57.29	100.00
	D16	490.26	403.10	6.36	7.31	6.89	7.50	0.00	4.53	5.10	7.01	17.78	48.68	100.00
	D17	488.38	426.10	6.76	7.40	5.87	7.20	4.90	7.39	7.12	7.40	12.75	25.00	60.54
	D18	487.26	431.30	5.33	7.23	7.24	7.44	5.34	6.54	7.31	7.44	11.48	25.47	53.31
	D19	485.38	423.00	5.84	7.38	6.94	6.14	4.15	7.24	6.91	7.16	12.85	31.20	71.69
	D20	490.26	429.00	6.17	6.82	6.89	6.98	5.97	5.19	7.40	7.25	12.49	28.75	55.73
	D21	489.13	420.50	7.20	7.02	7.30	6.90	5.48	6.12	6.86	7.50	14.03	24.05	50.64
	D22	487.63	416.60	7.36	6.36	7.24	4.83	4.97	7.36	6.69	7.51	14.57	29.70	61.66

Appendix D

C1	D23	488.01	423.20	5.51	6.99	5.98	5.49	6.11	7.14	7.11	7.04	13.28	32.23	50.46
	D24	490.63	414.70	6.26	6.52	6.11	7.54	3.79	6.54	6.46	7.02	15.48	35.18	76.39
	D25	488.01	415.10	5.45	7.28	6.38	6.92	6.38	6.77	6.75	6.90	14.94	28.32	51.18
	D26	484.26	407.10	6.21	7.12	6.59	5.97	4.49	6.23	6.36	5.86	15.93	38.76	66.86
	Average										14.94	34.82	68.83	
	V1	370.23	341.70	6.70	7.54	7.46	7.43	6.91	7.44	5.43	7.49	7.70	18.31	51.54
	V2	369.10	339.30	7.54	7.49	7.46	7.44	7.47	7.48	7.46	7.48	8.07	8.10	9.02
	V3	370.23	347.00	6.39	7.44	7.48	7.46	7.26	7.43	7.48	7.49	6.27	12.32	32.89
	V4	371.73	344.60	7.43	7.44	7.45	7.45	7.48	7.49	7.46	7.44	7.30	8.65	9.26
	V5	370.98	344.70	7.46	7.48	7.44	7.48	7.49	7.46	7.09	7.43	7.08	9.60	17.38
	V6	369.10	338.90	7.50	7.48	7.39	7.44	7.46	7.43	6.64	7.51	8.18	11.05	27.53
	V7	357.85	325.60	7.45	7.48	7.39	7.46	7.45	7.44	7.49	7.46	9.01	8.71	10.24
	V8	369.10	340.10	7.43	7.46	7.44	7.48	7.46	7.49	7.43	7.45	7.86	8.65	9.26
	V9	371.73	342.10	6.44	7.48	7.15	7.51	7.36	7.46	7.45	7.49	7.97	12.59	31.83
	V10	370.23	338.90	6.91	7.34	7.33	6.98	7.09	7.14	7.41	7.34	8.46	14.97	21.52
	V11	362.72	318.60	7.43	6.50	7.48	7.43	7.18	7.46	6.83	6.90	12.16	15.94	30.56
	V12	369.10	335.40	7.48	7.49	7.46	7.47	7.46	7.44	5.79	6.80	9.13	15.41	44.90
	V13	370.23	335.30	7.51	7.39	7.10	7.43	7.38	7.39	5.25	7.46	9.43	16.82	54.70
	V14	366.10	333.30	6.96	7.39	5.30	7.40	7.43	7.41	5.17	7.43	8.96	23.75	56.07
	V15	370.60	332.10	7.45	7.46	6.30	7.49	6.88	7.43	7.46	7.45	10.39	13.84	34.76
	V16	369.85	330.10	7.46	7.48	7.49	7.46	7.48	7.51	6.89	7.50	10.75	9.78	21.97
	V17	370.98	344.60	7.43	7.45	7.17	7.46	7.45	7.44	7.28	7.46	7.11	10.18	15.50
	V18	368.72	339.80	7.46	7.45	7.43	7.41	7.49	7.39	6.87	7.43	7.84	10.81	22.42
	V19	370.98	346.50	7.49	7.48	7.34	7.46	7.42	7.43	6.99	7.39	6.60	10.60	19.69
	V20	370.23	346.00	7.44	7.46	7.28	7.43	7.49	7.42	7.29	7.44	6.54	9.84	12.89
	V21	368.35	349.10	7.44	7.38	7.37	7.43	7.42	7.46	7.17	7.43	5.23	10.31	15.50

Appendix D

C1	V22	369.10	341.50	7.41	7.39	5.70	7.41	7.43	7.44	7.43	7.48	7.48	14.53	46.60
	V23	370.23	336.60	7.41	7.43	6.80	7.49	7.46	7.41	5.18	7.43	9.08	17.70	55.90
	V24	367.60	339.30	7.38	7.39	6.67	7.47	7.39	7.41	7.47	7.46	7.70	11.69	26.88
	V25	369.10	337.20	7.49	7.43	6.55	7.39	7.48	7.44	6.60	7.49	8.64	13.99	29.48
	V26	370.23	333.40	7.46	7.45	6.41	7.43	7.44	7.46	6.85	7.60	9.95	13.31	32.47
	Average											8.27	12.75	28.49
C2	D1	321.46	223.40	6.24	*	*	1.17	5.46	7.45	6.63	7.22	30.51	46.71	97.75
	D2	447.87	335.10	5.27	5.66	1.35	7.41	4.10	5.64	5.56	7.80	25.18	53.03	97.02
	D3	488.01	364.75	7.22	6.53	4.34	7.51	5.22	6.00	7.26	6.44	25.26	34.49	69.06
	D4	471.88	350.21	5.66	4.88	6.32	7.51	6.88	5.36	3.69	6.73	25.78	43.23	77.67
	D5	478.25	337.95	6.19	4.63	4.29	6.97	3.80	4.00	7.22	7.61	29.34	48.68	76.23
	D6	476.38	343.37	4.13	7.04	6.92	6.73	4.11	5.25	6.22	7.39	27.92	41.33	72.17
	D7	477.13	370.27	5.75	5.85	6.71	7.29	3.78	7.51	4.54	6.30	22.40	41.48	76.48
	D8	472.63	333.86	5.85	7.12	5.46	6.61	4.74	5.46	6.47	6.03	29.36	41.48	63.09
	D9	479.38	393.37	5.95	7.26	7.51	7.41	4.39	6.68	7.31	6.39	17.94	28.15	68.36
	D10	493.26	379.77	7.51	7.33	3.51	5.11	7.61	7.80	6.20	7.22	23.01	29.81	79.75
	D11	487.26	355.53	4.97	6.83	4.10	7.47	7.59	5.85	5.07	5.36	27.03	42.71	72.44
	D12	262.20	192.50	7.80	*	*	*	2.20	7.27	7.41	7.80	26.58	30.61	92.02
	D13	482.38	355.72	3.47	7.51	3.41	6.14	7.55	7.20	6.05	7.80	26.26	38.03	80.86
	D14	485.01	348.69	6.44	7.10	7.12	7.22	0.78	6.73	4.41	5.85	28.11	46.53	99.00
	D15	363.85	240.22	7.22	*	7.12	7.57	4.68	7.02	4.91	5.67	33.98	34.51	64.00
	D16	486.13	325.40	6.08	7.31	5.85	4.29	5.56	6.83	4.60	7.02	33.06	41.95	69.75
	D17	492.13	365.23	4.78	4.10	3.69	7.41	5.73	6.12	6.92	5.27	25.79	50.25	77.67
	D18	484.63	408.10	5.75	7.80	5.75	6.73	5.25	7.70	7.68	5.56	15.79	29.96	54.77
	D19	482.38	401.35	7.61	7.70	7.51	7.08	4.37	7.80	4.66	7.14	16.80	25.50	68.64
	D20	488.38	424.74	7.37	6.42	7.80	7.80	7.80	7.70	6.32	7.43	13.03	11.70	34.39

Appendix D

C2	D21	487.26	409.05	7.02	7.08	5.81	7.80	6.92	6.61	7.80	5.85	16.05	22.61	44.50
	D22	482.76	406.87	7.27	7.47	7.12	7.49	7.47	3.80	7.80	7.22	15.72	20.51	76.23
	D23	490.63	419.80	7.22	7.57	6.63	7.80	7.20	6.98	7.80	7.08	14.44	12.81	27.75
	D24	490.63	422.93	7.57	7.27	7.02	7.64	4.23	6.36	6.83	7.47	13.80	24.04	70.57
	D25	480.88	413.14	7.18	6.83	7.80	7.33	7.51	7.80	6.83	6.28	14.09	14.96	35.20
	D26	494.76	351.26	7.16	7.41	6.20	6.96	7.31	6.63	6.71	4.97	29.00	26.90	59.36
	Average										23.36	33.86	68.41	
	V1	367.22	340.04	7.31	7.51	7.80	7.80	7.66	7.66	7.68	7.74	7.40	3.90	12.11
	V2	369.85	313.52	6.87	7.80	7.75	7.65	5.85	7.80	7.07	7.80	15.23	11.67	43.75
	V3	357.10	345.93	6.34	7.80	7.80	7.80	7.80	7.80	6.19	7.80	3.13	6.61	37.00
	V4	361.60	357.63	7.66	7.80	7.41	7.70	7.61	7.80	6.26	7.80	1.10	7.42	35.60
	V5	361.97	350.50	5.31	7.80	7.31	7.80	6.83	7.80	7.80	7.80	3.17	11.08	53.59
	V6	365.35	346.31	6.05	7.80	7.64	7.80	4.74	7.80	7.80	7.80	5.21	15.30	63.09
	V7	360.47	346.98	6.58	7.80	7.80	7.80	6.83	7.80	5.95	7.80	3.74	9.30	41.86
	V8	355.22	351.16	6.63	7.80	7.31	7.80	5.85	7.80	6.68	7.80	1.14	11.23	43.75
	V9	371.35	352.30	6.97	7.80	7.80	7.80	6.53	7.80	7.56	7.80	5.13	5.85	29.86
	V10	366.85	350.31	7.80	7.80	5.95	7.80	7.80	7.80	7.80	7.65	4.51	4.79	41.86
	V11	360.10	339.37	7.80	7.68	7.31	7.57	7.62	7.62	7.02	7.80	5.76	6.21	19.00
	V12	361.97	346.50	7.80	7.80	7.78	7.80	7.80	7.80	5.75	7.57	4.27	7.24	45.61
	V13	360.47	336.24	6.22	7.80	7.55	7.80	7.80	7.80	7.80	7.80	6.72	5.79	36.40
	V14	364.22	329.01	7.80	7.80	7.80	7.80	7.41	7.80	7.70	7.80	9.67	1.56	9.75
	V15	363.10	354.58	7.80	7.80	7.80	7.80	7.80	7.25	6.28	7.80	2.35	6.52	35.20
	V16	364.97	340.89	7.72	7.76	7.80	7.80	7.66	7.80	4.97	7.80	6.60	9.63	59.36
	V17	370.23	314.66	6.58	7.56	7.26	7.41	7.31	7.41	7.41	7.56	15.01	12.11	28.81
	V18	362.72	353.25	7.61	7.80	7.70	7.80	5.07	7.80	7.70	7.80	2.61	9.75	57.75
	V19	365.72	355.34	7.80	7.12	6.61	7.02	7.23	6.98	6.71	7.08	2.84	17.87	28.17

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C2	V20	369.10	348.78	7.80	7.80	7.80	7.80	6.44	7.80	6.73	7.80	5.50	7.66	31.94
	V21	363.47	351.26	7.80	7.39	6.83	7.22	6.73	7.80	7.70	6.83	3.36	12.75	25.61
	V22	368.35	353.44	6.58	7.80	5.66	7.80	7.80	7.18	7.80	7.80	4.05	12.37	47.44
	V23	361.22	339.09	6.14	7.80	6.51	7.80	5.60	7.70	7.80	7.80	6.13	14.44	48.52
	V24	360.85	357.05	7.56	7.80	6.19	7.80	7.80	7.80	7.80	7.80	1.05	3.71	37.00
	V25	364.97	358.01	7.47	7.66	7.61	7.80	7.80	7.80	7.80	7.80	1.91	2.11	8.32
	V26	361.60	354.68	7.41	7.80	7.80	7.80	7.80	7.80	7.62	7.80	1.91	1.80	9.75
	V27	365.72	309.52	6.98	7.51	7.61	7.51	6.71	7.20	7.10	7.08	15.37	14.55	26.04
Average												5.37	8.64	35.45
C3	D1	436.62	266.30	*	4.60	5.30	7.00	6.00	3.90	3.70	6.00	39.01	55.31	77.50
	D2	431.37	306.20	5.90	7.10	7.40	*	6.50	7.50	5.40	5.80	29.02	30.25	52.07
	D3	457.62	319.10	7.50	7.40	*	4.00	*	7.10	5.80	4.90	30.27	38.50	73.70
	D4	295.20	197.10	*	*	*	6.00	5.10	4.80	5.00	*	33.23	55.13	62.13
	D5	488.38	323.90	6.60	7.40	5.40	4.90	*	7.40	*	6.90	33.68	31.97	60.54
	D6	411.49	273.70	6.90	7.80	*	7.30	5.70	*	*	3.00	33.49	38.03	85.21
	D7	399.48	275.70	*	7.70	*	7.00	8.00	5.50	*	5.40	30.99	25.78	52.07
	D8	361.97	261.00	7.00	7.40	*	6.80	*	*	*	7.70	27.90	14.20	24.00
	D9	422.36	302.10	*	7.20	*	7.10	6.60	*	*	*	28.47	20.23	28.40
	D10	363.47	231.20	5.80	*	*	*	6.60	7.70	*	7.40	36.39	22.31	44.71
	D11	420.11	287.30	7.60	7.20	*	4.20	6.20	6.60	*	6.50	31.61	33.03	71.01
	D12	441.12	297.10	*	4.40	*	4.00	4.10	5.40	7.40	7.20	32.65	51.77	73.70
	D13	349.22	263.70	7.00	8.00	*	7.40	*	*	*	7.10	24.49	10.60	19.46
	D14	447.12	334.80	7.20	7.50	*	6.00	7.90	7.70	*	7.50	25.12	12.41	40.83
	D15	335.34	233.10	6.90	5.60	*	*	*	5.50	*	7.00	30.49	35.79	50.28
	D16	446.37	348.40	*	6.60	4.50	4.30	5.80	8.00	6.90	7.40	21.95	36.53	69.61
	D17	483.88	345.00	8.20	6.30	5.50	6.00	*	7.40	7.20	7.20	28.70	23.36	50.28

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C3	D18	484.26	325.90	2.80	5.30	5.00	6.20	3.50	7.40	8.00	7.70	32.70	45.89	87.11
	D19	349.22	267.40	*	7.10	7.70	6.60	*	7.20	*	*	23.43	15.97	28.40
	D20	428.74	285.00	*	5.20	4.80	5.90	6.10	8.00	7.40	5.80	33.53	37.40	62.13
	D21	234.81	171.10	*	7.30	6.30	5.50	*	*	*	*	27.13	33.38	50.28
	D22	484.26	316.10	3.80	4.80	4.30	4.80	5.30	6.70	6.40	5.00	34.72	56.62	76.27
	D23	488.76	338.20	7.00	6.50	4.40	4.30	4.20	6.90	7.10	6.70	30.80	43.03	71.01
	D24	327.09	212.20	*	7.20	4.70	5.60	5.00	7.50	*	*	35.12	40.83	63.69
	D25	365.35	256.80	*	5.90	4.80	6.30	6.30	5.70	*	*	29.71	44.71	62.13
	D26	478.63	297.10	3.00	5.10	6.70	4.50	4.00	6.10	6.20	5.90	37.93	55.77	85.21
	Average											30.87	34.95	58.53
	V1	365.72	319.10	6.70	7.25	7.75	7.60	7.45	7.50	7.30	7.30	12.75	11.05	26.22
	V2	367.60	313.90	4.50	8.00	7.15	7.70	7.50	7.65	7.75	7.60	14.61	14.05	66.72
	V3	362.35	322.90	7.80	7.85	7.30	7.75	3.15	7.80	6.60	7.45	10.89	20.32	83.69
	V4	358.97	313.90	4.70	7.80	7.45	7.65	6.30	7.75	8.00	7.65	12.56	15.68	63.69
	V5	368.35	314.50	7.00	7.75	7.70	7.50	3.50	7.75	8.00	7.30	14.62	18.02	79.87
	V6	363.85	315.60	5.00	8.00	7.85	7.65	6.35	7.55	7.75	7.85	13.26	13.61	58.91
	V7	363.47	313.40	6.75	7.75	7.00	7.80	8.00	6.70	7.45	6.00	13.78	15.24	40.83
	V8	372.85	312.60	7.50	7.75	7.50	7.60	7.00	7.50	7.55	7.65	16.16	7.39	19.46
	V9	362.35	307.60	7.10	7.20	7.35	6.10	7.60	7.60	7.35	7.45	15.11	14.35	38.84
	V10	365.35	317.30	7.50	7.60	6.35	7.50	6.70	7.60	6.85	7.90	13.15	13.61	33.72
	V11	368.35	310.40	7.10	7.50	7.30	7.60	7.50	7.55	7.45	7.80	15.73	8.16	17.14
	V12	369.10	318.20	7.25	6.85	7.35	7.80	7.70	7.75	7.45	7.55	13.79	8.47	22.88
	V13	362.35	309.30	7.85	7.60	6.00	7.65	*	7.60	7.20	7.85	14.64	10.17	40.83
	V14	356.72	299.90	7.37	7.55	7.60	7.75	6.75	8.00	7.74	7.50	15.93	6.74	25.11
	V15	363.10	312.80	7.80	7.60	6.75	7.75	6.40	7.10	7.80	7.75	13.85	10.75	32.68
	V16	368.72	327.20	8.00	7.65	7.60	7.80	7.85	7.60	7.32	7.80	11.26	2.48	11.93

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C3	V17	367.97	325.50	7.85	7.65	7.35	7.95	6.60	7.75	7.00	7.70	11.54	8.01	28.40
	V18	366.47	336.40	6.75	6.70	6.35	7.80	7.80	6.30	6.35	8.00	8.21	19.32	34.76
	V19	364.60	321.00	7.10	7.90	3.00	8.00	4.85	8.00	6.10	7.85	11.96	28.40	85.21
	V20	363.47	325.20	3.75	8.00	3.90	7.75	7.30	7.80	5.10	7.85	10.53	32.02	76.89
	V21	359.35	315.00	7.60	7.85	5.20	7.80	*	7.30	*	7.85	12.34	13.21	55.56
	V22	361.22	311.70	3.30	7.85	5.55	7.80	7.60	8.00	*	7.50	13.71	24.00	82.10
	V23	365.35	334.70	7.60	7.40	6.65	7.50	6.65	7.80	7.70	7.75	8.39	10.45	27.31
	V24	366.10	316.40	6.35	7.75	7.30	7.80	7.85	7.55	7.20	7.55	13.58	9.54	33.72
	V25	367.60	320.50	7.80	7.80	5.65	7.75	6.75	7.80	6.85	7.75	12.81	13.16	47.53
	V26	367.97	308.00	7.60	7.80	6.15	7.75	4.75	7.70	7.50	7.75	16.30	16.56	62.92
Average												13.13	14.03	46.03
C4	D1	483.13	406.00	6.79	5.63	6.46	7.39	5.99	5.60	6.38	6.77	15.96	33.17	48.45
	D2	477.88	387.80	5.67	4.74	7.08	6.31	6.80	7.47	4.39	7.13	18.85	36.84	68.32
	D3	482.76	401.70	7.30	7.36	7.62	5.89	6.24	7.18	7.22	6.74	16.79	20.75	42.98
	D4	485.01	398.50	6.26	7.33	6.83	7.46	7.03	7.08	5.62	6.54	17.84	24.69	48.09
	D5	481.63	402.50	6.05	6.00	5.79	6.66	6.53	7.58	7.07	7.38	16.43	27.70	44.90
	D6	485.01	403.80	7.10	6.76	6.74	6.90	5.30	7.09	6.31	7.31	16.74	26.46	53.83
	D7	480.50	400.40	5.36	6.38	6.11	6.68	6.42	6.98	6.74	6.71	16.67	32.20	52.78
	D8	483.51	404.40	6.64	7.17	5.94	6.87	5.69	5.58	6.62	6.93	16.36	32.04	48.82
	D9	479.38	383.90	6.11	6.14	5.72	4.66	7.12	7.23	7.32	6.36	19.92	34.09	64.31
	D10	480.88	383.50	7.12	5.95	6.88	4.66	5.04	7.49	6.91	4.99	20.25	38.24	64.31
	D11	485.38	392.40	5.70	6.13	5.97	6.26	5.48	6.74	6.18	5.61	19.16	40.66	50.64
	D12	478.63	389.70	5.89	6.67	4.70	7.00	5.48	4.78	6.80	7.60	18.58	38.54	63.69
	D13	482.76	398.00	6.99	7.25	5.02	6.27	4.50	7.45	7.72	7.58	17.56	28.46	66.72
	D14	479.75	389.00	7.16	7.50	4.63	6.09	5.82	7.55	6.66	5.41	18.92	33.67	64.77
	D15	482.01	392.10	5.97	6.94	5.13	5.83	6.84	7.56	5.56	6.39	18.65	35.23	56.74

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C4	D16	486.51	384.50	6.85	7.32	6.44	6.78	5.68	7.34	6.89	6.09	20.97	26.79	46.97
	D17	476.75	395.70	5.98	5.43	6.72	7.12	6.70	7.50	6.20	6.38	17.00	30.48	51.54
	D18	482.76	401.70	7.57	5.18	6.01	7.18	4.80	4.99	6.53	6.54	16.79	38.84	62.13
	D19	480.13	385.40	7.36	7.24	4.29	4.77	7.17	7.38	7.18	7.00	19.73	29.51	69.75
	D20	483.51	378.30	6.71	6.83	7.04	6.44	6.03	7.48	6.00	5.72	21.76	29.89	46.22
	D21	481.26	391.00	4.30	6.20	5.65	7.64	6.53	7.00	7.00	*	18.75	31.62	69.61
	D22	483.51	393.30	6.30	6.56	7.23	5.18	4.82	6.00	5.92	5.83	18.66	41.22	61.81
	D23	484.26	405.30	6.20	6.10	6.00	7.05	7.38	6.80	6.74	6.51	16.30	28.46	40.83
	D24	482.38	388.40	6.51	7.19	3.87	4.68	4.91	6.97	5.85	5.81	19.48	46.15	75.38
	D25	482.76	399.30	7.20	6.09	6.38	4.96	6.91	7.60	7.41	7.03	17.29	26.27	59.56
	D26	478.63	385.80	5.82	5.09	4.69	6.87	5.99	4.92	5.63	5.91	19.39	48.18	63.85
	Average										18.26	33.08	57.19	
	V1	362.72	329.80	7.20	7.40	6.80	7.45	7.01	7.42	7.62	7.49	9.08	12.44	24.00
C4	V2	359.35	332.80	6.43	7.57	7.55	7.75	6.80	7.75	6.89	7.59	7.39	12.62	32.04
	V3	361.22	332.70	7.71	7.28	7.34	7.80	7.17	7.50	7.43	7.63	7.90	7.98	15.50
	V4	363.47	345.00	6.71	7.12	7.75	7.68	7.51	7.54	7.33	7.78	5.08	9.32	26.00
	V5	361.60	333.00	7.02	7.60	7.61	7.64	6.68	7.71	6.74	7.59	7.91	11.84	26.66
	V6	361.97	332.40	7.70	7.67	7.23	7.20	7.32	7.59	7.66	7.30	8.17	8.56	14.79
	V7	362.72	334.50	7.67	7.80	6.50	7.44	7.46	7.50	6.65	7.51	7.78	12.02	30.56
	V8	358.60	332.60	7.43	7.65	7.40	7.63	7.37	7.70	7.14	7.38	7.25	8.47	16.21
	V9	361.22	337.00	7.43	7.65	7.40	7.63	7.37	7.70	7.14	7.38	6.71	8.47	16.21
	V10	360.85	319.30	4.63	7.68	7.46	6.64	7.21	6.79	7.27	7.80	11.51	20.95	64.77
	V11	362.72	328.20	6.56	6.94	6.93	7.58	7.46	6.95	7.50	7.24	9.52	16.09	29.27
	V12	362.35	322.90	6.90	7.39	7.63	7.71	7.80	7.62	7.42	7.53	10.89	7.54	21.75
	V13	359.35	323.30	6.93	6.56	7.46	7.51	7.38	7.43	6.25	7.51	10.03	16.47	35.79
	V14	360.47	320.40	6.45	7.15	6.75	6.56	7.44	7.52	7.48	7.61	11.12	16.68	31.62

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C4	V15	364.60	322.60	7.25	7.48	6.20	7.70	7.30	7.42	7.51	7.48	11.52	12.59	36.82
	V16	358.97	322.40	7.00	7.62	7.71	7.53	7.62	7.70	7.59	7.63	10.19	6.31	19.46
	V17	358.60	331.80	7.78	7.68	7.70	7.40	7.73	7.80	7.17	7.65	7.47	4.72	15.50
	V18	362.35	337.90	7.50	7.38	6.83	7.23	7.25	7.80	7.21	7.19	6.75	12.44	23.33
	V19	360.85	330.60	7.40	7.62	7.31	7.25	7.41	7.38	7.24	7.16	8.38	11.30	15.74
	V20	358.22	321.40	7.03	7.37	7.16	6.81	6.67	5.68	6.77	7.10	10.28	23.47	46.97
	V21	360.85	328.50	7.21	7.40	7.01	7.58	6.77	7.56	6.90	7.62	8.96	13.46	24.67
	V22	358.60	321.60	7.40	7.30	7.00	6.91	7.25	7.58	7.60	7.66	10.32	11.51	21.52
	V23	360.85	322.50	7.20	7.41	7.80	7.11	7.05	6.88	7.21	7.34	10.63	13.61	22.20
	V24	361.22	324.90	7.32	7.12	7.18	7.31	7.12	7.15	7.16	7.22	10.06	14.85	16.68
	V25	359.72	329.30	7.41	7.30	7.12	7.51	7.38	7.19	7.28	7.02	8.46	12.98	19.00
	V26	361.97	321.70	7.31	7.35	7.16	7.52	7.38	7.46	7.82	7.64	11.13	8.65	15.74
Average											9.02	12.13	25.49	
C5	D1	456.87	361.90	*	6.04	4.90	7.09	7.00	5.18	4.42	4.15	20.79	49.55	71.69
	D2	459.87	361.40	*	6.80	3.89	*	6.80	6.44	5.62	6.46	21.41	40.80	75.13
	D3	488.01	361.20	4.11	6.39	4.18	5.55	5.98	4.81	*	5.46	25.98	55.36	72.24
	D4	487.26	365.90	7.11	7.12	5.36	2.41	*	5.72	4.38	6.11	24.91	51.03	90.45
	D5	488.38	393.00	6.11	6.34	6.36	6.26	4.17	5.68	4.00	7.23	19.53	45.30	73.70
	D6	483.51	369.00	6.82	7.30	4.53	6.51	3.93	3.36	2.61	7.14	23.68	54.26	88.80
	D7	485.38	380.00	4.68	7.00	6.34	7.39	4.09	5.11	4.61	7.00	21.71	45.14	72.50
	D8	486.13	406.00	6.77	7.34	6.48	6.82	6.40	6.80	5.80	7.07	16.48	26.55	44.71
	D9	486.88	402.30	3.97	6.70	6.50	6.08	6.24	6.50	6.57	7.02	17.37	36.87	74.09
	D10	457.62	359.70	*	7.04	5.39	6.69	7.11	7.30	4.46	4.63	21.40	39.07	67.31
	D11	489.51	352.80	2.89	7.37	7.25	7.41	2.96	5.43	*	3.00	27.93	55.78	86.27
	D12	277.58	225.50	*	7.24	4.09	7.34	7.41	*	*	*	18.76	30.13	72.50
	D13	489.51	388.10	3.77	6.16	4.90	6.50	6.86	6.92	6.91	4.98	20.72	43.27	76.64

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C5	D14	492.13	391.70	4.27	6.26	6.56	6.62	5.94	7.10	4.48	7.14	20.41	39.91	70.03
	D15	486.88	401.00	6.11	7.33	6.04	6.64	4.87	6.29	6.24	6.54	17.64	35.64	61.02
	D16	486.51	391.60	5.92	7.23	7.24	6.09	7.15	7.21	4.69	6.81	19.51	29.64	63.85
	D17	487.63	399.00	5.98	7.10	7.43	7.50	*	7.33	3.56	7.46	18.18	27.91	79.17
	D18	343.59	278.00	*	6.65	5.90	6.93	5.94	*	*	*	19.09	33.62	42.78
	D19	487.63	373.90	5.26	4.22	3.20	6.71	3.27	3.77	*	6.80	23.32	62.96	83.17
	D20	490.63	391.30	4.84	6.22	6.64	6.84	3.50	5.57	*	7.36	20.25	43.70	79.87
	D21	487.26	393.70	5.42	7.09	6.03	4.22	6.60	4.17	5.48	5.70	19.20	31.62	71.42
	D22	484.26	412.30	6.36	6.56	5.56	7.02	5.78	6.51	7.04	5.21	14.86	35.69	55.38
	D23	465.13	364.80	4.33	7.00	*	5.85	2.50	*	*	7.31	21.57	52.11	89.73
	D24	259.57	192.00	3.36	6.74	*	*	*	*	*	3.80	26.03	64.71	81.44
	D25	350.72	276.00	2.21	6.84	6.63	*	*	*	6.56	5.88	21.30	48.01	91.97
	D26	366.47	289.80	4.71	4.39	6.55	6.95	*	*	*	7.10	20.92	42.01	68.32
	Average											20.88	43.10	73.24
	V1	365.35	309.10	7.42	7.34	3.15	7.38	7.45	7.41	5.38	7.38	15.40	28.10	83.69
	V2	367.97	331.70	7.45	7.46	6.50	7.50	6.47	7.34	7.40	7.38	9.86	15.09	31.20
	V3	368.72	332.90	7.43	7.48	7.51	7.43	7.44	7.47	7.64	7.56	9.72	7.67	9.26
	V4	362.72	329.30	7.45	7.61	5.31	7.51	7.53	7.52	7.48	7.44	9.21	14.05	53.66
	V5	368.35	331.80	7.35	7.41	5.31	7.58	7.51	7.50	6.97	7.48	9.92	16.24	53.66
	V6	366.85	332.10	7.45	7.51	6.82	7.50	7.48	7.43	6.27	7.44	9.47	13.90	35.38
	V7	370.60	331.00	7.11	7.40	7.43	7.42	7.38	7.39	7.48	7.41	10.69	10.54	16.91
	V8	366.47	337.80	7.45	7.48	7.43	7.41	6.24	7.52	6.33	7.38	7.82	15.85	36.00
	V9	367.97	322.40	7.40	7.23	6.50	7.06	7.38	7.41	6.98	7.44	12.39	15.38	30.56
	V10	365.35	335.00	6.92	7.43	7.27	7.08	7.07	7.72	7.34	7.74	8.31	11.90	21.29
	V11	366.47	323.90	7.46	7.48	7.52	7.38	6.15	7.44	7.39	7.60	11.62	12.35	37.83
	V12	367.22	325.30	7.44	7.49	7.60	7.58	7.34	7.45	6.02	7.48	11.42	12.41	40.43

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C5	V13	366.47	325.00	7.06	7.45	5.10	7.39	5.21	7.48	7.44	7.47	11.32	23.44	57.25
	V14	367.60	316.70	4.60	7.48	7.46	7.44	7.54	7.51	4.95	7.60	13.85	23.49	65.22
	V15	370.60	327.60	7.54	7.48	5.54	7.46	7.44	7.43	7.39	7.37	11.60	14.64	49.55
	V16	366.10	327.60	3.87	7.68	6.76	7.45	7.51	7.53	6.64	7.43	10.52	22.68	75.38
	V17	366.47	334.50	7.54	7.53	7.48	7.49	6.73	7.45	4.54	7.46	8.72	18.83	66.12
	V18	364.60	336.60	7.58	7.56	7.54	7.52	7.54	7.53	7.48	7.49	7.68	6.80	8.04
	V19	372.10	337.90	7.48	7.46	7.47	7.43	7.38	7.49	7.38	7.31	9.19	9.38	12.17
	V20	366.85	334.70	7.38	7.49	6.42	7.32	7.38	7.47	7.41	7.23	8.76	13.31	32.25
	V21	363.47	333.20	3.68	7.38	7.47	7.43	7.51	7.28	7.34	7.64	8.33	20.24	77.74
	V22	366.10	329.00	4.67	7.42	7.50	7.38	6.04	7.48	7.49	7.38	10.13	21.29	64.15
	V23	370.23	325.30	7.57	7.48	7.61	7.49	7.60	3.72	7.56	7.48	12.13	17.99	77.25
	V24	367.22	338.70	7.49	7.46	7.48	7.49	7.48	7.45	7.43	7.46	7.77	8.34	9.26
	V25	366.47	333.00	7.49	7.48	7.57	0.75	7.49	7.48	7.47	7.51	9.13	27.22	99.09
	V26	372.10	340.20	7.56	7.54	7.48	7.39	6.56	7.51	7.49	7.60	8.57	10.21	29.27
Average											10.14	15.82	45.10	
C6	D1	414.49	275.48	6.76	6.27	6.75	5.14	3.25	6.69	6.41	6.24	33.54	42.02	82.61
	D2	474.13	311.68	6.27	7.00	6.03	4.31	6.15	6.18	6.58	4.52	34.26	43.21	69.53
	D3	435.49	269.66	5.64	6.27	6.95	6.00	6.53	6.89	6.81	5.34	38.08	34.69	53.21
	D4	476.38	278.41	2.08	3.69	5.19	6.19	1.83	6.24	6.97	5.14	41.56	64.22	94.52
	D5	476.38	309.08	5.43	6.18	6.80	6.89	6.93	5.30	5.15	6.86	35.12	37.01	56.44
	D6	476.38	319.02	6.90	6.74	5.10	6.21	5.93	3.12	7.02	2.29	33.03	51.79	91.36
	D7	479.00	328.22	7.00	5.34	6.93	6.29	6.54	6.94	5.31	6.45	31.48	33.75	53.62
	D8	474.50	329.71	7.00	4.28	7.01	6.28	6.95	5.50	6.31	6.67	30.51	35.81	69.86
	D9	473.75	335.67	7.01	6.68	6.13	6.54	5.71	3.84	6.97	7.01	29.15	36.08	75.79
	D10	473.75	336.31	2.87	5.80	6.53	6.79	6.45	5.92	7.00	6.42	29.01	41.39	86.49
	D11	474.50	340.02	6.94	4.96	6.79	6.68	6.34	7.01	6.76	6.53	28.34	30.54	59.55

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C6	D12	472.25	325.11	2.20	6.45	7.01	4.52	6.66	6.86	3.88	6.21	31.16	50.77	92.05
	D13	441.87	298.30	1.66	6.81	4.60	6.39	4.98	6.17	6.73	6.81	32.49	49.95	95.46
	D14	450.87	330.90	4.91	5.90	3.76	6.00	5.73	5.87	6.51	7.02	26.61	46.36	76.82
	D15	466.25	324.25	6.95	6.88	6.88	6.97	5.45	5.76	7.02	3.84	30.46	36.44	75.79
	D16	472.63	333.98	6.93	6.21	4.77	6.96	7.02	5.38	6.53	6.98	29.33	33.75	62.55
	D17	474.13	328.44	6.77	6.47	5.11	6.68	6.18	5.36	5.65	4.69	30.73	43.47	63.82
	D18	472.63	323.88	6.53	5.65	2.50	4.72	2.41	6.98	7.01	5.02	31.47	57.20	90.45
	D19	381.48	281.99	5.58	3.52	4.01	5.05	6.80	6.88	6.84	5.23	26.08	50.46	79.61
	D20	434.37	258.24	6.83	6.17	4.66	4.47	1.40	2.27	6.69	5.97	40.55	62.02	96.76
	D21	473.00	294.07	6.51	5.01	3.90	1.94	5.34	6.21	5.99	5.35	37.83	58.42	93.80
	D22	407.74	290.44	2.82	6.21	6.65	5.92	4.97	6.53	6.35	7.02	28.77	44.53	86.93
	D23	510.14	298.42	6.89	6.88	4.63	4.08	2.47	3.14	3.39	7.02	41.50	61.92	89.98
	D24	492.51	298.72	6.88	5.91	5.72	4.73	2.11	2.67	6.07	6.56	39.35	57.57	92.71
	D25	376.23	224.79	6.79	5.76	6.98	5.87	5.94	5.03	2.45	*	40.25	49.45	90.17
	D26	307.58	199.75	6.42	5.07	6.27	6.55	5.65	4.43	*	*	35.06	45.98	67.68
	Average											33.30	46.11	78.75
	V1	346.59	284.53	6.89	7.05	6.13	6.99	6.56	6.84	3.48	7.28	17.91	32.62	80.05
	V2	347.34	297.55	7.10	7.34	4.75	7.39	7.38	7.25	6.85	7.35	14.33	21.15	62.87
	V3	338.72	298.34	4.49	7.03	6.84	6.95	7.45	6.89	7.49	6.70	11.92	25.56	66.82
	V4	346.22	301.95	7.20	7.10	6.08	7.41	7.40	7.49	3.10	7.46	12.79	27.19	84.21
	V5	347.72	303.44	7.30	7.28	5.65	7.35	7.05	7.43	6.81	7.34	12.73	18.87	47.58
	V6	340.59	309.83	7.10	7.26	6.68	7.21	7.09	7.19	5.13	7.26	9.03	22.53	56.79
	V7	348.84	304.28	7.10	6.96	7.05	7.16	7.01	7.33	4.38	7.01	12.78	25.08	68.49
	V8	348.09	302.18	7.03	7.00	6.71	6.89	6.78	6.96	4.72	7.15	13.19	27.19	63.36
	V9	348.47	307.96	7.45	7.33	5.74	7.40	7.23	7.28	7.41	7.20	11.63	16.46	45.83
	V10	347.34	298.33	6.95	6.69	7.01	7.49	6.89	6.94	5.56	6.81	14.11	24.14	49.12

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C6	V11	348.84	304.88	7.49	7.31	7.15	7.43	7.45	7.49	5.94	7.35	12.60	14.78	42.04
	V12	349.22	305.63	7.39	7.43	7.41	7.48	7.45	6.00	7.40	7.38	12.48	13.81	40.81
	V13	351.85	296.21	3.74	7.46	6.81	7.49	7.30	7.41	6.76	7.45	15.81	23.89	76.96
	V14	360.10	287.80	7.19	7.05	6.68	7.23	6.02	*	3.13	7.49	20.08	32.75	83.89
	V15	347.72	287.09	6.25	6.51	6.59	7.00	6.78	6.64	5.14	6.70	17.44	31.59	56.62
	V16	347.72	301.17	7.33	7.31	7.43	5.99	7.24	7.21	7.31	7.20	13.39	16.50	41.02
	V17	349.59	297.92	7.06	6.88	6.95	7.04	5.45	6.90	6.71	7.36	14.78	24.11	51.19
	V18	338.34	300.40	7.15	7.41	5.57	7.38	7.33	7.19	7.31	7.34	11.21	17.49	48.93
	V19	346.97	300.11	7.46	7.36	6.65	7.25	4.86	7.48	6.73	7.49	13.51	21.53	61.23
	V20	348.09	280.64	3.91	7.04	5.59	6.50	6.88	6.29	5.98	6.75	19.38	38.49	74.87
	V21	348.84	306.31	7.41	7.38	4.86	*	6.86	7.49	6.29	7.34	12.19	23.92	61.23
	V22	262.20	222.49	6.91	6.94	4.65	7.09	7.25	7.24	6.71	*	15.14	26.55	64.48
	V23	256.57	223.12	7.49	7.49	6.68	7.49	4.63	7.30	7.24	*	13.04	21.72	64.80
	V24	274.57	135.89	1.33	4.70	3.79	4.99	4.89	5.44	6.60	2.36	*	70.11	97.09
	V25	349.59	300.66	6.07	6.51	7.25	7.40	7.13	7.39	4.13	7.49	14.00	26.87	71.98
	V26	255.44	217.93	7.30	7.41	6.76	7.45	4.47	7.49	5.84	*	14.69	26.75	67.13
Average											14.01	25.83	62.67	

Table D.3 Corrosion measurement of transverse reinforcing bars for test specimens in Series 3

Specimen	No.	W0	W1	R1	R2	R3	R4	R5	R6	R7	R8	$X_{corr}^{(1)}$	$X_{corr}^{(2)}$	$X_{corr}^{(3)}$
		g	g	mm	mm	mm	mm	mm	mm	mm	mm	%	%	%
CC1	D1	486.88	418.90	7.40	4.80	4.80	8.00	7.80	6.50	5.20	7.10	13.96	31.62	62.13
	D2	485.38	407.80	7.20	7.50	6.60	6.60	6.80	6.70	3.90	7.90	15.98	27.31	75.00
	D3	487.63	402.90	6.40	6.20	6.40	5.80	4.20	6.50	6.70	6.60	17.38	38.84	71.01
	D4	490.63	412.10	6.80	6.70	6.50	5.80	4.90	7.00	4.10	5.70	16.01	42.05	72.37
	D5	486.13	408.80	5.00	5.90	5.90	7.30	6.90	5.50	5.90	7.50	15.91	36.05	58.91
	D6	468.13	416.70	6.00	6.10	6.30	6.40	6.70	6.90	6.30	6.60	10.99	32.41	40.83
	D7	486.13	412.50	6.00	6.70	7.70	7.40	7.10	7.30	6.00	7.40	15.15	20.61	40.83
	D8	485.38	416.80	6.50	6.30	6.60	5.30	5.60	6.70	7.00	6.80	14.13	33.72	53.83
	D9	485.76	424.30	6.50	6.80	6.90	6.70	6.60	6.60	6.50	6.90	12.65	26.49	30.56
	D10	491.38	432.20	6.80	6.70	6.40	6.30	6.90	6.10	5.50	6.80	12.04	31.88	50.28
	D11	490.26	423.00	6.90	7.60	7.40	5.80	7.10	7.20	7.00	6.20	13.72	21.75	44.71
	D12	489.13	410.90	4.50	6.30	6.50	7.00	5.20	7.90	6.50	4.10	15.99	40.83	72.37
	D13	479.00	404.40	5.90	7.40	6.90	6.40	6.00	7.00	6.70	6.70	15.57	27.86	42.78
	D14	493.63	422.40	7.00	4.50	5.50	7.80	6.80	6.80	7.00	7.50	14.43	28.13	66.72
	D15	485.38	402.10	5.50	6.50	5.30	7.50	6.10	6.00	5.00	6.00	17.16	41.07	58.91
	D16	488.76	406.10	7.50	6.60	5.40	6.70	6.30	5.50	6.40	6.60	16.91	33.20	52.07
	D17	486.88	400.50	5.90	7.00	6.00	5.80	5.80	7.10	6.80	4.60	17.74	38.34	65.22
	D18	456.87	404.60	7.20	7.50	5.90	6.00	6.20	6.90	6.60	*	11.44	28.09	42.78
	D19	486.88	413.10	6.10	6.80	6.00	6.40	7.00	6.90	6.70	7.10	15.15	27.86	40.83
	D20	486.88	425.40	6.20	6.50	6.80	7.00	6.40	6.80	7.90	7.40	12.63	22.31	36.82
Average												14.75	31.52	53.95

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CC1	V1	369.10	337.30	7.20	7.40	7.60	7.60	7.00	7.40	7.70	7.70	8.62	8.77	19.46
	V2	370.60	340.90	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.70	8.01	0.32	2.55
	V3	369.10	335.80	7.20	7.30	7.10	7.00	7.80	7.40	7.30	7.50	9.02	11.81	19.46
	V4	369.85	342.30	7.40	7.20	7.80	7.60	7.70	7.50	7.50	7.80	7.45	6.00	14.79
	V5	371.35	341.10	7.10	7.70	7.20	7.80	6.50	7.50	7.00	7.70	8.15	12.11	30.56
	V6	363.47	335.20	7.00	7.60	7.50	7.80	6.60	7.80	7.80	7.80	7.78	7.85	28.40
	V7	370.23	342.60	7.10	7.60	7.80	7.40	7.50	7.60	7.80	7.70	7.46	6.00	17.14
	V8	368.35	345.30	7.20	7.60	7.50	7.40	7.30	7.50	7.10	7.70	6.26	9.69	17.14
	V9	369.47	342.30	7.80	7.40	7.50	7.10	7.00	7.20	7.00	7.40	7.36	12.41	19.46
	V10	372.85	351.20	7.50	7.40	7.30	7.80	7.60	7.10	7.80	7.80	5.81	6.62	17.14
	V11	370.23	342.70	7.20	7.30	7.50	7.80	7.40	7.50	7.30	7.60	7.43	8.77	14.79
	V12	369.10	343.30	7.50	7.40	7.30	7.40	7.10	7.50	7.60	7.80	6.99	8.77	17.14
	V13	366.85	341.20	4.80	7.80	7.80	7.30	7.50	7.50	7.80	7.80	6.99	12.71	62.13
	V14	370.23	336.80	7.40	7.30	7.20	7.70	6.40	7.30	7.50	7.30	9.03	13.31	32.68
	V15	364.60	337.70	6.50	7.80	7.20	7.50	6.90	6.60	6.80	7.50	7.38	17.14	30.56
	V16	366.47	336.40	7.50	7.10	6.40	7.80	7.40	7.10	7.80	7.30	8.21	12.41	32.68
	V17	365.35	334.00	6.50	7.60	7.00	5.90	5.90	7.50	7.50	7.50	8.58	21.18	42.78
	V18	367.22	331.00	7.10	5.90	7.00	6.50	4.30	7.20	7.00	7.50	9.86	29.21	69.61
	V19	372.48	338.40	7.60	7.80	7.40	7.80	7.10	6.90	7.40	7.60	9.15	8.77	21.75
	V20	377.73	340.10	7.20	7.20	7.60	7.70	7.20	7.10	7.20	7.50	9.96	11.51	17.14
Average												7.97	11.27	26.37
CC2	D1	477.50	372.33	7.52	6.77	6.11	5.26	6.30	7.52	7.61	7.80	22.02	22.64	54.48
	D2	482.01	364.92	7.71	4.51	5.17	7.52	7.52	5.26	5.17	6.86	24.29	36.53	66.56
	D3	482.38	344.16	6.20	5.36	6.95	3.95	1.88	8.18	6.20	7.52	28.65	45.10	94.19
	D4	474.88	352.46	7.33	4.60	6.01	6.30	7.24	6.67	6.39	6.01	25.78	34.35	65.15
	D5	481.63	349.02	4.23	7.24	6.95	4.89	6.39	6.67	5.83	6.01	27.53	40.31	70.61

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CC2	D6	480.88	292.06	5.92	6.86	3.85	5.54	5.73	5.64	5.73	5.73	39.27	47.96	75.60
	D7	474.88	281.37	2.91	3.01	5.64	6.67	5.64	6.39	2.82	6.86	40.75	59.03	86.94
	D8	477.13	289.85	5.73	3.76	2.26	6.11	2.63	5.26	3.38	6.67	39.25	67.08	91.64
	D9	471.88	289.58	4.60	4.04	2.73	6.39	5.17	4.04	6.48	5.45	38.63	61.13	87.79
	D10	480.88	304.16	5.45	5.36	4.42	5.07	6.67	6.48	5.36	6.86	36.75	46.43	67.93
	D11	480.13	309.45	6.48	5.83	6.01	2.16	6.95	6.20	5.45	6.95	35.55	45.54	92.32
	D12	480.13	316.34	5.26	4.13	3.57	7.24	6.30	7.05	7.05	6.20	34.11	43.75	79.04
	D13	475.63	301.86	2.63	4.98	5.07	7.05	5.36	4.70	6.20	6.30	36.53	54.07	88.62
	D14	482.38	305.04	6.48	7.24	5.54	6.01	6.39	1.88	4.13	7.14	36.76	48.39	94.19
	D15	481.26	306.89	6.67	6.48	5.07	4.32	6.20	3.85	2.63	6.58	36.23	55.09	88.62
	D16	481.26	346.02	6.58	7.42	6.39	6.58	5.64	4.70	2.91	2.73	28.10	52.63	87.79
	D17	479.00	307.78	2.26	5.73	4.70	6.30	6.11	6.30	5.64	4.89	35.75	54.88	91.64
	D18	481.63	325.00	5.83	4.98	6.39	5.17	5.64	6.58	5.92	6.20	32.52	43.98	59.22
	D19	483.13	370.92	6.67	3.67	6.20	5.26	5.07	6.39	7.42	7.05	23.23	41.47	77.92
	D20	486.88	376.75	6.39	6.77	5.83	7.61	6.77	7.52	3.57	6.20	22.62	34.11	79.04
	Average											32.22	46.72	79.96
	V1	360.10	326.59	7.80	7.80	7.80	7.61	7.80	7.80	7.61	7.71	9.31	1.50	4.76
	V2	362.72	317.14	6.86	7.61	5.64	7.71	5.07	7.80	7.75	7.80	12.57	18.76	57.67
	V3	351.09	325.00	7.71	7.71	7.33	7.80	7.75	8.03	7.71	7.75	7.43	1.95	11.69
	V4	360.85	327.65	7.05	7.80	5.92	7.80	7.80	7.80	7.38	7.80	9.20	9.55	42.39
	V5	360.85	331.45	7.61	7.52	7.52	7.52	6.16	7.71	7.00	7.66	8.15	11.54	37.72
	V6	359.35	325.97	4.98	7.71	7.71	7.61	6.67	7.71	7.52	7.61	9.29	15.05	59.22
	V7	360.10	327.74	7.52	7.71	7.14	7.80	6.77	7.61	7.80	7.71	8.99	7.39	24.75
	V8	358.60	324.29	6.11	7.80	7.80	5.87	7.61	7.75	7.80	7.80	9.57	11.97	43.30
	V9	364.22	327.91	7.52	7.71	7.61	7.80	7.80	7.61	6.58	6.44	9.97	10.41	31.89
	V10	362.72	325.26	7.14	7.71	7.28	7.61	7.33	7.80	7.80	7.80	10.33	6.08	16.16

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CC2	V11	362.72	327.91	7.57	7.75	7.57	7.61	7.47	7.75	7.66	7.80	9.60	3.88	8.26
	V12	360.47	322.53	7.00	7.61	5.64	7.80	6.48	7.80	7.33	7.57	10.53	15.88	47.74
	V13	360.10	287.99	7.71	7.71	7.42	7.42	7.99	6.72	7.33	7.28	20.02	8.83	25.79
	V14	350.34	318.11	7.05	7.61	5.64	7.80	7.80	7.80	7.33	7.57	9.20	11.83	47.74
	V15	360.10	318.37	7.52	6.58	7.24	7.80	7.52	7.80	7.52	7.71	11.59	8.54	28.87
	V16	360.47	325.44	7.24	7.71	4.70	7.80	7.71	7.61	7.80	7.52	9.72	13.38	63.71
	V17	364.22	319.08	7.52	7.61	5.17	7.80	7.89	7.66	7.75	7.57	12.39	10.69	56.09
	V18	358.60	323.67	6.67	7.71	6.39	7.71	8.18	7.52	7.52	7.52	9.74	9.98	32.88
	V19	359.72	323.41	7.05	7.80	6.58	7.52	5.64	7.61	7.71	7.71	10.09	14.77	47.74
	V20	363.10	327.38	6.91	7.80	7.80	8.08	7.42	7.80	5.64	7.80	9.84	9.84	47.74
Average											10.38	10.09	36.81	
CC3	D1	436.62	271.67	6.24	5.95	5.19	2.81	5.80	4.56	5.78	5.60	37.78	54.86	87.04
	D2	381.85	233.95	5.11	4.32	4.09	3.12	5.45	5.09	4.48	5.72	38.73	64.14	84.00
	D3	411.11	245.01	4.01	6.21	6.15	7.29	5.62	3.08	7.42	5.66	40.40	46.98	84.40
	D4	384.85	234.83	6.13	5.52	5.84	5.68	7.55	5.17	*	*	38.98	41.17	56.09
	D5	477.50	284.50	6.10	6.24	6.24	3.12	2.97	3.63	4.52	2.82	40.42	67.36	86.94
	D6	430.24	226.01	2.70	5.95	6.24	3.63	3.04	5.23	5.71	*	47.47	64.57	87.98
	D7	335.72	217.87	6.09	5.06	7.10	5.75	7.01	6.06	4.78	5.23	35.10	43.09	62.38
	D8	457.62	239.91	6.20	5.36	4.45	5.30	4.26	4.48	7.20	3.52	47.57	57.30	79.60
	D9	410.74	262.20	6.16	7.20	6.15	2.73	4.41	6.14	7.48	*	36.16	45.64	87.75
	D10	459.12	276.07	4.95	1.70	7.58	7.74	7.80	4.30	5.90	7.23	39.87	42.80	95.23
	D11	438.87	265.55	6.20	7.36	6.24	4.94	2.54	5.28	5.04	4.63	39.49	54.21	89.44
	D12	429.49	248.73	5.99	4.76	5.04	*	2.96	6.23	5.40	4.27	42.09	59.71	85.56
	D13	410.36	234.21	3.96	2.43	4.24	5.97	7.64	6.24	4.72	2.97	42.93	62.56	90.29
	D14	332.34	197.68	5.36	3.60	4.04	6.17	5.39	3.99	*	*	40.52	62.82	78.72

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CC3	D15	328.59	202.25	6.24	6.15	5.97	3.68	7.67	4.15	5.36	*	38.45	48.43	77.75
	D16	387.48	193.03	4.32	4.48	2.45	3.47	6.06	6.17	7.66	1.83	50.18	65.88	94.48
	D17	500.01	313.00	6.24	4.79	6.24	6.24	5.65	4.07	6.62	4.84	37.40	48.72	72.79
	D18	361.97	208.15	5.57	4.83	4.60	5.28	6.01	4.03	*	*	42.49	58.02	73.31
	D19	480.13	304.92	6.24	4.15	5.51	6.16	6.24	3.96	6.12	5.26	36.49	51.10	74.19
	D20	473.38	296.56	5.02	4.34	3.66	6.20	5.35	3.80	4.82	5.89	37.35	60.80	77.97
	Average											40.13	54.66	80.10
	V1	348.84	301.65	6.22	7.07	6.53	6.99	6.77	7.05	5.80	7.21	13.53	26.10	44.70
	V2	347.72	311.85	7.45	7.16	7.10	7.49	7.26	7.57	6.51	7.07	10.32	14.75	30.41
	V3	347.34	303.12	6.95	7.09	6.73	7.07	7.19	6.78	6.82	6.90	12.73	20.81	25.47
	V4	350.34	305.44	7.39	7.35	6.23	7.35	5.55	7.40	6.76	7.28	12.82	21.44	49.40
	V5	345.84	293.24	7.10	7.00	4.99	6.91	6.94	6.42	6.33	6.83	15.21	29.16	59.01
	V6	349.22	303.28	7.14	7.45	7.16	7.39	7.26	7.36	5.89	7.54	13.16	15.98	43.00
	V7	348.84	300.12	5.71	7.21	3.76	6.77	6.78	7.05	6.17	6.99	13.97	34.66	76.79
	V8	349.97	311.38	7.49	7.45	5.46	7.25	7.16	7.57	6.20	*	11.03	20.82	51.00
	V9	350.34	312.67	7.38	7.20	5.47	7.44	6.97	7.38	7.07	7.49	10.75	18.29	50.77
	V10	346.97	308.89	7.04	7.20	6.61	7.55	6.91	7.54	5.57	7.34	10.97	20.15	48.94
	V11	349.97	319.11	7.57	7.35	6.75	7.47	7.30	7.31	6.77	7.41	8.82	13.81	25.19
	V12	346.59	308.08	7.57	7.57	6.29	7.57	6.42	7.57	5.83	7.47	11.11	18.69	44.21
	V13	347.72	314.09	7.35	7.49	6.72	7.57	7.15	7.43	7.33	7.47	9.67	12.12	25.75
	V14	351.09	316.06	7.25	7.14	6.87	7.31	7.20	7.24	7.39	7.25	9.98	14.64	22.37
	V15	348.09	319.34	7.34	7.14	7.45	7.62	6.24	7.43	6.76	7.36	8.26	15.57	35.96
	V16	346.59	304.35	6.09	7.41	5.67	6.99	7.41	7.36	7.05	7.57	12.19	20.72	47.07
	V17	346.97	311.16	6.44	7.55	6.75	7.36	7.49	7.57	6.70	7.57	10.32	15.31	31.75
	V18	350.34	304.21	7.07	7.10	7.11	7.26	6.57	7.26	5.14	5.49	13.17	27.83	56.49

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CC3	V19	349.97	276.21	6.61	6.31	6.39	6.70	6.80	6.15	6.22	7.15	21.08	29.70	37.76
	V20	350.72	313.73	6.75	7.12	6.90	7.57	7.36	7.31	6.81	7.57	10.55	15.42	25.19
	Average											11.98	20.30	41.56
CC4	D1	482.38	429.60	6.26	6.81	7.24	6.70	6.96	7.10	6.92	7.40	10.94	21.21	35.59
	D2	483.13	433.10	7.44	7.39	7.28	7.07	6.08	7.21	6.33	6.96	10.36	20.15	39.24
	D3	479.38	421.70	6.54	6.90	7.19	7.15	6.99	6.79	6.57	7.16	12.03	21.49	29.70
	D4	483.13	420.90	6.32	7.34	4.64	5.40	4.67	7.18	5.30	6.60	12.88	42.18	64.61
	D5	481.26	421.80	7.56	7.26	6.48	6.33	6.39	7.19	7.16	5.57	12.35	25.28	49.01
	D6	479.75	416.70	7.11	6.96	7.18	6.83	6.04	6.73	7.09	6.66	13.14	23.44	40.04
	D7	482.76	418.90	5.75	7.38	7.44	7.39	7.22	7.04	7.91	6.83	13.23	16.68	45.66
	D8	485.38	429.00	7.55	7.33	7.11	7.12	4.64	7.14	6.93	7.35	11.62	21.83	64.61
	D9	484.26	432.30	6.31	7.44	6.97	7.28	6.92	7.12	6.79	7.44	10.73	18.68	34.56
	D10	481.63	427.60	7.25	7.24	7.27	6.87	6.50	7.10	7.02	7.34	11.22	17.75	30.56
	D11	486.13	435.50	6.99	5.99	7.05	7.29	5.60	7.45	7.08	7.49	10.42	22.48	48.45
	D12	482.38	429.10	7.28	6.80	7.06	7.12	6.89	7.43	6.64	7.20	11.05	18.25	27.53
	D13	486.13	426.60	7.35	7.34	7.06	7.12	6.02	7.01	7.07	6.51	12.25	20.95	40.43
	D14	484.63	430.20	6.93	6.92	6.94	9.80	9.70	7.15	7.34	6.72	11.23	2.86	25.78
	D15	485.01	416.70	6.09	7.04	6.65	6.31	5.36	7.03	6.90	7.07	14.08	29.35	52.78
	D16	482.38	417.60	5.83	6.36	7.09	7.22	5.99	6.88	6.38	6.59	13.43	29.64	44.13
	D17	483.88	424.00	5.99	6.50	6.65	7.35	7.31	7.01	6.74	7.50	12.38	22.17	41.03
	D18	485.38	418.10	6.88	7.21	6.62	7.35	7.31	5.24	6.69	6.81	13.86	24.81	54.87
	D19	477.88	420.30	6.73	7.24	7.03	7.12	5.65	5.77	5.61	6.30	12.05	32.02	48.27
	D20	483.51	413.90	6.73	6.76	5.33	6.35	5.64	6.09	4.63	5.80	14.40	42.47	64.77
	Average											12.18	23.68	44.08
	V1	370.98	335.00	7.36	7.41	7.49	7.34	7.52	7.46	7.41	7.33	9.70	9.63	11.69
	V2	372.48	330.10	7.48	7.43	7.51	7.48	7.46	7.50	7.39	7.40	11.38	8.62	10.24

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CC4	V3	372.85	333.70	7.38	7.44	7.60	7.51	7.48	7.49	7.46	7.44	10.50	8.16	10.48
	V4	373.60	328.60	7.50	7.48	7.12	7.44	7.29	7.48	7.39	7.51	12.05	9.96	16.68
	V5	368.35	332.60	7.44	7.45	7.46	7.48	7.43	6.84	7.42	7.43	9.71	10.75	23.10
	V6	373.23	335.60	7.45	7.44	7.39	7.38	7.41	7.43	7.38	7.46	10.08	9.57	10.48
	V7	370.23	337.30	7.46	7.74	7.40	7.37	7.47	7.48	7.39	7.46	8.89	8.24	10.72
	V8	369.85	334.50	7.46	7.43	7.50	7.43	6.97	7.50	7.49	7.46	9.56	9.87	20.15
	V9	370.60	343.30	7.43	7.49	7.22	7.48	7.31	7.49	7.28	7.47	7.37	10.08	14.32
	V10	370.60	342.60	7.48	7.43	7.46	7.45	7.39	7.34	6.99	7.39	7.56	10.81	19.69
	V11	372.10	343.60	7.43	7.46	7.48	7.47	7.48	7.43	7.49	7.45	7.66	8.50	9.26
	V12	372.85	340.50	7.46	7.50	7.51	7.49	7.34	7.39	7.38	7.46	8.68	8.99	11.45
	V13	371.73	342.00	7.39	7.44	7.52	7.49	7.48	7.53	7.58	7.48	8.00	7.82	10.24
	V14	371.73	337.70	7.46	7.43	7.39	7.48	7.41	7.47	7.43	7.42	9.15	9.11	10.24
	V15	375.48	339.10	7.48	7.43	7.44	7.47	7.00	7.46	7.10	7.43	9.69	11.18	19.46
	V16	371.73	333.40	7.46	7.48	7.25	7.43	7.08	7.40	6.76	7.43	10.31	12.74	24.89
	V17	372.10	338.30	7.49	7.48	7.20	7.46	7.13	7.46	7.45	7.41	9.08	10.36	16.44
	V18	374.35	335.10	7.05	7.44	7.43	7.48	6.98	7.60	7.45	7.50	10.49	10.81	19.92
	V19	370.98	322.90	7.44	7.43	7.46	7.38	7.39	7.43	6.65	7.41	12.96	11.84	27.31
	V20	368.72	332.30	6.86	7.10	6.77	7.24	7.46	7.43	7.39	6.96	9.88	15.94	24.67
	Average											9.63	10.15	16.07
CC5	D1	478.25	397.40	4.82	7.19	6.30	7.34	6.87	5.81	6.91	6.03	16.91	32.49	61.81
	D2	488.76	394.30	7.30	7.00	6.98	6.89	6.92	6.94	*	4.90	19.33	26.12	60.54
	D3	484.63	391.30	4.56	3.68	4.44	7.16	7.19	6.27	7.52	5.74	19.26	44.33	77.74
	D4	485.38	396.50	7.42	7.56	7.61	7.34	6.19	4.52	*	7.24	18.31	23.10	66.42
	D5	488.01	380.90	6.73	6.99	5.80	6.11	5.68	3.42	*	6.79	21.95	42.17	80.78
	D6	487.63	392.80	7.45	7.30	6.97	4.61	6.40	7.64	2.68	4.02	19.45	43.10	88.19
	D7	485.76	397.00	7.24	6.81	6.24	6.46	5.78	5.40	*	7.48	18.27	30.83	52.07

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CC5	D8	487.63	391.50	6.57	5.50	5.30	6.74	5.96	7.38	7.14	5.83	19.71	34.71	53.83
	D9	483.88	405.10	6.30	7.40	6.70	6.30	6.38	6.13	5.80	6.78	16.28	31.12	44.71
	D10	486.88	405.10	5.39	7.30	6.70	6.28	7.01	5.67	4.64	6.89	16.80	36.10	64.61
	D11	482.76	416.30	6.81	6.32	7.33	6.78	5.71	6.62	7.35	7.57	13.77	23.75	46.41
	D12	486.13	423.90	7.07	7.23	5.20	5.48	6.68	6.92	7.00	7.45	12.80	27.78	55.56
	D13	486.51	407.50	6.40	7.50	6.71	7.15	5.78	6.15	6.55	6.79	16.24	27.78	45.09
	D14	486.88	395.00	5.87	7.02	6.67	6.20	6.98	6.05	5.70	7.48	18.87	30.64	46.60
	D15	486.51	417.30	7.30	6.15	6.38	7.34	7.31	6.56	7.18	6.40	14.23	23.38	37.83
	D16	485.01	415.50	6.35	6.35	6.99	6.99	7.60	6.14	6.89	6.45	14.33	25.78	38.03
	D17	482.76	403.50	6.48	5.74	4.58	5.10	4.75	7.63	6.11	7.50	16.42	41.10	65.52
	D18	488.38	387.40	4.62	4.78	5.75	5.38	5.06	6.42	4.84	6.10	20.68	52.62	64.92
	D19	486.51	405.80	7.72	7.14	6.11	7.25	6.36	5.86	4.85	4.78	16.59	35.61	62.45
	D20	487.26	419.50	6.35	7.38	6.44	5.73	6.82	6.04	6.82	4.88	13.91	34.61	60.86
	Average											16.93	33.01	58.45
	V1	365.72	329.20	5.70	7.45	7.62	7.33	6.44	7.42	7.59	7.60	9.99	16.12	46.60
	V2	373.23	344.60	7.56	7.45	7.34	7.26	7.80	7.64	7.56	7.61	7.67	6.87	13.37
	V3	364.60	328.50	3.24	7.35	7.46	7.61	6.22	7.42	7.33	7.51	9.90	24.72	82.75
	V4	363.10	330.00	7.41	7.49	7.43	7.38	7.51	7.46	7.60	7.38	9.12	8.59	10.48
	V5	364.22	332.20	7.34	7.45	7.64	7.71	7.64	7.61	7.46	7.80	8.79	5.53	11.45
	V6	368.72	340.30	6.38	7.58	6.80	7.43	7.36	7.28	7.05	7.44	7.71	15.62	33.10
	V7	368.35	347.70	7.34	7.61	7.51	7.48	7.56	7.62	7.48	7.46	5.61	7.36	11.45
	V8	371.73	342.40	6.85	7.81	7.82	7.62	7.77	7.61	7.48	7.80	7.89	5.19	22.88
	V9	376.23	344.10	7.68	6.89	7.80	7.38	7.33	7.49	7.19	7.80	8.54	8.90	21.97
	V10	373.60	351.20	7.56	7.64	7.79	7.80	7.80	7.65	7.51	7.38	6.00	4.03	10.48
	V11	370.98	342.70	7.80	7.68	7.63	7.64	7.25	7.71	7.49	7.45	7.62	5.53	13.61
	V12	379.23	354.10	7.58	7.61	7.36	7.48	6.86	7.52	7.11	7.64	6.63	10.12	22.65

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CC5	V13	372.85	354.40	7.65	7.74	7.49	7.80	7.20	7.68	6.67	7.59	4.95	8.10	26.88
	V14	366.10	337.50	7.38	7.29	7.61	7.47	6.96	7.54	5.85	7.61	7.81	14.47	43.75
	V15	368.35	349.50	7.46	7.80	7.80	7.80	7.69	7.74	5.95	7.73	5.12	7.64	41.81
	V16	368.72	350.30	7.80	7.80	7.07	7.31	7.15	7.70	6.24	7.71	5.00	11.27	36.00
	V17	364.60	341.30	7.74	7.69	7.75	7.80	6.92	7.40	5.15	7.56	6.39	13.58	56.41
	V18	366.85	343.70	7.63	7.55	7.53	7.72	7.37	7.80	6.46	7.32	6.31	9.45	31.41
	V19	368.72	340.50	5.52	7.45	7.40	7.62	6.78	7.77	7.80	7.66	7.65	13.61	49.92
	V20	374.73	346.20	7.55	7.42	7.52	7.55	7.27	7.28	7.10	7.68	7.61	9.48	17.14
Average											7.33	10.32	30.02	
CC6	D2	439.24	311.70	6.00	7.65	6.75	7.95	6.00	*	5.65	3.08	29.04	37.75	84.41
	D3	441.12	296.70	3.25	6.30	6.45	7.65	7.00	7.35	5.00	4.75	32.74	41.44	82.64
	D4	482.76	332.40	1.40	6.50	6.00	*	5.45	7.45	7.55	7.55	31.15	41.11	96.78
	D5	413.36	318.80	5.70	7.75	*	5.00	*	7.25	7.00	7.50	22.88	26.22	58.91
	D6	354.10	247.10	5.00	8.00	7.00	7.60	2.00	2.75	*	*	30.22	52.22	93.43
	D7	376.98	288.30	6.25	6.35	6.70	7.75	6.45	5.00	6.75	*	23.52	31.32	58.91
	D8	321.46	236.60	7.00	7.70	*	7.20	7.10	5.40	*	*	26.40	22.20	52.07
	D9	486.13	378.70	5.25	7.70	5.65	7.45	7.70	7.70	7.65	7.45	22.10	17.87	54.70
	D10	495.13	379.80	7.00	6.35	*	7.45	7.30	7.20	4.10	7.35	23.29	26.69	72.37
	D11	481.63	375.80	7.30	7.00	5.30	7.35	8.00	7.10	6.80	7.50	21.97	18.45	53.83
	D12	482.38	385.90	7.55	7.70	1.75	7.75	7.25	7.50	6.50	6.85	20.00	28.27	94.97
	D13	460.62	346.90	7.70	7.00	*	7.30	8.00	7.40	6.00	7.50	24.69	13.09	40.83
	D14	457.62	331.10	6.65	7.20	7.00	7.50	*	6.55	*	7.85	27.65	16.56	29.48
	D15	468.13	365.90	7.75	7.20	*	6.75	7.25	6.45	*	6.35	21.84	20.42	33.72
	D16	337.97	219.70	6.50	5.00	*	7.25	8.00	7.20	*	*	34.99	24.22	58.91
	D17	481.63	352.30	7.70	7.25	7.55	7.50	7.00	7.00	4.25	4.05	26.85	29.75	73.04
	D18	477.88	341.80	7.50	6.00	4.00	4.45	4.45	6.30	5.65	7.75	28.48	45.42	73.70

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CC6	D19	458.00	333.80	6.20	7.75	7.35	6.65	6.75	5.00	*	7.75	27.12	24.48	58.91
	D20	465.13	362.70	8.00	7.20	*	8.00	1.50	8.00	7.50	6.85	22.02	25.74	96.30
	Average											26.08	29.16	67.08
	V2	352.60	311.70	7.60	7.70	7.75	7.50	*	7.00	7.25	7.50	11.60	8.25	19.46
	V3	358.97	318.10	7.80	7.80	5.50	6.45	7.70	7.80	7.00	6.50	11.39	17.87	50.28
	V4	258.82	226.60	4.45	7.80	6.50	6.00	5.90	5.95	*	*	12.45	38.84	67.45
	V5	358.22	323.70	7.80	6.90	7.80	6.35	7.70	7.45	7.75	6.45	9.64	13.01	33.72
	V6	264.45	240.40	7.75	7.80	7.79	7.80	7.45	7.80	*	*	9.09	1.74	8.77
	V7	363.10	328.60	7.80	7.75	7.80	7.30	7.80	7.80	7.60	7.65	9.50	2.86	12.41
	V8	367.97	311.50	6.15	6.35	7.25	6.05	7.00	6.10	6.20	7.75	15.35	28.27	39.84
	V9	358.97	321.50	7.80	7.80	6.80	6.55	6.20	7.75	7.60	7.80	10.44	12.71	36.82
	V10	352.60	314.00	7.00	6.85	7.80	6.80	6.75	6.60	7.50	6.60	10.95	19.75	28.40
	V11	360.47	329.60	7.80	7.75	6.50	6.79	7.75	6.85	7.80	6.70	8.56	13.78	30.56
	V12	357.10	325.70	7.00	7.50	7.70	7.00	7.70	7.65	7.75	7.80	8.79	7.24	19.46
	V13	357.47	328.20	7.80	7.80	7.80	6.85	7.80	7.80	7.65	7.80	8.19	3.49	22.88
	V14	358.60	318.10	7.00	7.00	7.00	7.80	6.50	6.65	7.75	6.75	11.29	18.16	30.56
	V15	362.72	331.60	7.75	7.80	7.70	7.80	7.80	7.75	7.80	7.80	8.58	0.64	2.55
	V16	354.47	322.10	6.00	7.75	4.65	7.80	7.45	7.70	7.75	7.70	9.13	17.14	64.46
	V17	359.35	324.80	6.50	7.75	7.25	6.75	6.50	6.59	6.55	6.95	9.61	22.75	30.56
	V18	359.72	323.70	7.80	7.80	6.90	7.75	7.50	6.80	3.25	7.00	10.01	22.88	82.64
	V19	363.10	329.20	7.80	7.80	5.65	7.80	6.85	7.50	7.80	7.80	9.34	10.60	47.53
	V20	358.60	324.50	7.80	7.80	7.80	6.50	6.50	7.70	5.85	7.80	9.51	14.35	43.75
	V21	361.60	318.90	6.70	7.80	6.65	7.80	7.80	7.80	6.25	6.75	11.81	14.94	35.79
	Average											10.26	14.46	35.39

Figure D.3 Labelling and Measurement of corrosion levels of longitudinal reinforcing bars for test specimens in Series 2 and Series 3

Table D.4 Corrosion measurement of longitudinal reinforcing bars for test specimens in Series 2

Spe.	No.	W0	W1	R1	R2	R3	R4	$X_{corr}^{(1)}$	$X_{corr}^{(2)}$	$X_{corr}^{(3)}$
		g	g	mm	mm	mm	mm	%	%	%
C1	L1.1	1487.09	1428.10	19.26	19.21	19.20	19.36	3.97	7.29	7.84
	L1.2	1311.99	1260.40	19.28	19.34	19.35	19.21	3.93	6.93	7.74
	L1.3	1218.28	1174.60	19.25	19.09	19.05	19.25	3.59	8.22	9.27
	L2.1	1556.14	1516.40	19.29	19.25	19.28	19.16	2.55	7.41	8.22
	L2.2	1183.75	1149.00	19.36	19.34	19.33	19.39	2.94	6.35	6.59
	L2.3	1257.74	1214.30	18.91	19.09	19.08	19.07	3.45	9.39	10.60
	L3.1	1509.28	1468.70	19.45	19.08	19.11	18.99	2.69	8.25	9.84
	L3.2	1196.08	1159.80	19.17	19.51	19.30	19.45	3.03	6.32	8.13
	L3.3	1307.06	1270.70	19.13	19.34	19.30	19.38	2.78	7.00	8.51
	L4.1	1467.36	1407.60	19.29	19.29	19.33	19.38	4.07	6.66	6.97
	L4.2	1321.86	1270.20	19.27	19.24	19.34	19.35	3.91	6.88	7.46
	L4.3	1220.74	1173.50	19.28	19.18	19.29	19.34	3.87	7.14	8.03
	L5.1	1447.63	1410.00	19.25	19.28	19.34	19.40	2.60	6.71	7.36
	L5.2	1183.75	1141.00	19.54	19.40	19.40	19.34	3.61	5.72	6.49
	L5.3	1368.71	1320.10	19.29	19.34	19.26	19.55	3.55	6.30	7.26
	L6.1	1450.10	1402.30	19.38	19.12	19.30	19.25	3.30	7.24	8.61
	L6.2	1329.25	1288.80	19.08	19.54	19.55	19.55	3.04	5.62	8.99
	L6.3	1223.21	1179.90	19.45	19.26	19.28	19.41	3.54	6.39	7.26
	L7.1	1464.89	1398.90	19.34	19.28	19.21	19.24	4.50	7.19	7.74
	L7.2	1334.19	1282.00	19.28	19.29	19.17	19.19	3.91	7.53	8.13
	L7.3	1213.35	1136.80	19.30	19.20	19.32	19.26	6.31	7.17	7.84
	L8.1	1442.70	1409.60	19.17	19.28	19.24	19.16	2.29	7.72	8.22
	L8.2	1361.31	1322.10	19.18	19.34	19.29	19.28	2.88	7.14	8.03
	L8.3	1238.01	1215.50	19.27	19.30	19.34	19.35	1.82	6.73	7.17
	Average							3.42	7.05	8.01
C2	L1.1	1432.83	1377.20	19.40	19.44	19.22	19.50	3.88	6.01	7.65
	L1.2	1440.23	1333.66	18.87	19.24	18.58	18.82	7.40	10.91	13.70
	L1.3	1462.43	1416.90	19.20	18.90	19.10	18.90	3.11	9.51	10.70
	L2.1	1462.43	1366.00	18.76	18.98	19.06	19.24	6.59	9.65	12.02
	L2.2	1501.89	1392.16	19.06	18.97	18.91	19.01	7.31	9.87	10.60
	L2.3	1245.41	1183.35	19.14	19.33	19.01	19.39	4.98	7.67	9.65
	L3.1	1289.80	1205.05	19.16	18.31	18.80	18.85	6.57	11.83	16.19
	L3.2	1447.63	1378.33	19.14	19.25	19.06	19.18	4.79	8.25	9.18
	L3.3	1324.32	1174.40	18.95	18.92	18.01	19.04	11.32	12.30	18.91
	L4.1	1585.73	1425.03	18.00	18.05	18.74	18.24	10.13	16.67	19.00
	L4.2	1240.47	1199.76	18.95	19.10	18.86	19.04	3.28	9.87	11.08
	L4.3	1511.75	1422.58	18.96	18.83	19.08	18.73	5.90	10.70	12.30

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C2	L5.1	1336.65	1251.21	18.50	18.87	18.70	19.30	6.39	11.24	14.44
	L5.2	1531.48	1449.08	19.23	18.15	18.90	18.34	5.38	13.00	17.64
	L5.3	1489.55	1438.28	19.07	19.39	18.80	18.67	3.44	9.92	12.86
	L6.1	1373.65	1306.00	18.82	18.80	18.92	18.70	4.92	11.55	12.58
	L6.2	1516.68	1431.57	19.20	18.82	19.18	19.30	5.61	8.56	11.45
	L6.3	1403.24	1261.86	18.36	18.00	18.38	19.02	10.08	14.99	19.00
	L7.1	1472.29	1420.21	18.90	18.75	19.35	19.24	3.54	9.18	12.11
	L7.2	1418.04	1287.13	18.90	19.20	18.65	18.61	9.23	11.26	13.42
	L7.3	1168.96	1106.98	18.86	18.69	19.07	18.85	5.30	11.00	12.67
	L8.1	1356.38	1238.62	18.82	19.40	18.99	18.71	8.68	9.94	12.48
	L8.2	1516.68	1440.05	19.20	18.80	18.20	19.98	5.05	9.32	17.19
	L8.3	1245.41	1191.72	19.36	19.13	19.30	19.25	4.31	7.26	8.51
	Average							6.13	10.44	13.14
C3	L1.1	1393.37	1153.00	15.60	14.16	15.89	14.96	17.25	42.60	49.87
	L1.2	1297.20	1105.10	17.12	16.75	16.09	16.77	14.81	30.42	35.28
	L1.3	1501.89	1352.00	18.92	19.27	18.46	18.89	9.98	10.84	14.81
	L2.1	1390.91	1285.60	17.54	19.43	19.62	18.80	7.57	11.19	23.09
	L2.2	1277.47	1140.90	18.29	18.32	18.48	18.33	10.69	15.77	16.37
	L2.3	1494.49	1365.90	18.48	18.83	18.38	18.60	8.60	13.77	15.54
	L3.1	1383.51	1267.80	17.43	19.25	19.11	18.86	8.36	12.93	24.05
	L3.2	1445.16	1349.80	19.28	19.25	18.63	18.38	6.60	10.84	15.54
	L3.3	1341.59	1185.40	19.09	17.44	18.50	18.23	11.64	16.14	23.96
	L4.1	1336.65	1212.50	17.14	18.63	19.12	18.07	9.29	16.83	26.56
	L4.2	1400.77	1231.40	19.05	18.53	17.65	17.85	12.09	16.55	22.12
	L4.3	1447.63	1315.80	18.35	19.15	19.27	18.83	9.11	10.70	15.82
	L5.1	1447.63	1269.40	16.63	16.98	18.23	15.94	12.31	28.22	36.48
	L5.2	1418.04	1158.20	15.33	13.58	13.65	16.92	18.32	44.72	53.90
	L5.3	1233.08	1094.00	17.73	18.24	17.34	17.18	11.28	22.36	26.21
	L6.1	1316.92	1207.00	17.08	17.76	18.68	18.58	8.35	18.77	27.07
	L6.2	1450.10	1359.50	16.83	19.17	19.08	18.45	6.25	15.52	29.19
	L6.3	1390.91	1245.00	18.59	18.17	17.88	18.92	10.49	15.45	20.08
	L7.1	1430.37	1276.50	16.55	17.88	19.24	18.48	10.76	18.66	31.52
	L7.2	1393.37	1105.30	14.76	14.19	14.44	15.96	20.67	44.96	49.66
	L7.3	1344.05	1157.10	16.07	16.71	18.10	14.56	13.91	33.09	47.00
	L8.1	1437.77	1351.70	18.59	19.16	19.23	19.18	5.99	9.37	13.60
	L8.2	1277.47	1212.40	19.46	19.42	19.58	19.44	5.09	5.18	5.72
	L8.3	1405.71	1246.50	18.49	16.35	15.58	19.10	11.33	24.48	39.32
	Average							10.86	20.39	27.61
C4	L1.1	1427.90	1379.40	19.49	19.75	19.30	19.71	3.40	4.33	6.88
	L1.2	1415.57	1358.90	19.33	19.67	19.69	19.58	4.00	4.28	6.59
	L1.3	1275.00	1231.10	19.59	19.65	19.29	19.57	3.44	4.69	6.97
	L2.1	1474.76	1419.50	19.79	19.41	19.55	19.34	3.75	4.72	6.49
	L2.2	1282.40	1253.00	19.45	19.63	19.82	19.63	2.29	3.64	5.42

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C4	L2.3	1405.71	1365.70	19.56	19.53	19.65	19.37	2.85	4.67	6.20
	L3.1	1292.26	1240.10	19.34	19.45	19.65	19.57	4.04	4.91	6.49
	L3.2	1472.29	1411.40	19.16	19.62	19.34	19.47	4.14	5.93	8.22
	L3.3	1331.72	1287.00	19.45	19.60	19.60	19.66	3.36	4.18	5.42
	L4.1	1450.10	1400.20	19.57	19.60	19.89	19.94	3.44	2.48	4.25
	L4.2	1287.33	1242.40	19.65	19.78	19.53	19.74	3.49	3.22	4.64
	L4.3	1385.98	1342.70	19.73	19.24	19.79	19.48	3.12	4.35	7.46
	L5.1	1272.53	1228.70	19.43	19.35	19.51	19.59	3.44	5.23	6.39
	L5.2	1344.05	1307.70	19.66	19.54	19.47	19.54	2.70	4.42	5.23
	L5.3	1447.63	1401.80	19.76	19.65	19.35	19.71	3.17	3.79	6.39
	L6.1	1455.03	1402.70	19.63	19.77	19.78	19.81	3.60	2.51	3.67
	L6.2	1324.32	1286.00	19.44	19.16	19.48	19.64	2.89	5.62	8.22
	L6.3	1309.53	1265.00	19.78	19.67	19.69	19.58	3.40	3.17	4.16
	L7.1	1294.73	1244.70	19.91	19.29	19.73	19.75	3.86	3.27	6.97
	L7.2	1334.19	1286.60	19.77	19.37	19.58	19.69	3.57	3.94	6.20
	L7.3	1425.43	1375.90	19.34	19.54	19.30	19.31	3.48	6.18	6.88
	L8.1	1487.09	1434.30	19.73	19.62	19.60	19.58	3.55	3.64	4.16
	L8.2	1297.20	1264.00	19.67	19.50	19.77	19.45	2.56	3.98	5.42
	L8.3	1309.53	1263.90	19.82	19.33	19.57	19.90	3.48	3.42	6.59
	Average							3.38	4.19	6.06
C5	L1.1	1395.84	1319.10	17.82	19.23	19.04	19.11	5.50	11.64	20.61
	L1.2	1326.79	1266.90	19.31	19.22	17.84	19.23	4.51	10.70	20.43
	L1.3	1223.21	1168.90	19.28	19.20	19.34	19.24	4.44	7.21	7.84
	L2.1	1492.02	1455.40	19.36	19.29	19.23	19.29	2.45	6.95	7.55
	L2.2	1267.60	1229.70	19.29	19.27	19.14	19.21	2.99	7.58	8.42
	L2.3	1262.67	1216.10	19.30	19.30	19.21	19.25	3.69	7.21	7.74
	L3.1	1270.07	1235.80	19.03	19.34	19.20	19.25	2.70	7.79	9.46
	L3.2	1279.93	1247.60	19.29	19.26	19.39	19.22	2.53	6.97	7.65
	L3.3	1418.04	1362.70	19.09	19.12	19.21	19.27	3.90	8.10	8.89
	L4.1	1238.01	1181.60	19.60	19.27	19.27	19.28	4.56	6.35	7.17
	L4.2	1331.72	1271.50	19.41	19.37	18.85	19.28	4.52	7.58	11.17
	L4.3	1247.87	1186.50	19.33	19.18	19.37	19.23	4.92	7.09	8.03
	L5.1	1514.22	1458.90	19.29	19.22	19.34	19.20	3.65	7.24	7.84
	L5.2	1205.95	1147.60	18.89	19.02	19.13	18.93	4.84	9.82	10.79
	L5.3	1287.33	1234.60	19.26	19.19	19.30	19.26	4.10	7.34	7.94
	L6.1	1260.20	1224.90	19.30	19.11	19.13	19.21	2.80	7.96	8.70
	L6.2	1383.51	1318.00	18.09	19.28	19.20	19.13	4.74	10.46	18.19
	L6.3	1166.49	1122.20	19.29	19.15	19.42	19.11	3.80	7.43	8.70
	L7.1	1131.96	1093.70	19.21	19.21	19.15	19.21	3.38	7.89	8.32
	L7.2	1430.37	1368.10	19.11	19.23	19.28	19.06	4.35	8.13	9.18
	L7.3	1432.83	1381.80	19.32	19.38	19.22	19.38	3.56	6.64	7.65
	L8.1	1050.58	1014.20	19.23	19.41	19.24	19.22	3.46	7.12	7.65
	L8.2	1603.00	1534.20	19.28	19.41	19.18	19.17	4.29	7.26	8.13

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C5	L8.3	1329.25	1283.70	18.80	19.33	19.15	19.14	3.43	8.75	11.64
	Average							3.88	7.97	9.99
C6	L1	1664.65	1515.72	19.28	18.98	19.10	19.10	8.95	8.65	9.94
	L2	1780.56	1524.58	18.41	18.04	18.42	18.18	14.38	16.62	18.64
	L3	1669.58	1614.92	19.20	19.02	19.29	19.23	3.27	7.98	9.56
	L4	1647.39	1449.62	18.87	18.95	18.34	18.14	12.00	13.74	17.74
	L5	1627.66	1500.87	18.99	18.98	18.72	19.01	7.79	10.46	12.39
	L6	1681.91	1523.35	19.01	18.70	18.67	18.64	9.43	12.06	13.14
	L7	1620.26	1537.98	18.99	19.47	19.31	19.17	5.08	7.50	9.84
	L8	1637.52	1459.12	17.82	18.42	19.05	19.10	10.89	13.53	20.61
	L9	1242.94	1162.81	18.90	19.08	18.89	18.85	6.45	10.41	11.17
	L10	1289.80	1208.35	18.76	18.87	18.73	19.11	6.31	11.00	12.30
	L11	1289.80	1205.21	19.22	18.83	18.16	18.84	6.56	11.99	17.55
	L12	1279.93	1194.55	18.93	19.07	18.05	19.14	6.67	11.66	18.55
	L13	1275.00	1191.82	18.83	18.68	19.10	18.90	6.52	10.91	12.76
	L14	1289.80	1191.52	16.75	17.91	18.83	18.83	7.62	18.28	29.86
	L15	1270.07	1192.39	18.88	18.77	19.02	18.94	6.12	10.67	11.92
	L16	1299.66	1210.61	18.68	18.82	18.96	18.90	6.85	11.26	12.76
	L17	1228.14	1152.00	18.54	18.98	18.98	19.14	6.20	10.60	14.07
	L18	1230.61	1140.31	18.83	18.78	18.87	18.72	7.34	11.64	12.39
	L19	1267.60	1205.26	18.96	18.96	19.23	19.24	4.92	8.82	10.13
	L20	1311.99	1227.81	18.89	18.81	19.06	18.97	6.42	10.39	11.55
	L21	1299.66	1217.29	19.00	18.90	18.72	18.80	6.34	11.12	12.39
	L22	1311.99	1239.82	*	*	18.64	18.94	5.50	11.73	13.14
	L23	1272.53	1194.24	18.82	18.78	18.22	18.83	6.15	12.93	17.01
	L24	1245.41	1164.39	18.66	19.04	18.88	18.81	6.51	11.19	12.95
	Average							7.26	11.47	14.26

Table D.5 Corrosion measurement of longitudinal reinforcing bars for test specimens in Series 3

Spe.	No.	W0	W1	R1	R2	R3	R4	X_{corr}	$X_{corr}^{(1)}$	$X_{corr}^{(2)}$
		g	g	mm	mm	mm	mm	%	%	%
CC1	L1.1	1191.15	1143.70	19.83	19.73	19.84	19.95	3.98	1.62	2.68
	L1.2	1233.08	1190.00	19.95	19.92	19.85	19.65	3.49	1.57	3.47
	L2.1	1201.02	1161.80	19.54	19.36	19.77	19.56	3.27	4.38	6.30
	L2.2	1134.43	1086.60	19.52	19.46	19.66	19.40	4.22	4.84	5.91
	L3.1	1171.42	1130.80	19.40	19.57	19.42	19.62	3.47	4.91	5.91
	L3.2	1154.16	1122.90	19.77	19.60	19.63	19.82	2.71	2.93	3.96
	L4.1	1220.74	1171.30	19.58	19.91	19.86	19.81	4.05	2.09	4.16
	L4.2	1122.10	1076.90	19.86	19.75	19.80	19.84	4.03	1.87	2.48
	L5.1	1168.96	1140.20	19.18	19.70	19.91	19.86	2.46	3.35	8.03
	L5.2	1149.23	1114.30	19.93	19.91	19.82	19.69	3.04	1.62	3.08
	L6.1	1240.47	1195.90	19.80	19.62	19.61	19.65	3.59	3.27	3.86
	L6.2	1159.09	1118.80	19.83	19.69	19.36	19.84	3.48	3.17	6.30
	L7.1	1136.90	1110.60	19.23	19.71	19.47	19.72	2.31	4.62	7.55
	L7.2	1183.75	1154.50	19.43	19.69	19.64	19.56	2.47	4.16	5.62
	L8.1	1210.88	1167.00	19.92	19.83	19.60	19.76	3.62	2.21	3.96
	L8.2	1228.14	1184.70	19.67	19.74	19.70	19.75	3.54	2.83	3.27
	Average							3.36	3.09	4.78
CC2	L1.1	1257.74	1203.91	19.50	19.17	19.20	19.27	4.28	7.02	8.13
	L1.2	1122.10	1049.54	18.98	18.70	18.80	19.00	6.47	10.98	12.58
	L2.1	1144.29	1083.94	19.30	19.27	19.24	19.00	5.27	7.82	9.75
	L2.2	1129.50	1056.81	19.37	19.34	19.20	18.61	6.44	8.51	13.42
	L3.1	1331.72	1267.19	19.10	19.00	18.98	19.36	4.85	8.70	9.94
	L3.2	1321.86	1262.77	19.34	19.30	19.36	19.34	4.47	6.54	6.88
	L4.1	1373.65	1320.17	19.20	19.34	19.27	19.26	3.89	7.19	7.84
	L4.2	1188.68	1106.51	19.23	19.30	19.05	19.20	6.91	7.89	9.27
	L5.1	1287.33	1214.12	19.10	19.30	19.17	19.20	5.69	7.91	8.80
	L5.2	1092.50	1005.10	19.22	19.86	20.20	19.32	8.00	3.47	7.65
	L6.1	1245.41	1158.20	19.30	19.16	19.26	19.26	7.00	7.41	8.22
	L6.2	1097.44	1042.02	19.30	19.30	19.26	19.30	5.05	6.97	7.26
	L7.1	1319.39	1233.51	18.90	19.30	19.05	18.74	6.51	9.77	12.20
	L7.2	1043.18	979.22	19.20	19.30	19.26	19.26	6.13	7.31	7.84
	L8.1	1275.00	1192.75	19.04	19.05	18.92	19.15	6.45	9.37	10.51
	L8.2	1144.29	1086.47	18.70	19.07	19.11	19.28	5.05	9.37	12.58
	Average							5.78	7.89	9.55
CC3	L1.1	1139.36	1062.70	18.97	19.02	19.40	19.50	6.73	7.62	10.03
	L1.2	1134.43	1070.60	19.35	19.13	19.20	19.20	5.63	7.65	8.51
	L2.1	1139.36	1068.29	19.03	19.22	18.95	19.05	6.24	9.16	10.22

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CC3	L2.2	1117.17	1082.03	19.40	19.18	19.26	19.69	3.15	6.08	8.03
	L3.1	1139.36	1106.00	19.34	18.70	18.91	19.20	2.93	9.39	12.58
	L3.2	1161.56	1055.30	19.16	18.35	19.15	19.16	9.15	10.18	15.82
	L4.1	1127.03	1037.24	18.96	18.80	19.23	19.50	7.97	8.58	11.64
	L4.2	1080.17	1018.33	19.19	19.13	19.52	19.02	5.73	7.70	9.56
	L5.1	1112.23	1061.43	18.95	18.96	19.26	18.98	4.57	9.39	10.22
	L5.2	1205.95	1072.32	18.75	18.75	18.93	18.72	11.08	11.76	12.39
	L6.1	1141.83	1071.63	19.16	18.98	19.15	18.92	6.15	9.25	10.51
	L6.2	1208.41	1044.65	18.70	18.52	19.06	19.15	13.55	11.10	14.25
	L7.1	1065.38	1110.77	19.06	19.02	19.09	19.04	*	9.25	9.56
	L7.2	1139.36	1088.04	18.94	17.30	18.80	19.10	4.50	14.11	25.18
	L8.1	1146.76	1057.54	19.12	19.20	19.10	19.29	7.78	8.06	8.80
	L8.2	1119.63	1122.35	19.36	19.50	19.70	19.40	*	5.03	6.30
	Average							6.80	9.02	11.48
CC4	L1.1	1117.17	1077.60	19.34	19.38	19.29	19.40	3.54	6.37	6.97
	L1.2	1307.06	1259.40	19.24	19.21	19.28	19.26	3.65	7.38	7.74
	L2.1	1117.17	1070.50	19.19	19.28	19.32	19.34	4.18	7.05	7.94
	L2.2	1245.41	1206.90	19.41	19.29	19.28	19.37	3.09	6.52	7.07
	L3.1	1275.00	1226.50	19.31	19.28	19.39	19.37	3.80	6.52	7.07
	L3.2	1159.09	1127.50	19.19	19.34	19.22	19.32	2.73	7.19	7.94
	L4.1	1149.23	1120.20	19.18	19.20	19.14	19.29	2.53	7.82	8.42
	L4.2	1282.40	1239.20	19.27	19.27	19.30	19.28	3.37	7.07	7.17
	L5.1	1257.74	1222.00	19.31	19.36	19.36	19.20	2.84	6.81	7.84
	L5.2	1196.08	1158.80	19.34	19.38	19.44	19.41	3.12	5.98	6.49
	L6.1	1183.75	1135.40	19.37	19.31	19.33	19.34	4.08	6.52	6.78
	L6.2	1186.22	1144.40	19.26	19.26	19.34	19.38	3.53	6.78	7.26
	L7.1	1149.23	1107.30	19.19	19.21	19.28	19.23	3.65	7.58	7.94
	L7.2	1247.87	1207.10	19.32	19.31	19.34	19.17	3.27	7.02	8.13
	L8.1	1075.24	1035.70	19.38	19.38	19.24	19.39	3.68	6.42	7.46
	L8.2	1252.80	1212.20	19.14	19.32	19.31	19.24	3.24	7.34	8.42
	Average							3.39	6.90	7.54
CC5	L1.1	1193.62	1158.70	19.58	19.49	19.63	19.56	2.93	4.30	5.03
	L1.2	1292.26	1245.90	19.51	19.54	19.15	19.26	3.59	6.25	8.32
	L2.1	1164.02	1118.30	19.08	19.37	19.45	19.39	3.93	6.66	8.99
	L2.2	1282.40	1237.00	19.43	19.35	19.34	19.40	3.54	6.10	6.49
	L3.1	1250.34	1221.30	19.42	19.48	19.42	19.39	2.32	5.64	6.01
	L3.2	1146.76	1118.40	19.20	19.26	19.30	19.44	2.47	6.88	7.84
	L4.1	1109.77	1062.40	19.39	19.54	19.19	19.09	4.27	6.85	8.89
	L4.2	1319.39	1270.90	18.92	19.19	19.42	19.40	3.68	7.53	10.51
	L5.1	1272.53	1235.20	19.44	19.39	19.12	19.26	2.93	6.85	8.61
	L5.2	1139.36	1105.70	19.28	19.35	19.13	19.25	2.95	7.34	8.51
	L6.1	1156.62	1116.20	19.15	19.33	19.35	19.37	3.50	6.88	8.32
	L6.2	1176.35	1138.30	19.08	19.48	19.31	19.26	3.23	7.05	8.99

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CC5	L7.1	1092.50	1063.60	19.21	19.39	19.27	19.30	2.65	6.95	7.74
	L7.2	1250.34	1221.10	19.51	19.19	19.28	19.38	2.34	6.49	7.94
	L8.1	976.60	940.60	19.37	19.37	19.03	19.07	3.69	7.74	9.46
	L8.2	1314.46	1252.90	18.95	19.05	19.05	19.10	4.68	9.39	10.22
Average								3.29	6.81	8.24
CC6	L1.1	1225.68	1100.60	17.78	17.93	18.47	18.67	10.20	17.08	20.97
	L1.2	1191.15	1090.10	19.35	19.54	18.67	18.62	8.48	9.32	13.32
	L2.1	1139.36	1080.70	19.33	18.72	19.29	19.23	5.15	8.39	12.39
	L2.2	1223.21	1162.50	17.75	19.38	19.20	19.18	4.96	10.91	21.23
	L3.1	1233.08	1122.40	17.35	18.75	18.90	17.86	8.98	17.05	24.74
	L3.2	1196.08	1087.60	18.75	18.88	18.65	17.45	9.07	15.06	23.87
	L4.1	1233.08	1141.00	19.11	18.65	18.93	18.10	7.47	12.60	18.10
	L4.2	1230.61	1113.40	17.91	19.12	19.32	18.84	9.52	11.66	19.81
	L5.1	1213.35	1134.20	19.45	19.55	19.68	17.28	6.52	9.84	25.35
	L5.2	1215.81	1146.40	18.79	18.81	17.03	18.89	5.71	15.54	27.49
	L6.1	1250.34	1170.90	17.02	19.20	18.79	18.95	6.35	14.53	27.58
	L6.2	1203.48	1112.70	18.44	19.34	19.21	18.86	7.54	10.11	14.99
	L7.1	1228.14	1117.50	18.06	19.03	19.03	18.80	9.01	12.30	18.46
	L7.2	1235.54	1123.10	19.21	18.76	18.69	17.27	9.10	14.60	25.44
	L8.1	1223.21	1144.10	19.46	19.31	19.30	18.55	6.47	8.27	13.97
	L8.2	1210.88	1143.20	19.16	19.27	19.14	19.29	5.59	7.70	8.42
Average								7.51	12.19	19.76