STRUCTURAL BEHAVIOUR OF CORROSION-DAMAGED RC SHORT COLUMNS WRAPPED WITH HYBRID FIBRE REINFORCED POLYMER REINFORCEMENT

EMAD POURNASIRI BASTI

Thesis submitted in fulfilment of the requirements for the degree of

Master of Science

Universiti Sains Malaysia

February 2013

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Dr. J. Jayaprakash, for his encouragement, supervision and endless support throughout my research. This study would not have been possible without his help. I would also like to convey my sincere words of appreciation to my co-supervisor, Dr. Fatimah De’nan, for her advice, guidance and help. I am grateful to all the academic and non-academic staffs in the School of Civil Engineering, USM for their support and assistance. This work was funded under the Post Graduate Research Grant 1001/PAWAM/8043022. My special thanks and love to my dear parents and brother for their support, patience and understanding throughout my study. Lastly, my profound gratitude to Ms. Armaghan Shafaei for her invaluable help, support and encouragement.

Most of all, I would like to thank God for giving me the ability, motivation, and focus to be successful throughout my studies. Many students who might like to pursue higher studies however, some might never get the opportunity, and therefore I am grateful to him for providing me the opportunity. He gave me the capability and talent to have much success throughout my academic career and in life. Whenever something would go wrong in this experiment, I would turn to God and asked him for help and guidance in solving the problems. I honestly believe that the God providing me or someone else insight to help me overcome the obstacles. I honestly believe that he sent me all the people I have thanked above to be positive influences in my studies and life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	Amperes
Am	Gram atomic weight
d_b	Diameter of steel bar
E	Tensile Modulus
F	Faraday’s constant
G	Weight of corroded steel reinforcement after corrosion activity
G_0	Initial weight of steel reinforcement prior to the corrosion activity
g_0	Weight per unit length of the reinforcing bar
I	Current
mA	Milliampere
l	Rebar bond length.
P	Applied load
t	Time
V	Voltage, Volts
w/c	Water/Cement Ratio
Z	Valency (ionic charge)
μA	Microamperes
μ_{ave}	Average bond stress
Δw	Amount of corrosion

ρ	Density of Steel

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
ASCE	American Society of Civil Engineers
BS	British Standards
CEB	Euro-International Concrete Committee
CFRP	Carbon Fiber Reinforced Polymer
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
NaCl	Sodium Chloride

KELAKUAN STRUKTUR TIANG PENDEK KONKRIT BERTETULANG ROSAK KAKISAN DILILIT DENGAN POLIMER BERTETULANG GENTIAN HIBRID

ABSTRAK

Kakisan tetulang keluli dalam struktur konkrit bertetulang adalah salah satu masalah utama dalam industri kejuruteraan awam. Kakisan adalah fenomena berbahaya boleh menjejaskan kebolehkhidmatan dan ketahanan anggota konkrit bertetulang. Dalam usaha untuk memulihkan prestasi struktur konkrit bertetulang, pembaikan dan pemulihan menggunakan Polimer Bertetulang Gentian (FRP) terikat secara luaran adalah teknik yang paling sesuai kerana ciri-ciri kelebihannya seperti ringan, kekuatan tinggi, dan pemasangan yang mudah tanpa menggunakan peralatan berat.

Tujuan kajian adalah untuk menyiasat kelakuan struktur konkrit bertetulang yang mengalami kerosakan kakisan dengan dililit luaran menggunakan tetulang FRP hybrid (kombinasi selapis CFRP dan selapis GFRP) dan bukan hybrid. Eksperimen terdiri daripada dua bahagian, iaitu tiang pendek konkrit bertetulang (Bahagian I) dan silinder konkrit yang tertanam dengan tetulang keluli (Bahagian II). Bahagian I terdiri daripada 23 tiang pendek bulat konkrit bertetulang dengan dimensi 130 mm × 780 mm. Spesimen ini telah terdedah kepada aktiviti kakisan secara sederhana (5-10% kehilangan jisim bar tetulang) dan teruk (15-25% kehilangan jisim bar tetulang) serta diuji di bawah pembebanan sipi. Aktiviti kakisan dalam tiang konkrit bertetulang telah dipercepatkan menggunakan pengesanan arus terus pada sangkar bar keluli, menambahkan 5% NaCl dalam campuran konkrit dan kitaran basah/

kering. Daripada hasil kajian, dapati bahawa pengurungan luaran FRP meningkatkan kapasiti pembawaan beban dengan ketara bagi tiang pendek bulat konkrit bertetulang yang mengalami kerosakan kakisan sebanyak 8% hingga 36% untuk tahap kakisan sederhana dan 21% hingga 34% bagi peringkat kakisan teruk untuk tiang pendek konkrit bertetulang kerosakan kakisan dalam keadaan tak terkurung. Selain itu, keputusan menunjukkan bahawa prestasi struktur tiang konkrit bertetulang yang mengalami kerosakan kakisan yang dikukuhkan dengan FRP hibrid adalah lebih besar berbanding CFRP bukan hibrid dan GFRP tiang konkrit bertetulang yang dikukuhkan dengan dua lapisan tetulang FRP. Walau bagaimanapun, keputusan tiang yang dikukuhkan dengan CFRP hampir kepada tiang yang dikukuhkan dengan FRP hibrid. Akhirnya, prestasi kerosakan pasca-kakisan tiang GFRP bukan hibrid terkurung adalah lebih baik daripada tetulang CFRP bagi pendedahan jangka panjang kakisan kerana kesan kerintangan kakisan.

Bahagian II terdiri daripada 30 silinder konkrit berdimensi 100 mm × 200 mm tertanam dengan bar tetulang keluli. Dua bar tetulang keluli yang berbeza diameter digunakan iaitu 10 mm dan 20 mm. Objektif khusus Bahagian II ini adalah untuk menyiasat kekuatan ikatan silinder konkrit yang tertanam dengan tetulang keluli yang mengalami kerosakan kakisan di bawah ujian tarik-keluar. Semua silinder konkrit ini terdedah kepada peringkat kakisan sederhana dan teruk serupa dengan tiang bulat konkrit bertetulang di Bahagian I. Semua spesimen ini yang mengalami kerosakan kakisan telah dibaiki dengan CFRP bukan hibrid, GFRP bukan hibrid dan tetulang FRP hibrid serta diuji di bawah ujian tarik-keluar. Keputusan eksperimen menunjukkan bahawa kekuatan ikatan yang diperolehi bagi kakisan ringan dan teruk CFRP & GFRP bukan hibrid dan FRP hibrid konkrit silinder terkurung dengan

tetulang tertanam berdiameter 10mm adalah berjulat antara 55% & 79% dan 61% & 160% lebih besar daripada spesimen tak terkurung.

Begitu juga kekuatan ikatan kakisan sederhana dan teruk CFRP dan GFRP bukan hibrid dan spesimen FRP hibrid terkurung dengan tertanam tetulang berdiameter 20mm mencapai peningkatan antara 65% & 127% dan 52% & 96% berbanding spesimen yang mengalami kerosakan kakisan. Pemerhatian umum menunjukkan kekuatan ikatan spesimen yang mengalami kerosakan kakisan telah dipertingkatkan dengan ketara. Selain itu, pemerhatian menunjukkan bahawa kekuatan ikatan spesimen FRP terkurung yang mengalami kerosakan kakisan telah menurun dengan peningkatan tahap kakisan. Keputusan telah menunjukkan bahawa kekuatan ikatan spesimen FRP hibrid terkurung adalah yang tertinggi berbanding dengan spesimen CFRP bukan hibrid dan spesimen GFRP terkurung.

STRUCTURAL BEHAVIOUR OF CORROSION-DAMAGED RC SHORT COLUMNS WRAPPED WITH HYBRID FIBRE REINFORCED POLYMER REINFORCEMENT

ABSTRACT

Corrosion of reinforcing steel bar in reinforced concrete (RC) structures is one of the predominant problems in civil engineering industry. Corrosion as a dangerous phenomenon could seriously affects the serviceability and durability of RC members. In order to restore the structural performance of RC structures, the repair and rehabilitation using the externally bonded Fibre Reinforced Polymer (FRP) composites is the most appropriate technique due to its advantages characteristics such as lightweight, high strength, and ease of installation without any heavy equipment.

The aim of study was to investigate the structural behaviour of corrosion-damaged RC members with externally bonded hybrid (combination of 1 ply carbon and 1 ply glass FRP) and non-hybrid FRP reinforcement. The experimental program consisted of two parts, namely RC short columns (Part I) and concrete cylinders embedded with steel bar (Part II). The Part I comprised of twenty three (23) RC circular short columns with dimension of 130 mm diameter and 780 mm in height. These specimens were exposed to mild (5–10% rebar mass loss) and severe (15-25% rebar mass loss) corrosion activity and tested under eccentric loading. The corrosion activity in RC columns was accelerated by impressing direct current on the steel bar cage, adding 5% NaCl in concrete mixture, and wet/dry cycles. From the results, it was found that the external FRP confinement significantly increased the load carrying capacity of the corrosion-damaged RC circular short columns by 8% to 36% for mild-corrosion level and 21% to 34% for severe-corrosion level over the unconfined corrosion-damaged RC short columns. Moreover, the results show that the structural performance of hybrid FRP strengthened corrosion-damaged RC columns was greater over the non-hybrid CFRP and GFRP strengthened RC columns with two plies of FRP reinforcement. However, the results of CFRP strengthened columns were close to the hybrid FRP strengthened columns. Eventually, the performance of post-corrosion-damaged non-hybrid GFRP confined column was better than CFRP reinforcement on long-term corrosion exposure due to the effect of corrosion resistivity.

The Part II consisted of thirty (30) concrete cylinders of dimension 100 mm × 200 mm embedded with steel bar. Two different diameter steel bars were used namely, 10 mm and 20 mm. The specific objective of this Part II was to investigate the bond stress of corrosion-damaged concrete cylinders embedded with steel bars under pull-out test. All these concrete cylinders were exposed to mild-corrosion and severe-corrosion levels similar to the RC circular columns (Part I). All these corrosion-damaged specimens were repaired with non-hybrid CFRP, non-hybrid GFRP, and hybrid FRP reinforcement and tested under pull-out test. The experimental results show that the obtained bond stress of mild and severely corroded non-hybrid and hybrid FRP confined concrete cylinders with 10 mm diameter embedded rebar was ranged between 55% & 79% and 61% & 160% greater than their unconfined specimens. Similarly, the bond stress of mild and severely corroded non-hybrid and hybrid FRP confined specimens with 20 mm diameter embedded rebar attained ranging between 65% & 127% and 52% & 96% over their respective corrosion-damaged specimens. It was generally observed that the bond stress of corrosion-damaged specimens was significantly enhanced. Moreover, it was observed that the bond stress of corrosion-damaged FRP confined specimens decreased as the degree of corrosion levels increased. Results have shown that the observed bond strength of hybrid FRP confined specimens was the highest as compared to the non-hybrid CFRP and GFRP confined specimens.

CHAPTER 1
INTRODUCTION

1.1 Background

For several decades, reinforced concrete (RC) has been extensively used as an economical construction material for construction of various structures such as high rise buildings, sky scrapers, bridges, etc. These RC structures are very susceptible to corrosion attacks as these structures have been exposed to different environmental conditions. It is well known that corrosion of steel reinforcement is one of the most predominant degradation mechanisms in RC structures, which could seriously affects the serviceability and the durability of the structures. In 2005, American Society of Civil Engineers (ASCE) reported that 27.1% of America's 590,750 bridges and 31.2% of urban bridges have been categorised as either structurally deficient or functionally obsolete due to the deterioration caused by corrosion of reinforcing steel. According to ASCE, a structurally deficient bridge as one that is closed or restricted to light vehicles due to the distressed structural components. These structurally deficient bridges have not been categorised as unsafe, however must have speed and traffic load limits. Moreover, the bridges have older design features and cannot safely accommodate the current traffic volumes and sustain vehicle sizes and weights are defined as functionally obsolete (Parish, 2008). Similarly, there is a urgent need of reliable method of bridge repair has become even more evident in the recent years due to the highly publicized concrete bridge failures, such as the I-70 overpass near Pittsburgh, Pennsylvania, shown in Figure 1.1 which is caused by prestressed reinforcement corrosion likely due to the application of deicing salts.

Figure 1.1: Partial collapse of the exterior girder of an overpass caused by pre-stressed reinforcement corrosion due to the application of deicing salts (Grata, 2005)

The main essential elements for occurrence of corrosion activity in reinforced concrete members are oxygen, moisture, and the flow of electrons through steel coupled by the flow of hydroxyl (OH^-) ions through concrete. Iron is converted into iron hydroxide in the presence of water and oxygen and is subsequently oxidised into iron (III) hydroxide (rust, $Fe(OH)_3$) due to the moist oxygen containing aqueous media which are nearly neutral to weakly basic. The main cause for initiation of corrosion of reinforcement is due to the ingress of chloride ions and carbon dioxide to the surface of the steel bars. The high alkaline environment of good-quality concrete forms a passive film on the surface of the embedded steel, which generally prevents the steel from further corroding. However, the passive film is destroyed due to chloride attack, and the embedded steel bar begins to corrode at faster rate (Maaddawy et al., 2006). The mechanism of corrosion activity in steel bar is shown in Figure 1.2.

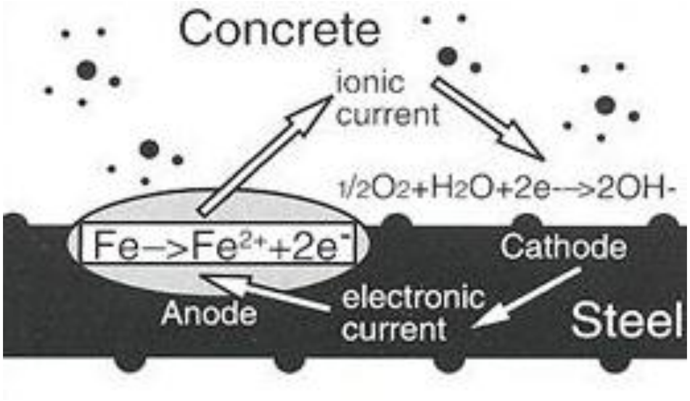

Figure 1.2: Mechanism of corrosion activity in steel bar (http://kcwardco.com/concrete-repair-services/concrete-and-reinforcement-repair)

Since the volume of rust products is about four to six times larger than that of iron. This volume increase induces the internal tensile stresses in the cover concrete, and when these stresses exceed the tensile strength of the concrete, the cover concrete damage by cracking, delamination, and spalling. Moreover, the loss of cover concrete in a reinforced concrete member might suffer structural damage due to the loss of bond between steel and concrete and loss of rebar cross-sectional area (Liu, 1996; ACI222R, 2005). Figure 1.3 shows the corrosion of embedded steel bar in concrete.

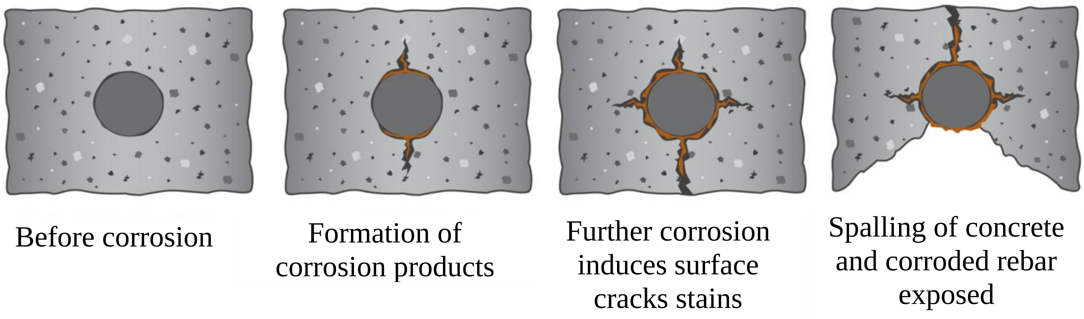

Figure 1.3: Corrosion of embedded steel bar in concrete (http://thehelpfulengineer.com/index.php/2010/10/carbonation-of-concrete-corrosion)

Fibre reinforced polymers (FRPs) is a new composite material which have been sought by structural engineers and researchers to repair and upgrade the damaged reinforced concrete structures. The use of FRP sheets in rehabilitation of concrete structures has been effectively demonstrated in various investigations as these materials are not affected by electro-chemical deterioration and can resist corrosive effects of acids, alkalies and salts under a wide range of temperatures. Thus, unlike steel reinforcement, FRPs can be applied on the surface of concrete with little apprehension of environmental degradation. Figure 1.4 shows the repair of damaged bridge columns using FRP.

Figure 1.4: Repair of damaged bridge columns using Fibre Reinforced Polymer (http://cceer.unr.edu/projects/repair_of_bridge_columns/nhs2r.html)

1.2 Problem Statement

Over three decades, fibre reinforced polymers (FRP) have received considerable attention from the civil engineers as an alternative material for repair, upgrade, and rehabilitation of damaged or distressed reinforced concrete structures. Corrosion of embedded steel bar in concrete has been recognized as being one of the most main destructive mechanisms in the reinforced concrete structures. Corrosion-damage to the concrete occurs in the form of reduction in steel cross-section and ductility due to the disintegration of steel bar, concrete cover cracking, spalling, and delamination due to the formation of extensive corrosion rust, and deterioration of bond between steel reinforcement and concrete. Thus, the serviceability, durability, and load capacity of the member has been considerably decreased (Lee et al., 2002). Previous studies (Wootton et al., 2003; Maaddawy et al., 2006; Gadve et al., 2009) have shown that FRP wrap can be used for structures those are subjected to corrosive environments. The application of FRP for retrofitting circular columns subjected to concentric or/and eccentric loading were proposed by some authors (Fu and Chung, 1998; Demers and Neale, 1999; Shahawya et al., 2000; Pessiki, 2001; Xiao et al., 2001; Li and Hadi, 2003; Hadi, 2006, 2007; Hadi, 2009; Bisby and Ranger, 2010). Since then, the feasibility and upgrading performance of FRP piles and columns have been established. Limited researches (Lee et al., 2000; Pantazopoulou et al., 2001; Balaguru et al., 2009; Revathy et al., 2009) have been investigated the performance of FRP for corrosion-damaged columns to demonstrate the feasibility of upgrading structural behaviour under axial loading. It is obvious that in real scenario, most columns with different sections are subject to a combination of axial and lateral loading. However, the structural behaviour of corrosion-damaged columns under eccentric loading has not yet received adequate attention. Therefore, it is necessary to establish the structural behaviour of corrosion-damaged columns subjected to eccentric loading.

1.3 Objectives of the Investigation

The objectives of this research are as follows:

1. To investigate the structural behaviour of corrosion-damaged reinforced concrete circular short columns confined with hybrid and non-hybrid FRP reinforcement under eccentric loading.

2. To investigate effect of bond strength of corroded steel bar embedded in concrete cylinders with hybrid and non-hybrid FRP reinforcement.

1.4 Scope of Study

The scope of this research is to study the behaviour of RC members using externally bonded hybrid and non-hybrid FRP reinforcement. The experimental program is divided into two parts. The first part of experimental program was on the behaviour of FRP repaired corrosion-damaged RC circular short columns under eccentric loading. The test parameters were level of corrosion, number of layers, hybrid and non-hybrid FRP reinforcement. The second part of experimental program was on the bond strength of FRP repaired concrete cylinders with embedded steel bars exposed to corrosion activity. All these specimens were tested under pull-out test. The parameters include level of corrosion, diameter of rebar, hybrid and non-hybrid FRP reinforcement. An accelerated corrosion process via induced anodic current technique was applied to corrode all reinforced concrete columns and concrete cylinders embedded with steel bar for different period of corrosion.

1.5 Layout of Thesis

This thesis comes in five chapters. The layout of this thesis is described below:

Chapter 1 deals with a brief introduction, statement of problem, objectives of this study and scope of research.

Chapter 2 presents the review on corrosion mechanism of steel bar in concrete, repairing techniques, and previous and recent developments on the effect of FRP reinforcement on corrosion-damaged members.

Chapter 3 narrates the research methodology including experimental programs for eccentrically loaded FRP strengthened corrosion-damaged RC columns and pull-out test on FRP enveloped concrete cylinder embedded with steel bar. Moreover, it describes the material properties, description of specimen, fabrication, application of FRP reinforcement, and experimental test set-up, and testing procedures of RC short columns and concrete cylinders embedded with steel bar.

Chapter 4 deals with the experimental results of FRP strengthened corrosion-damaged RC circular short columns tested under eccentric loading and FRP enveloped concrete cylinders with embedded steel bar subjected to pull-out test. It includes the results of accelerated corrosion, crack measurement, half-cell potential, rebound hammer, and eccentric and pull-out loading tests. Moreover it also describes the failure pattern and ultimate load, load-deflection relationship, and load-strain profiles in FRP reinforcement.

Chapter 5 concludes with the major findings of the experimental research investigation and proposed recommendations for future investigations.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Corrosion of steel bars in reinforced concrete structures such as high rise buildings, bridges etc. is one of the predominant problems in civil engineering industry. It is well known that the concrete is a solid porous material containing an alkaline solution in pores, which allows the moisture, oxygen and electrolytes to disrupt the passive layer in steel bar. It is the greatest challenge for structural engineers and researchers to protect and improve the life span of reinforced concrete structures. Thus, the goal of this investigation is to study the structural behaviour of corrosion-damaged RC members with externally bonded hybrid and non-hybrid FRP reinforcement.

The chapter presents the effect of corrosion of steel reinforcement in RC structures. The different types of repairing techniques and previous experimental investigations on the behaviour of FRP on reinforced concrete columns under axial and eccentric loading are addressed. Moreover, it focused the effect of FRP reinforcement on corrosion-damaged RC columns. Eventually, the bond strength of corrosion-damaged concrete cylinders embedded with steel bar at the centre is presented.

2.2 General Corrosion Mechanism of Steel bar in Concrete and Types of Corrosion Attacks

2.2.1 Corrosion of Steel bar in Concrete

Reinforced concrete is a very strong building material and to improve the tensile strength in concrete, steel bars are used as an internal reinforcement. The steel bar in reinforced concrete members begins to corrode slowly as exposed to natural environmental condition. As discussed in Chapter I, the corrosion of embedded reinforcing steel is one of the primary causes of deterioration in reinforced concrete structures. When the steel bar undergoes corrosion, the resulting rust accumulates on a greater volume than the steel. This expansion induces tensile stresses in the concrete, which could eventually cause cracking, delamination, and spalling of concrete. Generally, the corrosion of steel may occur in the presence of these three elements; a) there must be at least two metals at different energy levels or two locations on a single metal, b) an electrolyte, and c) a metallic connection. The steel bar in any reinforced concrete members probably have several distinct areas with different energy levels. Concrete material is acting as an electrolyte, and the metallic connection is provided by wire ties, or the rebar itself (http://www.cement.org/tech/cct_dur_corrosion.asp, 2012). The corrosion process is an electrochemical oxidation-reduction reaction occurs as the steel exposed to moisture and oxygen. From Figure 2.1, it is obvious that how the flow of electrons and OH^- ions in the presence of oxygen and moisture are essential to aggravate the corrosion activity.

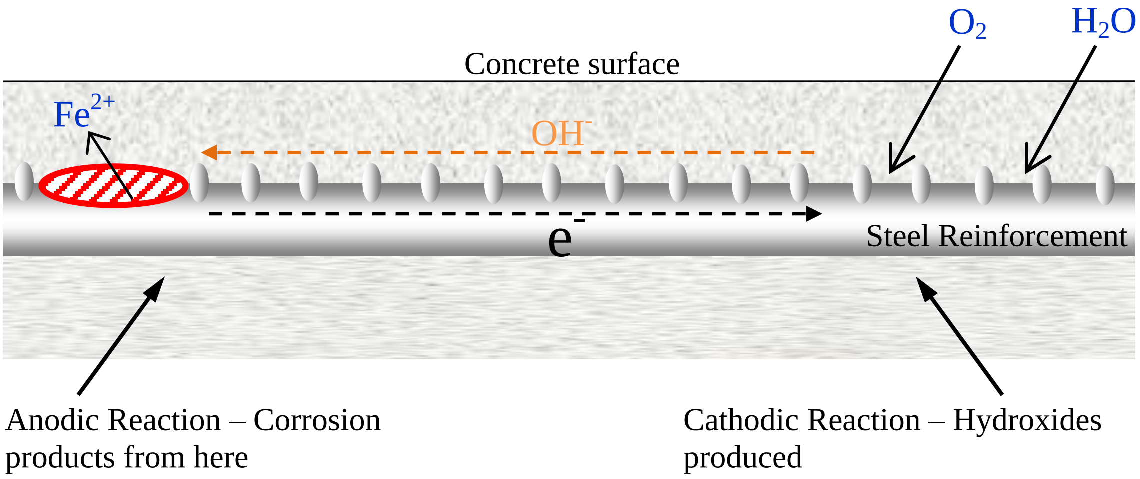

Figure 2.1: Initiation of corrosion process in reinforced concrete member (http://img.alibaba.com)

The metallic *Fe* at the anode is oxidised to form ferrous ions ($Fe2^{+}$) and it discharge the electrons.

$$Fe \longrightarrow Fe^{2+} + 2e^{-} \tag{2-1}$$

The above reaction is initially balanced by cathodic reaction of dissolved oxygen (O_2) to hydroxides (OH^{-}).

$$½\, O_2 + H_2O + 2\, e^{-} \longrightarrow 2OH^{-} \tag{2-2}$$

Subsequently, Fe^{2+} and hydroxides (OH^{-}) from the concrete combined to form ferrous hydroxide.

$$Fe^{2+} + 2(OH^{-}) \longrightarrow Fe(OH)_2 \tag{2-3}$$

If the concrete pH is less than 11.5, the ferrous hydroxide combines with oxygen and water to produce $Fe(OH)_3$ and then separated into ferric oxide and water.

$$2Fe(OH)_2 \xrightarrow{O_2,\ H_2O} 2Fe(OH)_3 \longrightarrow Fe_2O_3 \cdot nH_2O \qquad (2\text{-}4)$$

Ferric oxide (Fe_2O_3) is the product increases the volume of steel bar, which could yield cracking, spalling, and delamination of concrete.

If the concrete pH is greater than 13 due to the presence of potassium hydroxide and sodium hydroxide in the concrete pore solution, the ferrous hydroxide combines with oxygen to form ferric hydroxide and water.

$$Fe(OH)_2 + O_2 \longrightarrow Fe(OH)_3 + H_2O \qquad (2\text{-}5)$$

Corrosion of embedded reinforcing steel in concrete is initiated by two primary forms of attacks namely, carbonation and chloride penetration. The occurrence of either of these attacks could trigger the corrosion process in the steel reinforcement embedded in concrete members.

2.2.2 Chloride Attack

Marine environment is one of the main external sources for diffusion of chlorides into the concrete. Other sources of chloride ingress, which could initiate the corrosion of steel in concrete, are airborne salts, groundwater salts, and use of de-icing salts. In a highly alkaline concrete environment, the steel reinforcement could corrode in the presence of free chloride, oxygen, and moisture. This is due to the percolation of Cl^- present in saltwater to the level of steel reinforcing bars embedded in concrete destroys the passive oxide film on the steel in localized regions and can set a resource for active corrosion in steel reinforcement (CEB, 1992; ACI, 2005). Figure 2.2 shows the pitting corrosion of steel reinforcing bar by chloride attack.

The role of chloride is distinctive and the contamination creates an environment favourable to the corrosion in reinforced concrete even if the carbonation has not occurred and the pH of the concrete is high. Chloride can be re-used more times and hence even a small amount of chloride can sustain the corrosion process. Therefore, the iron-chloride reaction is self-perpetuating and the free chloride acts as a reaction catalyst (Thangavel and Rengaswamy, 1998).

$$Fe^{2+} + 2Cl^{-} \longrightarrow FeCl_2 \qquad (2\text{-}6)$$

Subsequently, the ferrous chloride complex combines with hydroxides in the concrete and forms ferrous hydroxide and chloride ions.

$$FeC1_2 + 2H_2O \longrightarrow Fe(OH)_2 + 2Cl^{-} \qquad (2\text{-}7)$$

Figure 2.2: Pitting corrosion in steel reinforcing bar by chloride attack (Parish, 2008)

2.2.3 Carbonation

Carbonation of concrete occurs due to the reaction of alkaline components of the cement paste ($NaOH$, KOH, $Ca(OH)_2$ and calcium-silicate hydrates) with the atmospheric carbon dioxide (CO_2). The carbonation will instigate at surface of concrete and propagate into the concrete. The rate of ingress depends on the porosity and permeability of the concrete. This reaction process can occur in the presence of a certain amount of water. The carbonation reaction will reduce the concentration of hydroxides (OH^-) and the pH value falls from the original value of > 12 to a lower PH value in the range of 6 to 9, thus it destroys the passive film of steel reinforcement (Liu, 1996; Böhni, 2005).

In the presence of CO_2, the portlandite ($Ca(OH)_2$) and CSH, can react with CO_2 and become carbonated.

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O \qquad (2\text{-}8)$$

2.3 Repair and Rehabilitation Techniques

Various rehabilitation techniques for reinforced concrete structures have been recognized during the last decades such as: (1) Protection technique, (2) Physical technique, and (3) Retrofitting technique.

Electrochemical technique has been used to suppress the corrosion in concrete structure embedded with steel reinforcement. The movement of charged ions and the separation of anodes and cathodes along the steel bar triggers the corrosion problem however, the corrosion activity in reinforced concrete member can be further controlled by making all the steel as a cathode. This can be made by adding an external anode on the surface or embedded in the concrete member. The DC power supply, known as a transformer rectifier, will then pass current between the anode and the reinforcing steel bar. This electrochemical protection technique can be used in three different ways namely, (i) cathodic protection, (ii) electrochemical chloride extraction, desalination or chloride removal, and (iii) re-alkalisation (Broomfield, 2003).

Physical technique is one of the methods used for repairing corrosion-damaged RC member. In this method, the damaged portions of member are required to cut-off and then replace the weakened or damaged part of steel bar by section loss and filled with freshly prepared concrete. However, some of the shortcomings in this approach are listed below:

(i) *Cutting-off the damaged area probably leave other areas about to crack and spall (Broomfield, 2003).*

(ii) *As a result of the electrochemical nature of corrosion process, repairs can actually leads to an acceleration of corrosion in adjacent areas, especially with chloride-induced corrosion, as the removal of the corroding anode also cause the loss of the protective cathodes around it and new anodes form when the material is renewed (Broomfield, 2003).*

(iii) *Extensive removal of concrete requires significant temporary support, adding to the complexity of the project as well as expense (Broomfield, 2003).*

External jacketing using ferrocement is a simple method for strengthening of reinforced concrete or masonry members; it consists of light structural steel, wire mesh layers, high quality cement matrix, admixtures, super plasticizers, fibres etc. The high quality cement matrix has a ratio of 1:1.5 to 1:2.5 or so. At the outset, a layer of steel wire mesh wrapping around the column and nailed using U nails or tied around using steel wires. Subsequently, the freshly prepared cement mortar is applied through the wire mesh and adheres on to the surface of concrete substrate. The application of ferrocement jacketing is almost similar to that of plastering application (see Figures 2.3 and 2.4). It is obvious from previous studies that the use of ferrocement jacketing increased stiffness, strength, and ductility of column member. Ferrocement can be described as a modified form of reinforced concrete with elimination of coarse aggregate, large-size reinforcement, sometimes shuttering, however the properties of concrete is quite different with increased strength. As the surface of ferrocement jacketing had wire mesh layer, this wire mesh could prevents the formation of cracks at the surface of the ferrocement jacketing layer and propagates further deep into the material. Ferrocement has a crack-arrest mechanism and is a denser material as compared to the concrete with hard surface. However, this technique has some disadvantages such as structures made with ferrocement jacketing can be punctured by forceful collision with pointed objects. For corrosive environmental conditions, it is often observed that the reinforcing material might be corroded. However, this failure is always due to the incomplete coverage of the metal by mortar during construction. Moreover, it is nearly impossible to fasten objects to ferrocement with bolts or screws, because the drills usually break against the lightly covered reinforcing material. Fastening with nails or by welding is not possible and the gross cross section of member is the most important demerit of this method (Nedwell and Swamy, 1994).

Figure 2.3: Ferrocement jacketing
(Kumar et al., 2007)

Figure 2.4: Spacer rods
(Kumar et al., 2007)

The most common retrofitting technique used is steel jacketing, which apply in conjunction with epoxy-bonded or grout-bonded steel plates on the surface of concrete. For instance, the cross section of column member is circular, two half shells of steel plate rolled to a radius of 12.5 to 25 mm larger than the column radius are positioned over the area to be retrofitted and are site-welded up the vertical ridge to provide a continuous tube with a small gap around the column. This gap is grouted with a pure cement grout, after flushing with water (Xiao et al., 1993). Figures 2.5 and 2.6 show the two half shells of steel plates and steel plate enveloped around the column, respectively. This method has a significant effect on increasing of load-resistance capacity and improving performance of the structures. However, the steel plates have a stability problem because the steel jacket can be easily damaged by marine environments and de-icing salts. Hence, they are vulnerable to corrosion and also heavy equipments are required to install these heavy steel plates (Masoud and Soudki, 2006).

Figure 2.5: Two half shells of rolled steel plat

Figure 2.6: Steel plate around column

(http://www.johnwilkinsonltd.com/road-safety/strimmex.html)

A new technique for strengthening the reinforced concrete members through the adhesive bonding of Fibre Reinforced Polymer (FRP) was developed in 1980s (Tan, 2003). This technique has been extensively applied all over the world due to potential advantages of FRP materials such as high strength to weight ratio, ease of bonding to any reinforced concrete members, increase the cross-section dimensions negligibly, and durable in adverse environmental conditions. The use of FRP sheets in rehabilitation of concrete structures was proven to be successful in various investigations, since these materials are not affected by electro-chemical deterioration and can resist forceful corrosive effects of acids, alkalis, salts and under a wide range of temperatures. Therefore, unlike steel reinforcement, FRPs can be applied on the surface of concrete with little apprehension of environmental degradation. Figure 2.7 shows the installation of FRP reinforcement. The details of FRP application procedure are discussed in Chapter 3.

Figure 2.7: Installation of FRP reinforcement
(http://www.compositesmanufacturingblog.com)

2.4 Literature Review of Experiments Conducted to Examine FRP Wrap of RC Members

2.4.1 FRP Strengthened RC Columns without Corrosion Activity

Li and Hadi (2003) investigated the effectiveness of FRP confinement on reinforced high strength concrete columns under eccentric loading. They investigated the effectiveness of two different FRP materials such as carbon and E-glass FRP. Variables used were plain and internally reinforced columns, number of FRP layers, and type of wrapping materials (i.e. carbon and E-glass). A series of seven high strength RC columns were casted with a diameter of 235 mm and 150 mm for both end corbels test region, respectively. The overall height of each RC column was of 1400 mm and the length of test region was 620 mm, as shown in Figure 2.8. Five columns were wrapped with one and three layers of CFRP, and one, three, and five layers of E-glass reinforcement. All columns tested under eccentric loading with

42.5 mm eccentricity. For the purpose of comparison of concentric and eccentric loading, some of plain concrete columns were also tested under concentric loading. The results showed that the external confinement of RC columns with FRP reinforcement could increase the load capacity of the specimen under eccentric loading. However, it was found that the enhancement of eccentrically loaded columns was not as significant as that of columns under concentric loading. The effect of number of FRP layers on RC columns under eccentric loading was not well pronounced as that of specimens under concentric loading.

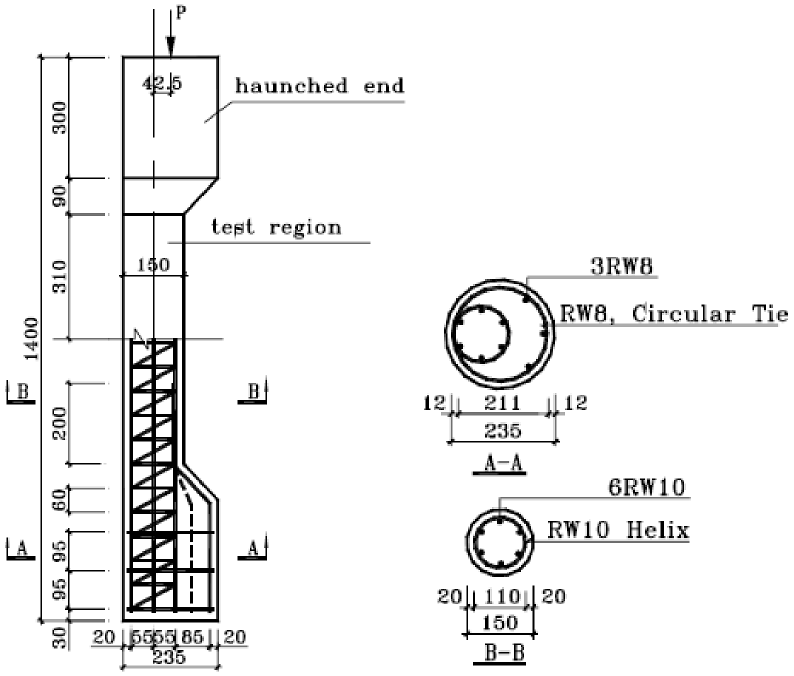

Figure 2.8: Dimension and internal steel reinforcement details of RC circular column (Li and Hadi, 2003)

Similarly, Hadi (2009) further investigated the performance of RC circular cross section specimens to investigate the influence of FRP on high strength concrete RC columns under concentric and eccentric loading. A total of sixteen specimens were divided into four groups; first group was made of reinforced concrete, second group was made of reinforced concrete and wrapped with three plies of CFRP, third group was made of reinforced concrete with added steel fibres, and the last group was made of reinforced concrete, steel fibres, and three plies of CFRP confinement. All columns were reinforced with the same amount of longitudinal and transverse reinforcement. The average compressive strength at 28 days was 49.90MPa for concrete without fibres and 53.26MPa for concrete with 1% fibres. Three specimens of each group were tested under 0, 25, and 50 mm under eccentric loading, and fourth specimen was tested as beam under four point loading system. The eccentric loading was applied using two knife edges, one knife was placed on top of the column, and the other knife was placed on the bottom of the column. The key findings were: (i) using CFRP reinforcement increased the load capacity of the column over the unconfined column. (ii) ultimate load carrying capacity of the columns decreased by increasing the eccentricity (iv) adding steel fibre to the reinforced concrete column increased the ductility, however did not increased the strength of column as much as FRP composites and (v) the bending test results have shown that FRP wrap increased the maximum bending moment and lateral deflection.

Bisby and Ranger (2010) also investigated the effect of FRP strengthened RC columns with different eccentricities (i.e. e = 0 mm, 5 mm, 10 mm, 20 mm, 30 mm, and 40 mm). These fourteen columns were cast with a cross section of 152 mm in diameter and 608 mm in height. They were all internally reinforced with four 6.4 mm diameter steel bars as longitudinal reinforcement and with circular ties of 6.4 mm diameter spaced at 100 mm centre to centre. The experimental set-up for column specimen is shown in Figure 2.9. All, except control specimens, were strengthened with one layer of CFRP reinforcement. From the results, it was observed that the load capacity and deformation of columns, which were confined using CFRP reinforcement significantly improved under eccentric loading. Significant differences were observed in failure modes of CFRP confined and unconfined columns. There was no rebar buckling for CFRP confined columns, therefore, these specimens failed by violent tensile rupture of CFRP wraps in the hoop direction, whereas all unconfined specimens failed by crushing and spalling of concrete cover at the compressed zone due to the buckling of internal reinforcement steel bar.

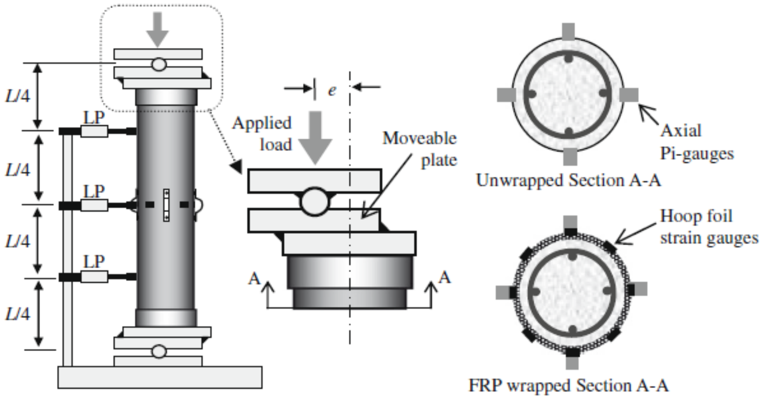

Figure 2.9: Instrumentation and experimental set-up for column specimens (Bisby and Ranger, 2010)

Parvin and Wang (2010) studied the effect of strain gradient, FRP jacket thickness, and various eccentricities on FRP strengthened square columns. Nine square columns were tested under concentric and eccentric loading with 7.6, and 15.2 mm eccentricity. Three un-confined columns as control specimens were loaded until the failure by crushing of concrete. Six columns were wrapped using one and two plies of CFRP, and were tested under concentric and eccentric loading. Results have shown that the FRP confinement increased the load carrying capacity and ductility of RC columns under eccentric loading. However, it was observed that all CFRP confined specimens failed due to rupture of CFRP at corner of columns. It is essential to note that the sudden failure in CFRP strengthened columns decreased as the applied eccentricity increased. Moreover, local axial buckling was observed in columns confined with two plies of CFRP, however, no buckling was observed for one plies of CFRP confined columns.

2.4.2 FRP Strengthened RC Columns with Corrosion Activity

Pantazopoulou et al., (2001) studied the performance and efficiency of jacketing with FRP wraps for corrosion-damaged reinforced concrete columns under axial loading. These cylindrical columns with a dimension of 150 mm in diameter and 300 mm in height were reinforced with three 10 mm longitudinal steel bars and two types of transverse reinforcement configurations (i.e. spiral transverse reinforcement, and without transverse reinforcement except two triangular hoops at the top and bottom of column for supporting the longitudinal reinforcement). The accelerated corrosion activity was applied electrochemically using a fixed potential of 6V between the anode and the cathode of each specimen. Moreover, the specimens were placed in a tank of 2% Cl^- solution and lasted for 5 to 6 months. The repair of corrosion-damaged specimens was carried out in three steps: the damaged concrete was overlaid by a layer of grout, and a diffusion barrier was used to minimize the penetration of moisture, and oxygen, and reverse leaching of alkalies from the grouting material. Eventually, the FRP composites were wrapped around the pre-repaired specimens. After repairing with FRP reinforcement, some of specimens were subjected to second phase of accelerated corrosion to induce post-corrosion activity. The key finding of this investigation were: (i) external confinement in the form of jacketing could slow down the rate of corrosion reaction, and imparting ductility and strength to the FRP confined column, (ii) FRP wraps, as a strong and corrosion-resistant material, was the most effective jacketing and repairing methods as compared to the conventional repair methods which consists primarily of removing the contaminated concrete cover and replacing with low permeability patch, and (iii) the performance of FRP was markedly improved when the number of FRP layers was increased.

Belarbi and Bea (2007) explored the long-term behaviour of reinforced concrete columns strengthened with carbon and glass fibre reinforcement and subjected to axial loading. Testing process was performed into two types of deterioration conditions namely, ambient environment and corrosion tests. The ambient environmental tests dealt with effects of various environmental conditions such as freeze–thaw cycles, high-temperature cycles, high humidity cycles, saline solutions, and ultraviolet (UV) radiations. However, the corrosion tests dealt with the effects of steel reinforcement corrosion. The corrosion process was accelerated by wet–dry cycles and electric potential was impressed between the anode and cathode. To accelerate corrosion process, 5% saline solution was also used to simulate excessive chloride concentration such as de-icing salt attack. The comparison of the results showed that the combined environmental exposure did not provide any significant effects on CFRP wrapped RC columns. Moreover, the saline solution attained the most depreciating environmental effect on GFRP wrapped columns, resulting in significant reduction in failure load and ductility. However, the CFRP wrapped columns showed slight decrease in failure load and ductility.

Lee et al., (2000) studied the effect of large-scale corrosion-damaged RC columns wrapped with CFRP sheets and tested under axial load. The columns were subjected to an accelerated corrosion activity, wrapped using CFRP sheets, and then tested to failure. The accelerated corrosion was achieved by adding sodium chloride to the mixing water, applying a current to the steel reinforcement cage, and exposing to cyclic wetting and drying. The effect of pre and post corrosion activity was investigated in this study. The dimension of column was 305 mm in diameter and 1016 mm in height. Results have shown that the external CFRP bonding increased the load capacity of the corroded column by 28%. Moreover, the rate of corrosion was decreased by 50% during post-corrosion activity.

Maaddawy (2008) studied the effectiveness of CFRP on corrosion-damaged RC square columns tested under eccentric loading. Sixteen square RC columns with end corbels subjected to eccentric loading by eccentricity-to-section height (e/h) ratio of 0.3, 0.43, 0.57, and 0.86. Total length of specimens was 1200 mm, however the length of test region was 350 mm width and 125 mm × 125 mm in cross section, and each end corbel had a cross section of 250 mm × 250 mm. Figure 2.10 shows the experimental setup of RC columns with end corbels. Two different FRP wrapping schemes were used namely, full-wrapping by applying one layer of CFRP reinforcement around the column section in the test region, and partial-wrapping by applying one layer of CFRP strips at 40 mm spacing with a strip width of 65 mm. Mass loss of reinforced steel bars reached about 4.25% by exposing corrosion process for 30 days in accelerated condition.

The experimental results showed that there was no significant difference in strength between the fully and partially wrapped CFRP RC columns, however the strength of the partially wrapped specimen was 8% lower than that of the fully wrapped at e=h ratio of 0.3. Moreover, the strength gain was inversely proportional to the eccentricity ratio.