CYCLIC BEHAVIOUR OF REINFORCED CONCRETE COLUMNS INTERNALLY CONFINED BY CARBON FIBRE REINFORCED POLYMER STRIPS

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DEDICATION

This thesis is dedicated to ummah, parents and husband

"Indeed, Allah will not *change* the condition of a people until they *change* what is in themselves." -*Qur'an* (13:11)

"The best of people are those that bring most benefit to the rest of mankind." [Daraqutni, *Hasan*]

Also, to my supervisors

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ABSTRACT

Carbon fibre reinforced polymers (CFRP) sheets have been widely used in reinforced concrete (RC) structures for retrofitting. This study proposed the application of CFRP strips for internal confinement of RC columns. Experimental works, numerical simulations and analytical calculations were included in this study. Experimental works involved in quasi-static cyclic testing of eight full-scale RC columns that were internally confined by CFRP strips with different distances and widths. The specimens were divided into two groups a) column confined by CFRP stirrups (FRP) and b) column confined by CFRP spirals (SFRP). The obtained results from each group were compared with a reference column that was confined with the carbon steel bar. Numerical studies involved in a parametric investigation about the effects of different intensities of axial load and distances between CFRP strips on the cyclic responses of CFRP confined columns. Finite element models of two columns confined with CFRP stirrups and spirals were established in ABAQUS software and validated using the experimental results. Analytical calculations involved in proposing a step-by-step method for estimating the ultimate load of CFRP confined columns. The proposed method was verified through a comparison between experimental results and analytical calculations. Results of experimental works showed that all columns experienced a flexural type crack along their height. No buckling of longitudinal bars and CFRP rupture were observed. CFRP confined columns had up to 73% larger effective stiffness when compared with the reference columns. The CFRP confined columns also showed up to 63% larger ultimate load and effective yield strength when compared with the reference columns. Besides, the ductility ratio of CFRP confined columns was up to 48% larger than the reference columns. Moreover, the CFRP confined columns exhibited up to 96% larger cumulative energy dissipation and equivalent damping ratio when compared with the reference columns. Numerical simulation showed that the increase in the axial force of columns increased the stress on the surface of the concrete. The simulated columns showed buckling in longitudinal bars when the axial force was increased to 400 kN. Moreover, up to 45% reduction in the ultimate strength and its corresponding displacement were observed when axial force was increased to 400 kN. Increase in the axial force decreased the ductility ratio and effective yield strength of simulated columns up to 29%. Meanwhile, an increase in the distance between strips enlarged the area of the plastic zone in the concrete and longitudinal bars. Increase in the distance between CFRP strips decreased the ultimate load of columns up to 40%. The ductility ratio of columns was decreased by 22% when the distance between their strips was increased to 250 mm. Results also indicated that increase in the distance between strips decreased the effective yield strength of columns up to 35%. In summary, it was concluded that columns confined internally by CFRP stirrups and spirals had a superior cyclic behaviour when compared with the columns confined by carbon steel.

ABSTRAK

Lembaran polimer bertetulang serat karbon (CFRP) telah digunakan secara meluas dalam struktur konkrit bertetulang (RC) untuk tujuan pengubahsuaian. Kajian ini mencadangkan penggunaan jalur CFRP untuk pelitupan dalaman tiang RC. Kerja-kerja eksperimen, simulasi berangka dan pengiraan analitik dimasukkan dalam kajian ini. Kerja-kerja eksperimen melibatkan ujian kitaran kuasi-statik terhadap lapan tiang RC berskala penuh yang dilitup secara dalaman oleh jalur CFRP dengan jarak dan lebar yang berlainan. Spesimen-spesimen dibahagikan kepada dua kumpulan a) tiang yang dilitup oleh jalur CFRP (FRP) dan b) tiang yang dilitup oleh lingkaran CFRP (SFRP). Keputusan yang diperoleh dari setiap kumpulan dibandingkan dengan tiang rujukan yang dilitupi dengan keluli karbon. Kajian berangka melibatkan penyiasatan parametrik mengenai kesan intensiti beban paksi yang berbeza dan jarak antara jalur CFRP dengan tindak balas kitaran bagi tiang yang dilitup oleh CFRP. Dua tiang model elemen terhingga yang dilitup dengan jalur dan lingkaran CFRP telah dibangunkan dalam perisian ABAQUS dan disahkan dengan menggunakan hasil eksperimen. Pengiraan analitik terlibat dalam mencadangkan kaedah langkah demi langkah untuk menganggar beban muktamad tiang yang dilitup oleh CFRP. Kaedah yang dicadangkan telah disahkan melalui perbandingan antara hasil eksperimen dan pengiraan analitik. Hasil kerja eksperimen menunjukkan bahawa semua tiang mengalami retakan jenis lentur sepanjang ketinggiannya. Tiada tetulang yang bengkok dan CFRP yang pecah dapat diperhatikan. Tiang yang terlitup oleh CFRP mempunyai kekukuhan berkesan 73% lebih besar jika dibandingkan dengan tiang rujukan. Tiang terlitup oleh CFRP juga menunjukkan kekuatan muatan tertinggi dan kekuatan muatan berkesan 63% lebih besar berbanding dengan tiang rujukan. Di samping itu, nisbah kemuluran tiang yang dilitup oleh CFRP adalah sehingga 48% lebih besar daripada tiang rujukan. Selain itu, tiang-tiang terlitup oleh CFRP mempamerkan pelesapan tenaga kumulatif dan nisbah redaman setara sehingga 96% lebih besar apabila dibandingkan dengan tiang rujukan. Simulasi berangka menunjukkan bahawa peningkatan kekuatan paksi tiang meningkatkan tekanan pada permukaan konkrit. Tiang simulasi menunjukkan tetulang membengkok apabila daya paksi dinaikkan kepada 400 kN. Selain itu, pengurangan sehingga 45% kekuatan muktamad dan jarak lenturan dapat diperhatikan apabila daya paksi dinaikkan kepada 400 kN. Peningkatan daya paksi didapati menurunkan nisbah kemuluran dan kekuatan efektif tiang simulasi maksimum sebanyak 29%. Sementara itu, peningkatan jarak antara jalur meningkatkan pembesaran kawasan zon plastik dalam konkrit dan tetulang. Peningkatan jarak antara jalur CFRP mengurangkan beban muktamad tiang sehingga 40%. Nisbah kemuluran tiang pula berkurang sebanyak 22% apabila jarak antara jalurnya meningkat kepada 250 mm. Hasil analisa juga menunjukkan bahawa peningkatan jarak antara jalur menurunkan kekuatan muatan berkesan tiang sehingga 35%. Ringkasnya, boleh disimpulkan bahawa tiang yang dilitup secara dalaman oleh jalur dan lingkarang CFRP mempunyai kelakuan kitaran yang tinggi apabila dibandingkan dengan tiang yang dikurungi oleh keluli karbon.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACI	-	American Concrete Institute
AFRP	-	Aramid Fibre Reinforced Polymer
ASTM	-	American Society for Testing and Materials
BFRP	-	Basalt Fibre Reinforced Polymer
BS	-	British Standard
CDP	-	Concrete Damage Plasticity
CFL	-	Carbon fibre laminates
CFRP	-	Carbon Fibre Reinforced Polymer
CFST	-	Concrete-filled Stainless-Steel Tubular
CFST	-	Concrete-filled Steel Tubular
CSA	-	Canadian Standards Association
DCH	-	High Ductility Class
DCL	-	Low Ductility Class
DCM	-	Medium Ductility Class
DOT	-	Departments of Transportation
EC	-	Eurocode
FE	-	Finite Element
FEMA	-	Federal Emergency Management Agency
FHWA	-	Federal Highway Administration
GFRP	-	Glass Fibre Reinforced Polymer
HCC	-	Hollow Concrete Column
JBDPA	-	Japan Building Disaster Prevention Association
JSCE	-	Japan Society of Civil Engineers
NaCl	-	Sodium Chloride
OPC	-	Ordinary Portland Cement
RC	-	Reinforced Concrete
SEM	-	Scanning Electron Microscopy
SFCB	-	Steel-FRP Composite Bar
SSTCC	-	Stainless-Steel Tube Confined Concrete

LIST OF SYMBOLS

A_{CFRP}	-	cross-section area of CFRP strips
$A_{con.}$	-	cross-section area of concrete
A_{rein}	-	cross-section area of reinforcement
A_{sw}	-	cross-section area of transverse reinforcement
b_w	-	width of the web on T, I and L beam
d	-	effective depth of section
d_b	-	nominal diameter of bar, wire, or prestressing strand
$d_{bl,max}$	-	maximum longitudinal bar diameter
$d_{bl,min}$	-	minimum longitudinal bar diameter
d_w	-	diameter of stirrups
E_d	-	energy dissipated in one cycle
E_p	-	the nominal elastic potential energy
F_y	-	effective yield strength
F_u	-	ultimate lateral force
h_e	-	cumulative energy dissipation
f_{cc}	-	characteristic compressive strength of concrete
f_{CFRP}	-	tensile strength of CFRP
f_{yh}	-	yield strength of stirrups
f'_c	-	compressive strength of concrete
l_{cl}	-	clear length of the column
l_{cr}	-	length of critical region
s	-	stirrup spacing or pitch of continuous spirals, and longitudinal FRP bar spacing
w	-	width of CFRP strip
ρ	-	transverse reinforcement ratio
ε_{cu}	-	ultimate strain of concrete
ε_{CFRP}	-	ultimate strain of CFRP
$\varepsilon_{rein.}$	-	strain in the reinforcement
ε_y	-	yield strain of reinforcement
μ	-	ductility ratio of displacement $(\frac{\Delta_u}{\Delta_y})$

Δ_u	-	displacement at ultimate lateral load
Δ_y	-	displacement at effective yield strength
˚C	-	temperature level

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The majority of structures and infrastructures worldwide use reinforced concrete (RC). For many years, carbon steel has been used for making reinforcement bars, hoops and ties. However, in addition to corrosion of steel reinforcements, RC faces other problems which relate to confinement in RC elements. Lateral reinforcements used to confine the longitudinal bars play a vital role in the ultimate load capacity and ductility of RC members like columns (Jing *et al.*, 2016). While corrosion of steel degrades tensile capacity and service life of the structure, improper design and inadequate transverse reinforcement may lead to buckling of main rebars and shear failure (Murray, 2013; Goretti *et al.*, 2017). In many existing columns, lateral reinforcement is provided using 6 to 8 mm diameter bars with 90˚ hooks at about 200-250 mm spacing (Kaushik and Jain, 2007). As can be seen from Figure 1.1, these RC columns are vulnerable when subjected to severe ground motions.

As Figure 1.2 shows, in recent decades, the usage of Fibre-Reinforced-Polymer (FRP) has significantly increased due to its durability, higher strength-to-weight ratio and ability to be formed in any shape and size (Tamon, 2005; Burgoyne, 2009). The FRP bars have been introduced to replace steel bars as longitudinal reinforcements and stirrups due to their high corrosive resistance (Mohamed *et al.*, 2014; Maranan *et al.*, 2018). So far, researchers have studied the effect of externally bonded FRP sheets on the increase in the axial load capacity of columns.

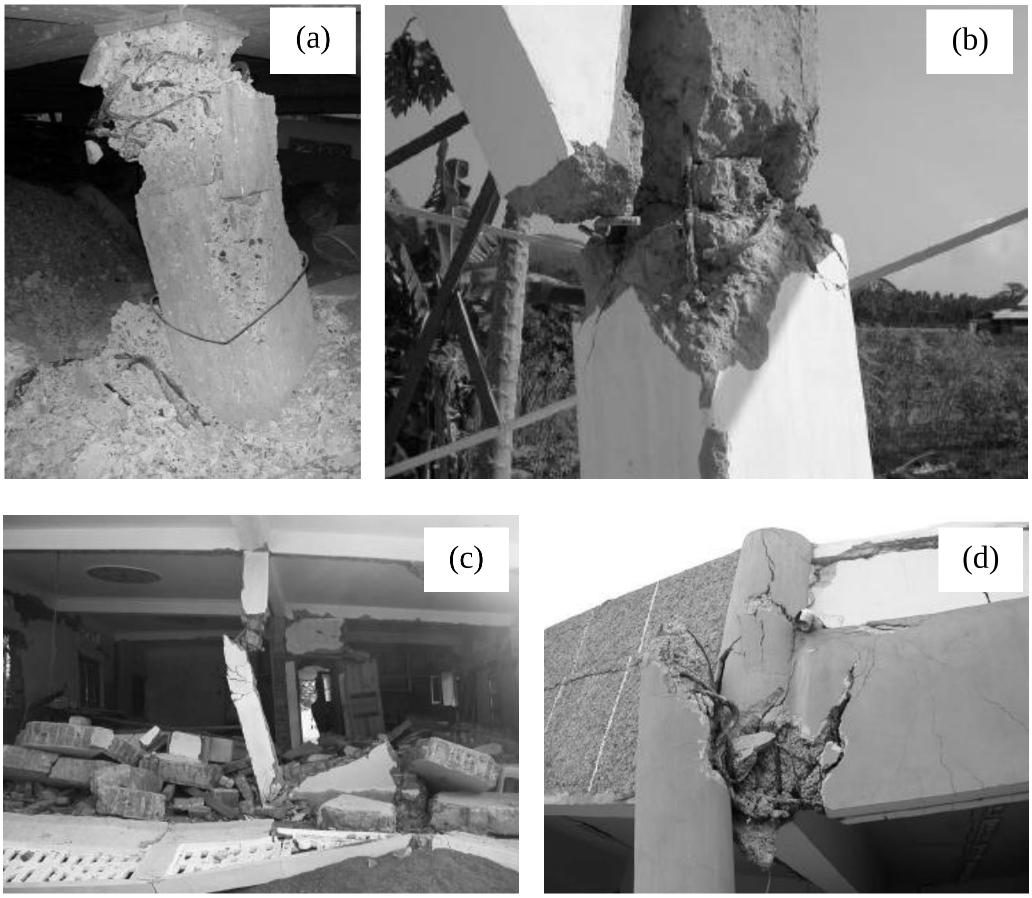

Figure 1.1 Columns failure in RC buildings due to poor shear design during 2004 Sumatra Earthquake and Tsunami; (a), (b) and (c) buckling of longitudinal bars due to 90˚ hooks opened up and (d) shear failure of column at beam-columns joint (Kaushik and Jain, 2007)

(a) (b)

Figure 1.2 FRP sheets wrapped around RC parts to enhance shear and flexure strength; (a) columns and (b) garage beams (Alkhrdaji, 2015)

Due to the potential of FRP composites in RC construction, the application of FRP has become an interesting topic among researchers. Several design guidelines have been published including ACI 440.1R-15 (2015), ACI 440.2R-08 (2008), CAN/CSAS806-12 (2012), CSA-S806-02 (2002), CNR-DT 202 (2005, 2004) and CNR-DT 204 (2006, 2007). Some studies on durability of FRP composites have also been conducted under harsh environment and severe loadings. So far, FRP composites show good durability in accelerated aging test and excellent response under cyclic load, blast load, and impact load.

This study is conducted to investigate the behaviour of internally confined RC columns by FRP strips under a constant axial load and cyclic lateral loading. The failure mode, ultimate load capacity, ductility and energy dissipation capacity of columns were studied experimentally. Numerical studies were performed to investigate the effect of different intensities of axial load and different configuration of FRP strips on the cyclic response of columns.

1.2 Problem Statement

Axial load capacity of RC columns is directly related to the confinement condition that is provided for concrete (Mander *et al.*, 1988). As can be seen from Figure 1.3, the higher the confinement rate in concrete the higher its compressive strength. Therefore, columns with a better confinement condition have a higher axial load capacity (Mohamed *et al.*, 2014). In general, confined condition for concrete in RC columns is provided through transverse reinforcements (Vellenas *et al.,* 1977; Scott *et al.*, 1982; Mander *et al.,* 1988). Transverse reinforcements that can also increase the shear force capacity can be in the shape of circular hoops, spirals and cross ties. For many years, carbon steel has been used for making the reinforcement bars, hoops and ties. Different shapes, types, cross-section and arrangement of transverse reinforcement contribute to different level of confinement (Mander *et al.*, 1988). However, one main problem with carbon steel stirrups is its corrosion in humid and harsh environmental condition (Apostolopoulos and Papadakis, 2008; Zhao *et al.*, 2018). Figure 1.4 shows an example of corroded stirrups in RC columns. The corroded stirrups have caused the loss of bond between reinforcement and concrete (Tapan *et al.*, 2016). Thus, the axial load carrying capacity of the column decreased due to the loss of core concrete confinement and heavily cracks of concrete cover. This can be seen in Figure 1.5, where the compressive strength of corroded concrete is lower than the compressive strength of uncorroded concrete.

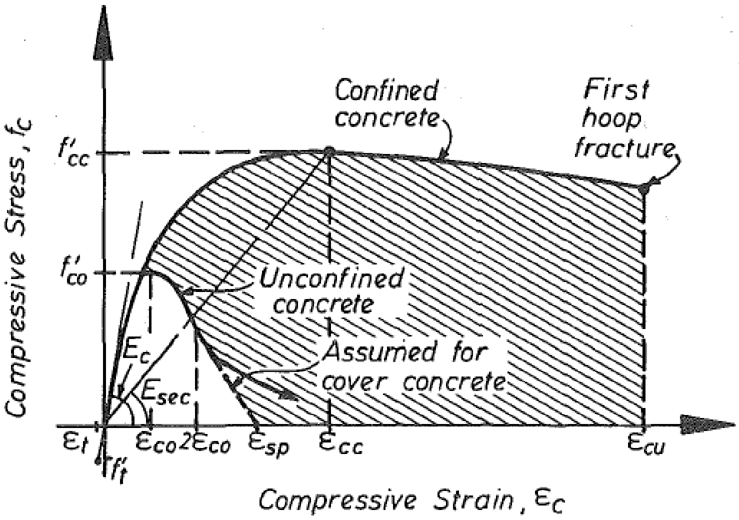

Figure 1.3 Typical stress-strain curves of confined and unconfined concrete (Mander *et al.*, 1988)

(a) (b)

Figure 1.4 Corrosion damage of RC columns; (a) completed deteriorated of stirrups and (b) severe damage of steel rebars (Tapan *et al.*, 2016)

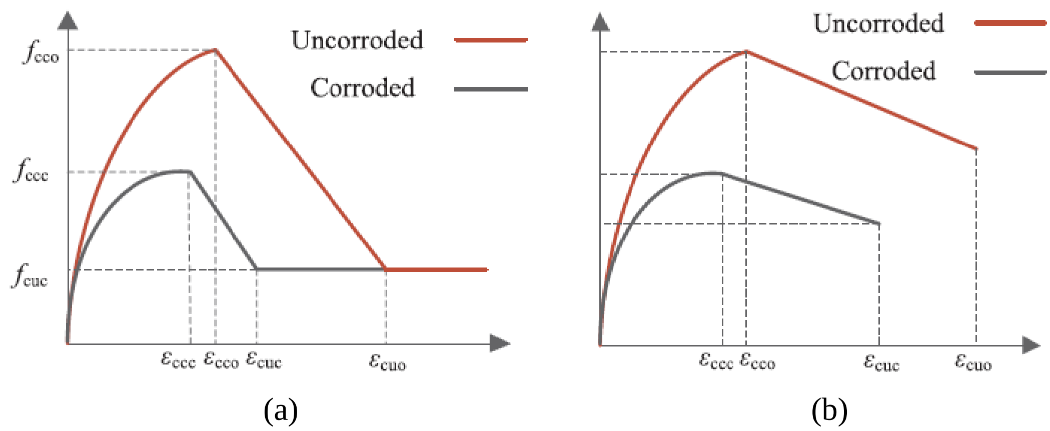

Figure 1.5 The compressive strength of (a) corroded core concrete and (b) corroded concrete cover (Yu *et al.*, 2020)

Another main issue with confinement in RC element is the improper design and inadequate transverse reinforcement which may lead to structural failure during earthquake (Lynn *et al.*, 1996; Alih and Vafaei, 2019). As can be seen from Figure 1.5 and 1.6, large spacing between stirrups and the usage of 90˚ hooks have been found in many of the damaged columns during past earthquakes. In addition, according to Bikçe and Çelik, (2016), failure analysis of newly constructed RC buildings designed according to 2007 Turkish Seismic Code (TEC) during the October 23, 2011 Van earthquake were severely damaged. Based on the analysis, it was found that the building has not been constructed in accordance with the project and thereby TEC 2007. Inadequate stirrups without crossties, and short length and insufficiently dilatation of hooks have been found in the damaged columns. This shows difficulties to designers and engineers to ensure the implementation of the restrictions stated in the design codes during construction.

Nowadays, when it comes to corrosion problems of carbon steel reinforcements, two options are available: a) usage of stainless-steel reinforcements and b) application of Fibre Reinforced Polymers (FRP) (Burgoyne, 2009; Alih and Khelil, 2012). The main issue with stainless steel reinforcements is related to their expensive cost compared to carbon steel and FRPs. Usage of FRP bar as the replacement for carbon steel reinforcements has been studied by other researchers (Mohamed *et al.*, 2014; Kosmidou *et al.*, 2018; Maranan *et al.*, 2018). Many studies have investigated the effect of externally mounted FRP sheets on the increase in the axial load capacity and the dynamic performance of columns (Kim *et al.*, 2013; Jiang *et al.*, 2016; Alotaibi and Galal, 2017; Campione *et al.*, 2018). Previous investigations have mostly been conducted for the purpose of retrofitting of existing columns and promising results were obtained. However, so far, there is very limited study has investigated the usage of FRP strips for the internal confinement of RC columns (Tahir *et al.*, 2019). Therefore, this study investigates the cyclic behaviour of concrete columns internally confined by carbon fibre reinforced polymer (CFRP).

(a)

(b)

Figure 1.6 Large spacing between the stirrups lead to column failure; (a) damaged column during 2015 Gorkha Earthquake and (b) column failure lead to building collapses during 2004 Sumatra Earthquake and Tsunami (Saatcioglu *et al.*, 2005; Sharma *et al.*, 2016)

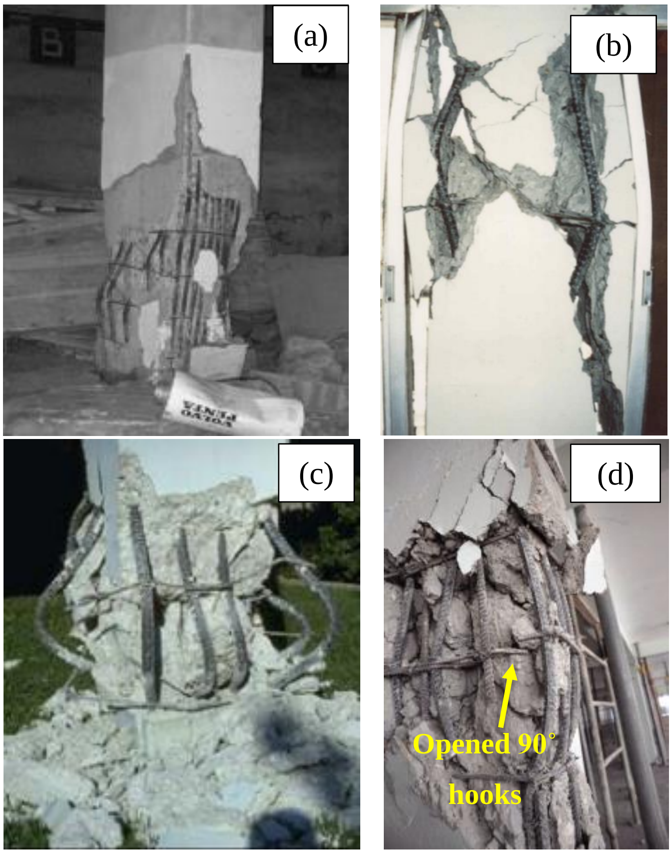

Figure 1.6 Buckling of longitudinal reinforcement during earthquakes due to improper detailing of confinement; (a) Expo building, Talcahuano during 2010 Chile Earthquake and Tsunami, (b) Van Nuys Holiday Inn building, California 1994 Northridge Earthquake, (c) Imperial County Services building California 1994 Northridge Earthquake and (d) Parking garage of the Digicel building 2010 Haiti earthquake (Olsen *et al.*, 2010; Faison *et al.*, 2004; Paultre *et al.*, 2013)

It should be mentioned that CFRP strips have superior properties compared to the mild steel used as stirrups in conventional designs (Quiertant and Clement, 2011; Alsayed *et al.*, 2014; Chellapandian *et al.*, 2017). Table 1.1 shows the comparison between these two materials. As can be seen, CFRP composites have more than 10 times the tensile strength and are 60 times lighter than the carbon mild-steel reinforcements used in conventional stirrups. Not only is the CFRP superior in terms of tensile strength compared to carbon steel, the light-weight property of FRP will reduce the overall weight of the structure in which it will improve seismic resistance in buildings (Lee *et al.*, 2016; Vandanapu and Krishnamurthy, 2018). This research may be used by practicing engineers and designers and therefore will help reduce maintenance and repair cost. These benefits together with the high resistance of CFRP against corrosion and harsh environment were the motivations for conducting this study.

Table 1.1 Summarised properties of FRP sheets and mild steel grade

Properties	CFRP composites	Mild steel
Modulus of elasticity	200-800 GPa	200 GPa
Density	1.75-1.95 g/cm^3	7.8 g/cm^3
Strength	2500-6000 MPa	200-380 MPa
Weight	0.0062 kg/m	0.395 kg/m

1.3 Objective of Study

As mentioned earlier, the application of CFRP sheets as a transverse reinforcement in RC columns resulted in many benefits for the construction industry. Therefore, the main objective of this study is to investigate the cyclic response (i.e. ultimate load, ultimate displacement, ductility ratio, energy dissipation, effective yield strength, etc.) of RC columns that have been internally confined with CFRP strips when subjected to a reversed cyclic loading. The following are the specific objectives:

(a) To experimentally investigate the cyclic response of RC columns internally confined with CFRP strips and compare them with that of carbon steel.

(b) To numerically determine the effects of different axial force and distance of CFRP strips on the cyclic response of RC columns internally confined with CFRP strips.

(c) To analytically propose a method for estimating the ultimate load of RC columns internally confined with CFRP strips.

1.4 Scope of Study

This study focused on the cyclic response of reinforced concrete columns internally confined with CFRP strips. Experimental works were conducted on eight ful-scale RC columns with the height of 1500 mm and cross-sectional size of 200 mm x 200 mm. The samples consisted of two main groups: a) three columns with CFRP stirrups and b) three columns with CFRP spirals. For the sake of comparison, two columns were confined with carbon steel stirrups and spirals with the spacing of 100 mm as reference samples. The compressive strength of concrete used in this study was 25 MPa. The yield strengths of steel bars with the diameter of 12 and 6 mm were 391 and 563 N/mm^2, respectively. In this study, columns confined with stirrups were reinforced with four longitudinal reinforcement bars, while six longitudinal reinforcement bars were employed in columns confined with spirals. Carbon fibre reinforced polymer (CFRP) sheets with the tensile strength of 4900 MPa were used in this study. In order to study the effect of thickness and distance between the CFRP strips, two samples were constructed and tested using a double layer of CFRP strips with 150 mm distance between the strips, respectively. The column samples were tested experimentally under a constant axial load together with a cyclic load based on FEMA 461 loading protocol. Moreover, in order to conduct a parametric study on the cyclic response of RC columns, a nonlinear analysis by means of Finite Element (FE) software ABAQUS 6.14 was performed. In the numerical study, different intensities of axial loads and different configurations of CFRP strips were investigated. An analytical method was proposed for estimating the ultimate load of columns internally confined by CFRP strips.

1.5 Significance of Study

This study examined the efficiency of CFRP strips to be used as the replacement for conventional carbon steel stirrups in RC columns. The outcome of this research can reduce the corrosion problem as well as increase the axial load capacity of the columns. By using CFRP composites in concrete structures, the dynamic behaviour of RC columns can also be improved. Easy installation and construction of CFRP strips as transverse reinforcement allow designers and engineers to make sure that the real design is implemented during the construction process. This is important because lack of attention to the implementation of the restrictions given in the design codes could cause failure of the building when subjected to severe loading such as earthquake.

1.6 Outline of the Thesis

This thesis consists of seven chapters. The arrangement of the chapter is as follows:

Chapter 1 describes the introduction of the study, the problem statement, the objectives, and the scope of the study, and explains the significance of this research.

Chapter 2 presents the literature review regarding the failure of columns due to seismic events and existing guidelines for the seismic design of columns, as well as the effect of steel corrosion in concrete. A detailed explanation about FRP composites reinforced concrete members and the durability of FRP under harsh environment are presented in this chapter. Advantages and disadvantages of FRP composites are discussed in this chapter as well.

Chapter 3 describes the methodology employed for achieving the defined objectives. The details of experimental works and their properties are explained in this chapter. This chapter also explains about the test setup and the employed loading protocol. It also describes the procedure of numerical studies and analytical calculations.

Chapter 4 discusses the obtained results from the experimental tests. The failure mechanism of columns, ultimate load, ductility and energy dissipation capacity of each sample are calculated and explained in this chapter.

Chapter 5 describes the numerical analysis used to conduct a parametric study on the CFRP strip internally confined RC columns. Validation of Finite element models is presented in this chapter. Results of the parametric study which included the effect of different intensities of axial load and different configurations of FRP strips are presented in this chapter.

Chapter 6 presents the proposed method for analytical calculation of ultimate load of RC columns internally confined with CFRP strips. The comparison between analytical and experimental results is also presented in this chapter.

Finally, Chapter 7 summarises and concludes the entire thesis. The research findings, contributions of the thesis and recommendations for future work are also discussed in this chapter.

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