Study of SFRP and SFRG in Retrofitting of Columns

By

Nikunj M. Patel

12MCLC22

DEPARTMENT OF CIVIL ENGINEERING

INSTITUTE OF TECHNOLOGY

NIRMA UNIVERSITY

AHMEDABAD-382481

May-2014

Study of SFRP and SFRG in Retrofitting of Columns

Major Project

Submitted in Partial Fulfillment of the Requirements for the degree of

MASTER OF TECHNOLOGY

IN

CIVIL ENGINEERING

(Computer Aided Structural Analysis and Design)

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Declaration

This is to certify that

i) The thesis comprises my original work towards the degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis And Design) at Nirma University and has not been submitted elsewhere for a degree.

ii) Due acknowledgement has been made in the text to all other material used.

Nikunj M. Patel

Certificate

This is to certify that the Major Project Report entitled **"Study of SFRP and SFRG in Retrofitting of Columns"** submitted by **Mr. Nikunj M. Patel (Roll No: 12MCLC22)** towards the partial fulfillment of the requirements of Master of Technology (Civil Engineering) in the field of Computer Aided Structural Analysis and Design of Nirma University is the record of work carried out by him under our supervision and guidance.The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

Mr. Varinder K. Singh
External Guide,
Deputy General Manager (civil),
ONGC, Ahmedabad Asset,
Ahmedabad.

Dr. Paresh V. Patel
Co-Guide,
Professor and Head,
Department of Civil Engineering,
Institute of Technology,
Nirma University, Ahmedabad.

Dr. K. Kotecha
Director,
Institute of Technology,
Nirma University,
Ahmedabad.

____
Examiner

____
Date of Examination

Abstract

Strengthening of RC structures using different retrofitting materials has a substantial growth in construction industry since last decade. Fiber reinforced polymer (FRP) composite materials have come to the forefront as promising materials and systems for structural retrofit. Today, mostly steel plates, carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymer (GFRP) are used as external reinforcement.

Steel fiber reinforced polymer (SFRP) composite materials have recently been introduced as an alternative to glass and carbon fiber reinforced polymer (GFRP and CFRP) composite materials. There are many benefits to using SFRP over GFRP or CFRP. Significantly, the steel cords that make up SFRP have some inherent ductility. Also, when cementitious grout is used rather than epoxy as the bonding agent, the SFRG can exhibit excellent fire resistant properties. Similar SFRP/SFRG has advantage of being relatively lightweight in comparison to steel plates, making it relatively easy to install.

The main objective of the present study is to evaluate axial load carrying capacity of SFRP/SFRG strengthened columns of M15 grade of concrete with and without reinforcement.An experimental investigation carried out on P.C.C. and R.C.C. columns of square (200mm x 200mm) and circular (200mm dia) shaped having 1200mm length. Total 32 concrete column specimens were cast including 8 control specimens, 24 specimens were strengthened using SFRP/SFRG. A direct tension test and bond test were done for finding tensile strength and bond behavior of SSWM. Out of three sample of SSWM of different weight/sqm (GSM), wire dia and no of wires tested, best two SSWM material were used with two different bonding agent epoxy and polymer cement grout. Based on results, it is observed that one layer of SFRP/SFRG increases compressive strength by 20-32% and two layers of SFRP/SFRG are further increase the strength by 65-89%. Wrapping efficiency in circular column is better as compared to square column. The cost of SFRP/SFRG less than GFRP and CFRP, therefore it

recommended to use SFRP and SFRG as a retrofitting material.

Acknowledgement

I would like to thank my guide **Dr. Paresh V. Patel** and from whose keen interest and knowledge base helped me to carry out the major project work. His constant support and guidance during my project work equipped me with a great understanding of different aspects of the project work. He has shown keen interest in this work right from beginning and has been a great motivating factor in outlining the flow of my work.

I would also like to thank my external guide **Varindar K. Singh**, Dy General Manager(Civil), ONGC, Ahmedabad Asset. He has vast knowledge and experience in structural repair and strengthening work. I found him very helpful me throughout my project work. He has provided me full guidance and support me in selection of column samples, steel wire mesh, wrapping material and epoxy adhesive for project work. I was able to successfully complete the research work under his practical guidance and support.

I further extend my thanks to **Dr. Urmil V. Dave and Dr. Sharad P. Purohit,** Department of Civil Engineering and **Dr. K. Kotecha,** Director, Institute of Technology, Nirma University, Ahmedabad for providing all kind of required resources during my study.

Finally, I would like to thank The Almighty, my father Mahendrabhai N. Patel, my mother Ramilaben M. Patel, and all my friends, for supporting and encouraging me in all possible ways throughout the dissertation work.

Abbreviation, Notation and Nomenclature

FRP .... Fiber Reinforced Polymer

GFRP .... Glass Fiber Reinforced Polymer

CFRP .... Carbon Fiber Reinforced Polymer

SFRP .... Steel Fiber Reinforced Polymer

SFRG .... Steel Fiber Reinforced Grout

gsm .... Gram per meter square

FRCM .... Fiber Reinforced Cement Mortar

WSB .... Wide Shallow Beam

f_c .... Compressive strength of concrete cube

f_c' .... Compressive strength of concrete cylinder

Ac .... Area of concrete

Asc .... Area of compression reinforcement

b_p .... Width of FRP plate

t_p .... Thickness of FRP

A_p .... c/s Area of FRP

E .... Modulus Of Elasticity

β_p .... Width ratio co-efficient

L_e .... Effective Length of FRP

L .... Actual length of FRP

β_L .... Length ratio co-efficient

P_u .... Analytical ultimate Load

σ_p .... Analytical FRP plate debonding strength

$P_{u,exp}$ .... Experimental ultimate load

$\sigma_{p,exp}$ .... Experimental FRP plate debonding strength

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Chapter 1

Introduction

1.1 General

Column elements potentially support a variety of structures, e.g. bridge decks and floor slabs, and can act as piers or piles, and may do so whilst above or below water. Columns vary in physical shape depending on their application within a situation, although typically they are either circular or rectangular for ease of construction. Repair and retrofit of structures will be an increasingly important issue as infrastructure continues to age and deteriorate. More options are becoming available for those structures for which it is more economical to retrofit than to demolish. During the early 90s, most of the external confinement techniques for columns included increasing the section by either constructing an additional concrete cage or by installing grout-injected steel jackets. Both methods are labour intensive and present difficulties at the site. Fiber reinforced polymer (FRP) composite materials have come to the forefront as promising materials and systems for structural retrofit. Presently, fiber-reinforced polymer (FRP) confinement of reinforced concrete (RC) columns has been shown to be a very effective technique for structural enhancement. FRP's also present various advantages such as, light weight, high confinement strength, high strength-to-weight ratio, easier installation and maintenance and also durable. FRP wrapping, prefabricated laminate jacketing and filament winding can substantially enhance the axial compressive strength and ductility of concrete columns due to lateral confinement as demonstrated by numerous investigators.

1.2 Retrofitting of Structures

Strengthening techniques for columns other than SFRP is given below.

- **Concrete Jacketing:-**Concrete jacketing applicable with reinforcement and without reinforcement periphery of column and joint with existing steel by welding and concrete done by either pressure grout or cast in situ concrete with high strength concrete. It have some disadvantages like increase in cross section sizes.

- **Steel Jacketing:-**Steel jacketing applicable with steel plates applied either by welding or bolting with existing columns.But handling of steel plates and corrosion of steel are major challenges.

- **Precast Concrete Jacketing:-**Precast concrete jacketing is very easy to install and less time consuming but bond between new and old concrete is very weak.

- **FRP Composite**:-"Fiber Reinforced Polymer (FRP) Composites are defined as "A matrix of polymeric material that is reinforced by fibers or other reinforcing material." Fiber Reinforced Polymers FRP composites comprise fibers of high tensile strength within a polymer matrix such as epoxy. FRP composites have emerged from being exotic materials used only in niche applications following the Second World War, to common engineering materials used in a diverse range of applications such as aircraft, helicopters, spacecraft, satellites, ships, submarines, automobiles, chemical processing equipment, sporting goods and civil infrastructure. The role of FRP for strengthening of existing or new reinforced concrete structures is growing at an extremely rapid pace owing mainly to the ease and speed of construction, and the possibility of application without disturbing the existing functionality of the structure.

Figure 1.1: Various Types and Shapes of FRPs Used in the Construction Industry

Many types and shapes of FRP materials are now available in the construction industry. For the purposes of external reinforcement of concrete, there are essentially two classes of FRP materials currently available: plates and sheets. Plates are rigid FRP strips that are manufactured using a process called pultrusion. Sheet FRPs are supplied as flexible fabrics of raw (or pre-impregnated) fibers. The sheet FRP materials are applied by saturating the fibers with an epoxy resin and laying-up the sheets onto the concrete surface. In both of the above applications, the FRP materials used are usually unidirectional (with all fibers oriented along the length of the sheet). Figure 1.1 shows various types and shapes of currently available FRP materials.

Steel fiber reinforced polymer (SFRP) composite materials have recently been introduced as an alternative to glass and carbon fiber reinforced polymer (GFRP and CFRP) composite materials (Hardwire, 2002). There are many benefits to using SFRP over GFRP or CFRP. Significantly, the steel cords that make up SFRP have some inherent ductility. Also, when cementitious grout is used rather than epoxy as the bonding agent, the SFRG can exhibit excellent fire endurance properties (Casadei et al., 2005a). Similar to GFRP and CFRP, SFRP has the advantage of being relatively lightweight in comparison to steel plates, making it relatively easy to install.

1.3 Stainless Steel Wire Mesh(SSWM)

SSWM material popular with various names like Steel fiber reinforced polymer (SFRP), Steel fiber reinforced grout (SFRG), stainless steel cord reinforcement (SSCR) etc. steel mesh wrapped with epoxy material than it is called SFRP similarly steel mesh wrapped with cementitious than it is called SFRG. A foreign company hardwire made this types of material. Hardwire is a family of reinforcements made from ultra high strength twisted steel wires. It is a revolutionary material that affords end users the ability to put ultra high tensile strength steel (11 times stronger than typical steel plate) inside or outside just about any material. Simply worded, Hardwire is moldable steel. Hardwire can be molded into thermo-set, thermoplastics or cementitious resin systems with never before seen ease and it occupies a new reinforcement niche between fibers and steel rebar. This creates a new class of reinforcements, micro-rebar, that will work with composite, plastic, and cement based processes. Further, Hardwire can be used to upgrade steel, wood, or concrete structures in both new construction and in retrofit applications. Composites made from Hardwire are up to 70% thinner and 25% lighter than composites made with glass fibers. When it comes to cost Hardwire is in a class by itself. Hardwire is priced like glass, yet performs like carbon at a fraction of the cost.

HARDWIRE (3x2 and 3x2 Tapes)

The 3x2 Hardwire is a high carbon steel cord with a micro-fine brass coating. The 3X2 wire cord is made by twisting 5 individuals wires together - 3 straight filaments wrapped by 2 filaments at a high twist angle. The result is an easy to handle cord that combines the best engineering values with great economics. If your application is tension dominated, choose the 3x2.

Table 1.1: Single Roving Cord Properties

Description	Filament Diameters (mm)	Cord Dia (mm)	Break (N)	Break (kN)	Break (kips)	Strain To Failure	Length per Kg. (m)
3X2	All Filaments are 0.35	0.889	1539	1.54	0.3462	2.10%	54.19

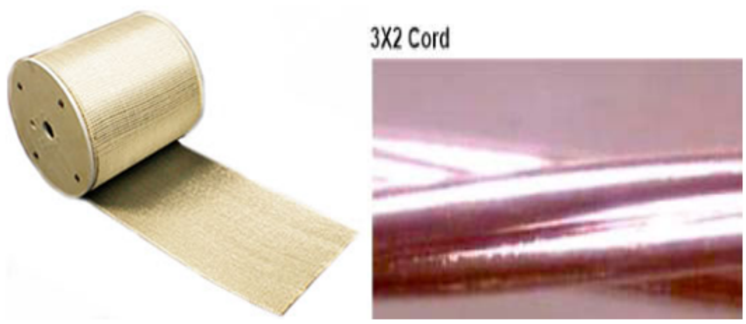

Figure 1.2: (a) SFRP Material of Hardwire (b) Steel Cord of SFRP

In this experimental work, stainless steel wire mesh which is manufactured in India for multi purpose use and locally available has been investigated. These meshes are easily bendable and light weight than steel plate. SSWM meshes are cheaper than CFRP/GFRP and steel plates.

Stainless steel wire meshes are square woven and Dutch woven. Some technical information about steel wire meshes given in table 1.2 and figure 1.3

Table 1.2: Technical Data of Steel Wire Meshes

Woven type	Mesh per inch	SWG	gsm	Diameter of Wire (mm)	Size of Opening (mm)
Square	40	32	1104.85	0.27	0.365
Square	80	40	302.63	0.122	0.196
Dutch	50 × 250	-	895.75	0.14 × 0.11	0.056-0.063

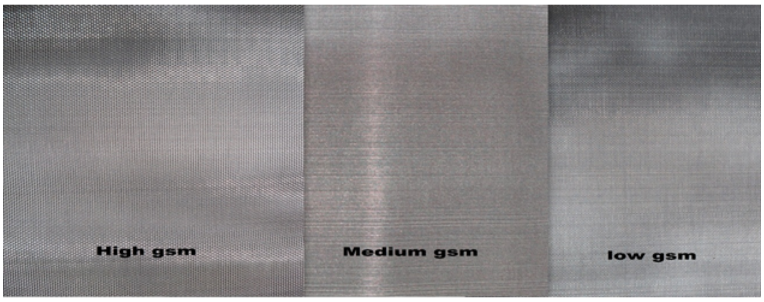

Figure 1.3: Three Types of Steel Wire Mesh

1.4 Research Significance

Various types of strengthening methods are used in the construction industry. Externally bonded steel plate and CFRP/GFRP techniques are more popular with small increment in size of elements. Steel plate handling is very difficult at site due to heavy weight and CFRP/GFRP are not ductile and also costy. It is essential to find other alternative products. SFRP/SFRG have both advantage of light weight, more ductile and economical, so research has been carried out.

1.5 Objective

The purpose of this thesis is to investigate and gather more information regarding the behavior of surface bonded steel fiber reinforced polymer (SFRP) and steel fiber reinforced grout (SFRG) retrofit methods for reinforced concrete columns subject to axial loading. The other objectives are as:

- To understand the bond-slip behavior of SFRP and SFRG under the application of direct tension.
- Find tensile strength of steel wire meshes

1.6 Scope Of Work

The scope of present study is decided as follows:

- Direct tensile test of SSWM for producing load vs. deformation curve.

- Casting of 6 dumbbell shaped specimens having size of 100mm x 100mm x 520mm and testing under direct tension for measuring bond strength.

- Casting of 16 square columns having dimension of 200mm x 200mm x 1200mm and 16 circular columns having 200mm diameter and 1200mm height.

- Retrofitting of columns with SFRP and SFRG as shown in table:1.3

- Comparisons of result related to axial compressive strength of columns.

Table 1.3: Column Test Matrix

	Circular specimens		Square specimens	
	R.C.C. specimens	P.C.C. specimens	R.C.C. specimens	P.C.C. specimens
control specimens	2	2	2	2
1-layer SSWM + epoxy	-	2	-	2
2-layer SSWM + epoxy	2	2	2	2
1-layer SSWM + polymer	-	2	-	2
2-layer SSWM + polymer	2	2	2	2

1.7 Organization of Report

This study is related to the evaluation of bond characteristics of concrete with different SFRP and SFRG fabric and concrete confining effect with SFRP and SFRG. The organization of report is as follows:

- Chapter-1 gives general introduction of the project. Introduction to SFRP and SFRG, Types of SFRP/SFRG, Importance of bond in SFRP/SFRG is discussed along with objectives and scope of the project.

- The literature review related to the experimental and analytical study related to SFRP and SFRG with concrete, is presented in chapter 2.

- Chapter 3 describes the details about the experimental program which includes casting of specimen, application of SFRP/SFRG fabric and preparation of test set-up to evaluate bond strength, direct tension test on steel wire meshes, axial load carrying capacity of retrofitted column.

- Chapter-4 includes results and discussion and failure pattern of columns.

- The summary of project work, concluding remarks and recommendation for future works are presented in chapter 5.

Chapter 2

Literature Review

2.1 General

As current infrastructure ages, and load demand continues to increase, both rehabilitation (restoring to original capacity) and strengthening measures must be made. Fiber reinforced polymer (FRP) materials have been successfully used for rehabilitation and strengthening efforts for the past two decades. Recently, a new form of FRP: steel fiber reinforced polymer (SFRP), has been introduced as an alternative to more conventional carbon or glass fiber reinforced polymers.

2.2 Bond Behavior

W. Figeys et al.(2008) [1] executed of 8 direct shear test. Two concrete prisms are bonded together with SCRP on two opposite sides which are grit blasted on beforehand. Between the two prisms, there is a small gap of 18 mm. Bonding length is 150 mm or 200 mm. On the two other sides, steel plates are glued. In all test specimens, failure was due to failure of concrete.

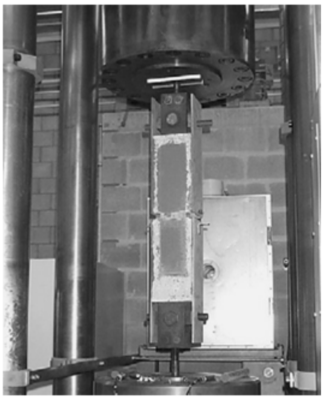

Figure 2.1: Test Setup for Direct Tension

Figure 2.2: Failure Mode

M. Matana et al. (2005) [2] present the results of an experimental study to evaluate the bond between SRP/SRG and concrete substrate using direct shear test. The variables included type of reinforcement, concrete surface roughness and bonded length. SRP specimens experienced concrete shearing failure with considerable damage of the concrete, while SRG specimens experienced failure in the grout layer. The existence of the effective bond length after which the load can no longer increase was proven and calculated for SRP specimens. Due to the cracking of the cementitious matrix at low load levels, it was not possible to calculate an effective bond length for SRG specimens.

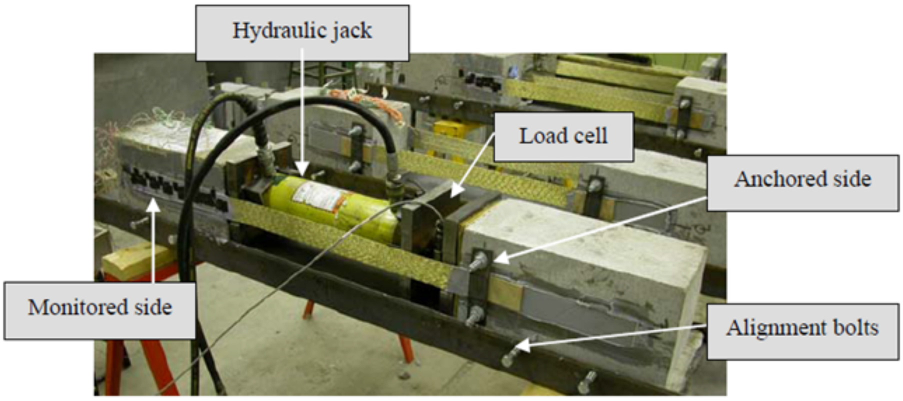

Figure 2.3: Test Setup for Direct Shear Test

2.3 Axial Strengthening

Khaled Abdelrahman et al.(2012) [4] studied behavior of large scale column with SFRP sheets. Non-reinforced and reinforced large-scale columns (300 × 1200) mm wrapped with CFRP and SFRP sheets is examined and compared with that of unwrapped columns. Results indicate that the overall performance of the SFRP-wrapped concrete columns is superior to that of the CFRP-wrapped concrete columns. rapping of SFRP sheets was very effective in increasing the axial strength and deformability of the concrete columns. Columns wrapped with SFRP sheets showed superior performance compared to columns wrapped with CFRP sheets in terms of the stress-strain behavior, axial strength, axial strain,and hoop strain. The strain efficiency analysis based on the DICT data and the readings from the conventional foil strain gauges for non-reinforced and reinforced concrete columns show that the columns wrapped with the SFRP sheets achieved higher strain efficiencies than did the columns wrapped with the CFRP sheets.

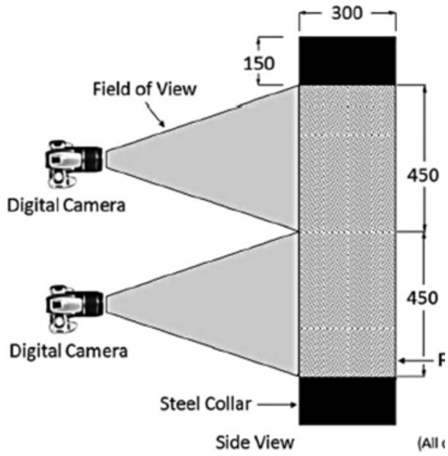

Figure 2.4: DICT Test Setup

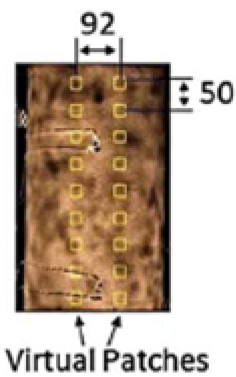

Figure 2.5: Field of View with Virtual Patches

Raafat El-Hacha et al.(2012) [3] investigated on circular specimens confined with SFRP sheets. The experimental program included eighteen specimens with varying slenderness ratios (height-to-diameter ratio) of 2 (150 mm × 300 mm), 4 (150 mm × 600 mm), and 6 (150 mm × 900 mm). Six specimens were constructed in each size, where three specimens were left unwrapped as control specimens and three specimens were wrapped with SFRP sheets.

All specimens were loaded in uniaxial compression until failure. The specimens were also instrumented with a photogrammetric method termed Digital Image Correlation Technique to measure the hoop strains from the surface of the SFRP confined concrete specimens. The experimental investigation showed that the effectiveness of the SFRP sheets, measured in terms of the percentage increase in the ultimate axial strength, axial and hoop strains, and the ductility was significantly enhanced compared to the unwrapped specimens. The results also indicate that the overall performance of the SFRP wrapped concrete specimens was reduced with the increase in the slenderness of the specimens, when compared to the standard size cylinders.

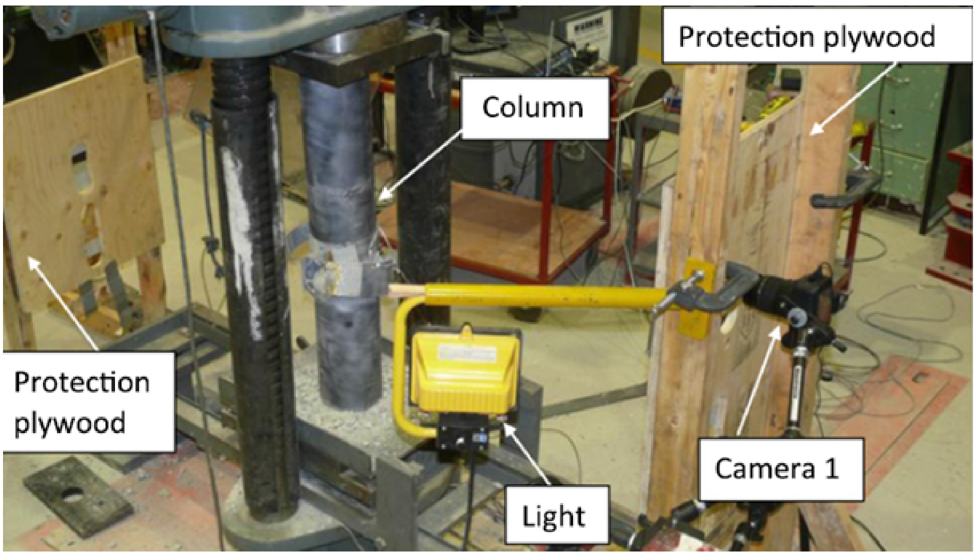

Figure 2.6: Test Setup for Concrete Specimens

2.4 Flexural and Shear Strengthening

Konstantinos katakalos et al.(2013) [8]compare between carbon and steel fiber reinforced polymer with or without anchorage. Totally nine 1:1 scale beams with a span of 3000mm where fabricated and tested. The experimental results indicate that the failure of the strengthened beams was based on the debonding of the strengthening sheet when no anchoring system was used. At the other cases the failure occurred due to fracture of the FRP sheet or failure of the anchoring system. Furthermore, the use of an anchoring system increases the overall capacity of the beam. In conclusion a strengthening system with SFRP can provide an effective alternative to commercially available systems.

Figure 2.7: Experimental Setup for Beam

Y.j. kim et al. investigated on Flexural strengthening of RC beams using SFRP. Test parameters include variation of the width of SRP sheets and the use of SRP U-wraps to prevent premature failure.caused by delamination of the longitudinal sheet. Significant increase in flexural capacity, up to 53 percent, and pseudo-ductile failure modes were observed in SRP strengthened beams. Failure was governed primarily by concrete cover delamination at the ends of SRP sheets or concrete crushing. The U-wraps improved flexural stiffness by means of controlling diagonal cracking and providing anchorages to the longitudinal SRP sheets, which reduced their slip. Shear stress concentrations near cut-off points of SRP sheets have also been investigated.

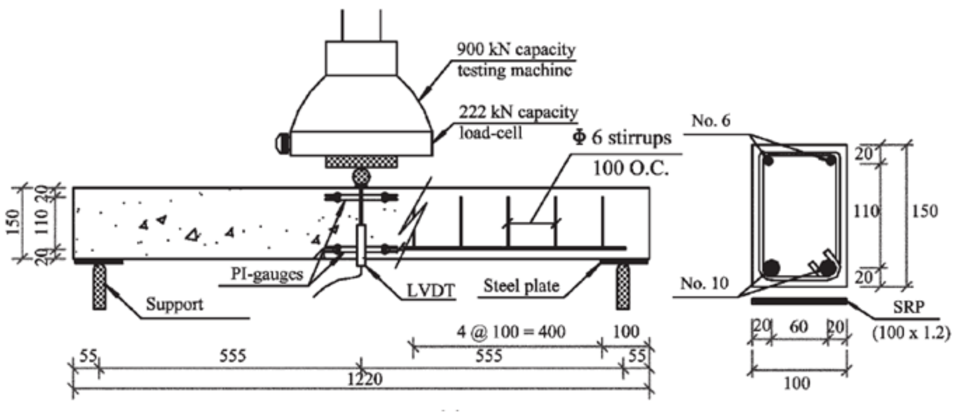

Figure 2.8: Experimental Test Setup and Beam Detail

Andrea prota studied on performance of shallow reinforced concrete beams with externally bonded steel reinforced polymer. Total 11 Rc shallow beams 400 × 200 × 3700mm were cased and tested in flexure load. Strength increases provided by SRP bonded with cementitious grout were smaller than those obtained using epoxy. CFRP was more effective than epoxy-bonded SRP in terms of strength; the trend was inverted in terms of ultimate deflections. Compared with the unstrengthened beam, SRP allowed attaining strength increases ranging between 46 and and 145percent, while reductions of ultimate deflections ranged between 13 and 55 percent. A comparison between beams with equivalent reinforcement ratio highlights that epoxy-bonded SRP tapes provided ultimate strength approximately 10 percent smaller than CFRP with deflections approximately 24 percent larger.

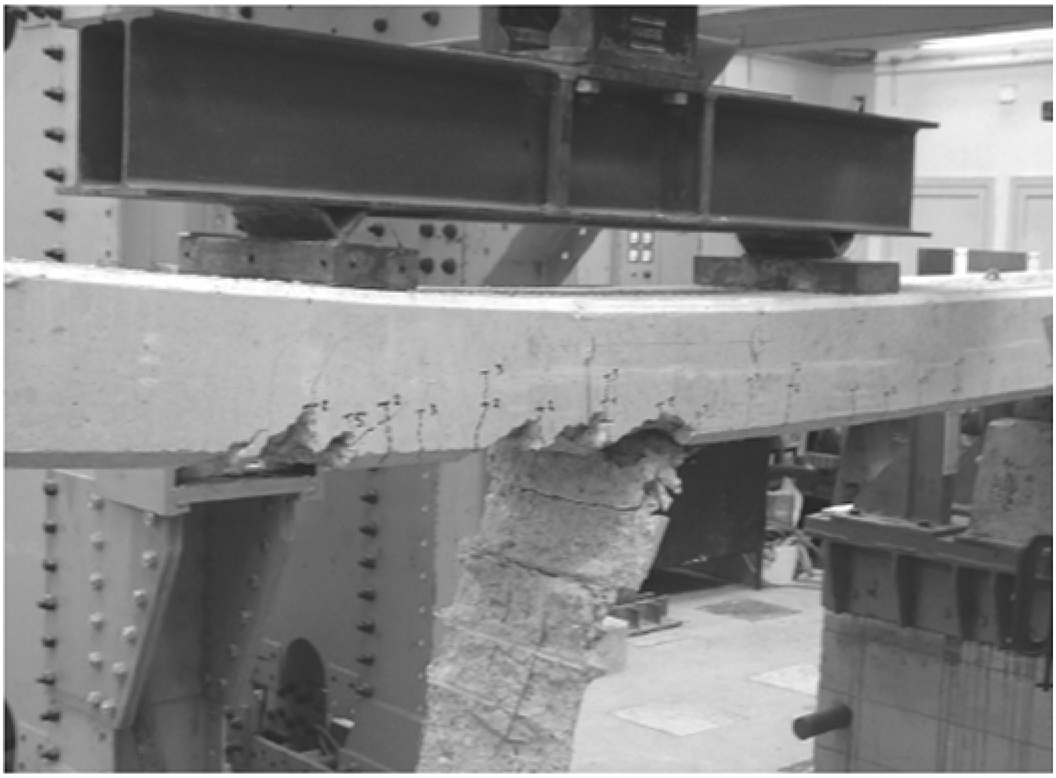

Figure 2.9: Lateral View of Failure of Beam

Casadei et al. (2005) [6] compared the use of SFRP to CFRP as a retrofit measure for concrete beams. They conclude that CFRP was more effective than SFRP in terms of ultimate strength. Due to its inherent ductility, however, SFRP performed better than CFRP in terms of achieving a higher ultimate deflection. It should be noted that the axial stiffnesses of the SFRP and CFRP retrofit measures were not equivalent in this study. Pecce et al. (2006) report that when the reinforcement percentage is the same and epoxy is used as the bonding agent, steel cords and carbon fibers give very similar results.

Chapter 3

Experimental Programme

3.1 General

The objective of project is to understand bond behavior of concrete with SFRP/SFRG, and the axial load carrying capacity of column wrapped with SFRP/SFRG. To fulfill the objective, casting of 6 specimens for bond strength and 32 specimen of column are made. Detailed specifications of specimen and test setup are discussed in this chapter.

3.2 Tensile Test for SSWM

3.2.1 Specimens Preparations

Three different types of SSWM are tested each have two sample to find out average value. 100mm wide and 500mm long SSWM strip fixed at both ends by 100 mm $\times$ 150mm metal plates and epoxy.Prepared epoxy sikadure-31 mix base and hardener 2:1 and applied on clear rough surface of metal plates with the help of spatula and SSWM was applied on it. Applied second coat of epoxy on SSWM and put another plates on it and applied constant pressure by some weight for proper bonding. Plan and section of SSWM specimens are shown in figure: 3.1. Ambient curing is required for seven days for sufficient bond strength. This sample tested under tensile test in universal testing machine and measured ultimate tensile strength and elongation by help of dial gauge. Three samples of SSWM are shown in figure: 3.2.

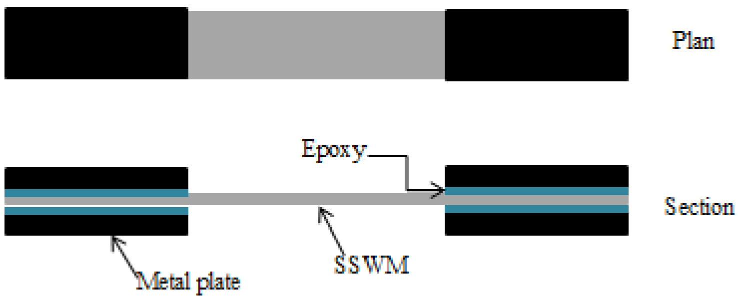

Figure 3.1: Sketch of SSWM Specimen

Figure 3.2: Tensile Test Samples

3.2.2 Test Setup for Tensile Test

Sample griped between upper and middle cross head by fixing of particular metal plate grip and by moving up of upper cross head and middle fixed head the SSWM sample in tension. Between two cross head LVDT dial gauge fixed for measuring elongation of SSWM. Detailed test setup shown in figure: 3.3.

Figure 3.3: Test Setup for Tensile Test

3.2.3 Results of Tensile Test

A failure of SSWM was slowly with crack sound and cracks propagation one side to other side. Result and calculation of SSWM of tensile strength are shown in table: 3.1.From above calculation SSWM-2 and SSWM-3 are good in tension its tensile strength higher than HYSD reinforcement but less than CFRP and GFRP. SSWM sources more ductility than CFRP and GFRP. Ductility is very important terminology in terms of failure. Failure of SSWM as shown in figure: 3.4.

Table 3.1: Calculation of tensile test

Sr.no	Calculation Steps	SSWM-1		SSWM-2		SSWM-3		Unit	Remark
1	Wire mesh no.	80		50x250		40		-	
2	Width of SSWM	100		100		100		mm	
3	Thickness of SSWM	0.112		0.22		0.27		mm	
4	No of wires	314		984		156		No.	
5	c/s Area of wire	0.01169		0.009499		0.05722		mm^2	
6	Total c/s Area	3.668		9.34		8.923		mm^2	4 x 5 = 6
7	Load (Reading in kgf)	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2		
		270	390	710	680	580	720	Kgf	
8	Load	2646	3825.9	6965.1	6670.8	5684	7063.2	N	
9	Avg Load	3235.95		6817.9		6373.6		N	
10	Avg ultimate TS of wire	882.2		729.96		714.28		N/sqmm	9 / 6 = 10
11	Ultimate load per cm width SSWM	323.59		681.79		637.3		N/Cm	9 / 2 = 11
12	Avg ultimate TS of SSWM	288.9		309.9		236.1		N/sqmm	9/(2 X 3) =12
13	Avg elongation of SSWM (δl)	4.7		10.25		12		mm	
14	Repture strain (δl/L)	0.016		0.034		0.040		mm/mm	L=300 mm

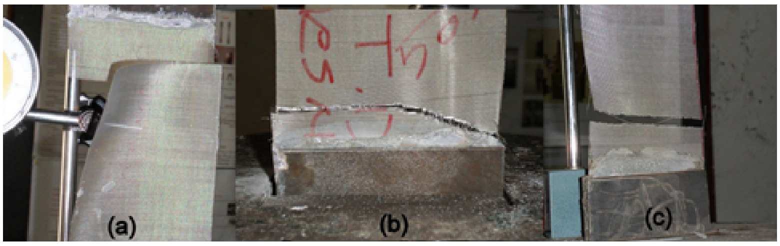

Figure 3.4: (a) Failure of SSWM-1 (b) Failure of SSWM-2 (c) Failure of SSWM-3

3.3 Evaluation of Bond Characteristics

3.3.1 Specimen Preparation

From tensile test of SSWM-2 and SSWM-3 are suitable for wrapping material therefor bond test carried out on these two meshes. Total 4 plain concrete dumbbell shaped specimens are cast having M40 grade of concrete as shown in table: 3.2. All the four samples have different material applied.

Table 3.2: Bond Characteristics Specimens

Types of Steel wire mesh	Types of bonding material	No. of dumbbell shaped specimens
SSWM-2	Epoxy	1
	Polymer	1
SSWM-3	Epoxy	1
	Polymer	1

Epoxy resin coated steel wire mesh refers as a SFRP and Polymer grout coated steel wire mesh refer as a SFRG.There are two types of steel wire mesh used with different gsm 1104.85, 895.75 for high(SSWM-3) and medium(SSWM-2) gsm respectively.

Figure 3.5: Epoxy Resin (Sikadur-31)(Left) and Cementitious Polymer Grout (Tapecreate P-151)(Right)

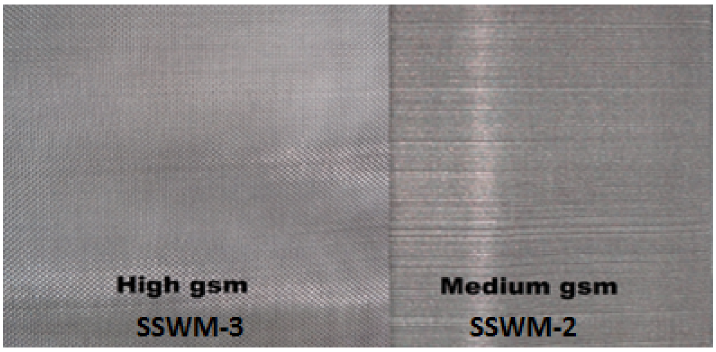

Figure 3.6: Stainless Steel Wire Meshes

Plain Concrete specimens of dumbbell shaped 4 specimens casted in two part with putting separation wood. And keep left for curing for 28 days. Than after specimens surface grinned to aggregate seen on top. Aggregate blasting surface prepared. Specimens put in same level and applied cement and polymer for SFRG specimens. And applied epoxy for SFRP specimens. SFRP required 7 days for ambient curing and SFRG required 28 days water curing.

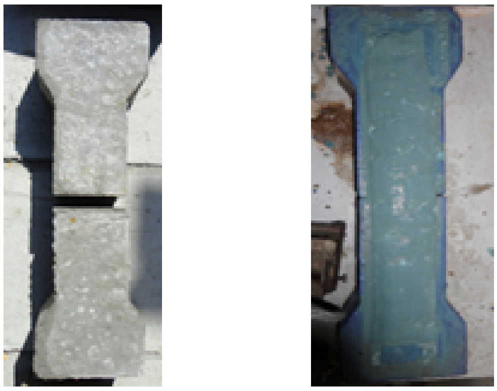

Figure 3.7: Casted Concrete Specimen (Left) and SFRG Coated Specimen (Right)

3.3.2 Test Set-Up for Bond Test

A loading frame is fabricated to apply direct tension on the specimen. Universal Testing Machine (UTM) is used to apply load on the loading frame. The main advantage of the loading frame is to convert the axial compressive load of the UTM into axial tensile load on the specimen. The frame consists of two U-shaped frames fabricated in such a way that under the application of load both frames can slide vertically with respect to each other as shown in Figure: 3.8.

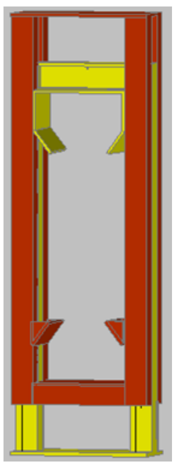

Figure 3.8: Loading Frame

Due to two individual specimens concrete tensile strength does not come in picture. In dumbbell shaped frame load applied by universal testing machine is compression the specimens fill direct tension. Universal testing machine give direct tension result. We coated SFRP/SFRG at both side of specimens hence result given by UTM is double. Failure of specimen is sudden with crack sound.

Figure 3.9: Test Setup of Bond Test

3.3.3 Results for Bond Test

In this test bond of SFRP/SFRG does not fail therefore it gives tensile strength of SSWM. Results calculation shown in table: 3.3 and failure mechanism shown in figure:3.10.Both the epoxy and cementitious materials were tested in bond but there was no bond failure. At ultimate loads, the SSWM failed in tension simultaneously indicating uniform distribution of load on all wires.

Table 3.3: Calculation of Bond Strength

Sr.No.	Calculation steps	SSWM-2	SSWM-3	unit
1	Wire Mesh No.	50 x 250	40	
2	gsm	895.75	1104.85	
3	size of opening	0.063	0.365	mm
4	Dia of bar	0.11	0.27	mm
5	Width of mesh	75	75	mm
6	No of wires = Width of Mesh/(Dia of Bar + size of opening)	738	118	No.
7	c/s Area of one wire	0.009499	0.057227	mm^2
8	Total c/s Area	7.01	6.75	mm^2
9	Load (Reading in kgf)	950	840	kgf
10	Load (N)	9319.5	8240.4	N
11	half load on each side	4660	4120	N
12	tensile strength (Mpa)	**664.7**	**610.2**	N/mm^2

Figure 3.10: Failure of Bond Specimen

3.4 Axial Strengthening of Column

3.4.1 Mix design for column

Column sample were casted with M15 grade of concrete. The mix design of concrete as shown in table:3.4 The mix design of concrete done as per IS 10262: 2009 and each Batch of concrete for casting column three cubes of 150mm x 150mm x 150mm were cast and tested for measuring compressive strength of concrete. Compressive strength of cubes are shown in table: 3.5.

Table 3.4: Mix Design for Column Specimens

Mix design For M15 grade	
Cement - OPC 53	329 kg /m^3
Water	197 kg /m^3
Fine Aggregate	768 kg /m^3
Coarse Aggregate	1131 kg /m^3
Water - Cement Ratio	0.60

3.4.2 Specimens Preparation

Total No. of 32 column specimens of square and circular shaped were cast. The detail scheduled of column specimens are shown in table 3.6 below and drawings of formwork as shown in figure 3.11 and details of reinforcements are shown in figure 3.12.

Table 3.5: Compressive Strength of Cubes

Target Mean strength (Mpa)	Avg Comp. Strength of three cube (Mpa)	Average comp. strength (Mpa)
15 + 1.65 x 3.5 = 20.77	19.8	20.55
	21.6	
	19.6	
	21.7	
	21	
	21.2	
	20.9	
	19.7	
	21.5	
	18.5	

Table 3.6: Column Specimens Matrix

	circular specimens 200mm Dia x1200 mm length		square specimens 200 x 200 x 1200 mm	
	R.C.C. specimens	P.C.C. specimens	R.C.C. specimens	P.C.C. specimens
control specimens	2	2	2	2
1-layer SSWM-2 + epoxy	-	2	-	2
2-layer SSWM-2 + epoxy	2	2	2	2
1-layer SSWM-3 + polymer	-	2	-	2
2-layer SSWM-3 + polymer	2	2	2	2

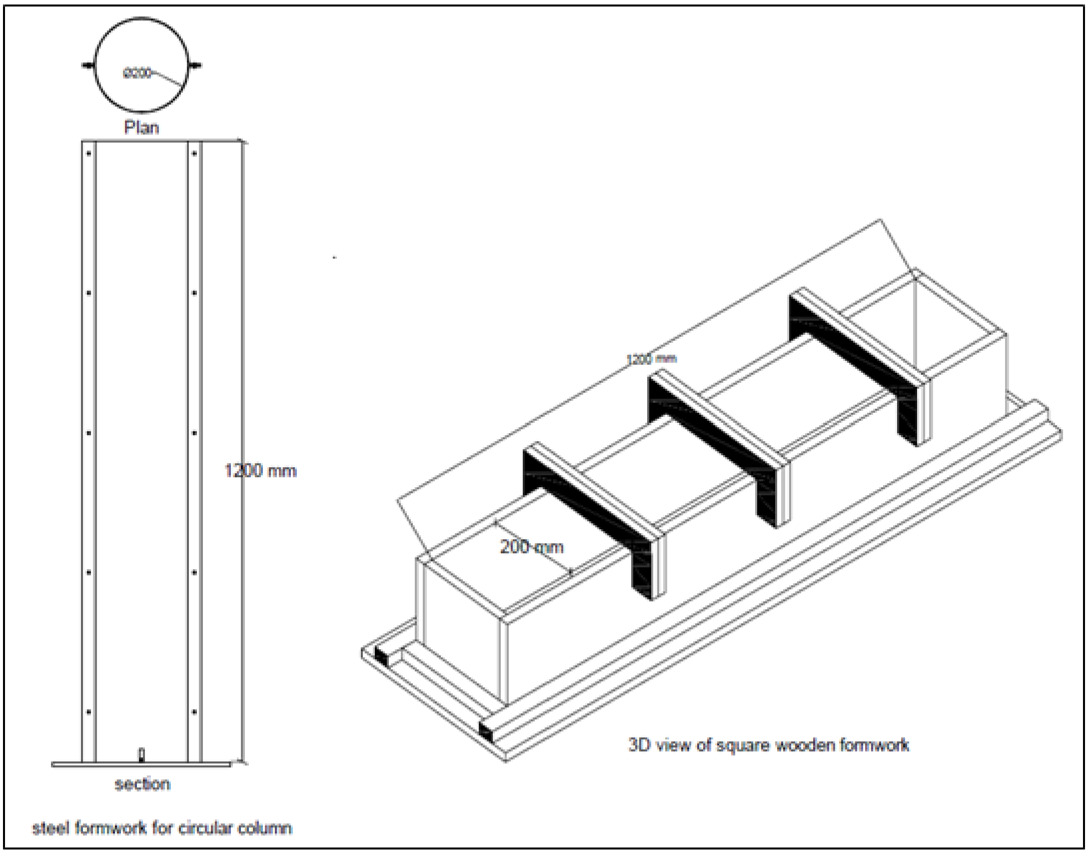

Figure 3.11: Drawing of Formwork

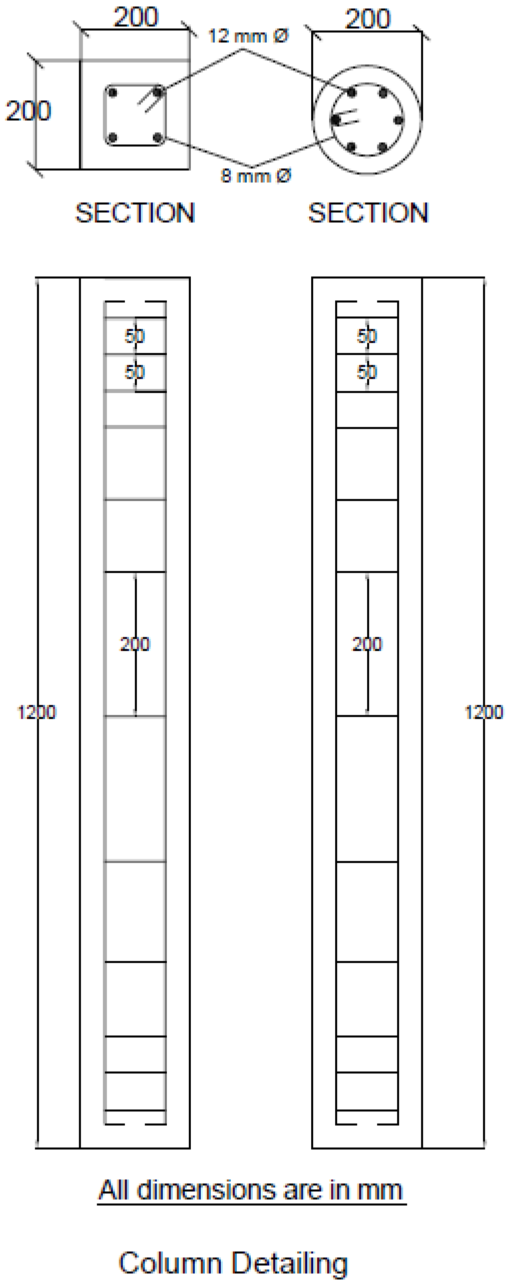

Figure 3.12: Reinforcements Details for Square and Circular Column

200 x 200 x 1200 mm size square columns were caste horizontally and 200 diameter x 1200 mm height circular columns were caste vertically. Two sample for each types of specimens, two types of bonding agent, two types of SSWM and single and double layers and control specimens were cast for both shape square and circular specimens for testing under axial loading. column specimens are shown in figure:3.13.

Figure 3.13: Casting of Specimens

3.4.3 Strengthening of Column

Strengthening of columns was divided in two parts as strengthening of column by SFRP and SFRG. SSWM-2 with having 895.75 gsm and BASF product Masterbrace 4500 epoxy were using in preparation of SFRP similarly SSWM-3 with having 1104.85 gsm and Tapecreare p-151 plus cement (1:2) were using in preparation of SFRG.

Following steps required for strengthening of column using SFRG:

- Grinding
- Cutting of SSWM
- Making of polymer Grout
- Applying of first coat
- Wrapping of SSWM
- Applying of final Coat
- Binding of column
- Curing

1.**Grinding**: Grinding of concrete surface after 28 period of concrete curing and grinding should be till aggregate appear on surface. And molding of corner radius up to 25mm in square column Grinding of specimens are shown in figure:3.14.

Figure 3.14: Grinding of Specimens

2.**Cutting of SSWM**: Cutting of SSWM-3 as per dimension of column by use of scissor. And the overlap in vertical joints should be considered 200mm by using debonding calculation. There was no requirement of horizontal overlaps. cutting of SSWM is shown in figure:3.15.

Figure 3.15: Cuttings of SSWM-3

3.**Preparation of Polymer Grout:** Mix polymer (Tapecrete P-151) with cement with 1:2 ratios as per requirement of first coat as shown in figure:3.16. Steer well for proper mixing of cement and polymer. There was small amount of mixing of polymer and cement for remaining of hardening of grout.

Figure 3.16: Preparations of Polymer Grout

4.**Applying of First Coat:** Remove dust of grinding with help of water. Before applying of first coat of polymer grout, apply putty of making by cement and Tapecreate -P151 with 3:1 proportion. Than after apply first coat of polymer grout. applying of first coat of polymer grout as shown in figure:3.17.

Figure 3.17: Applying First Coat

5.**Wrapping of SSWM-3:**Wrapping of column with SSWM before drying of first coat of polymer grout. And wrapped column bonded by bonding wire. There was tight wrapping by help hands pressure. wrapping of SSWM as shown in figure:3.18

Figure 3.18: Wrapping of SSWM-3

6.**Applying of Final Coat:** Apply final coat on SSWM which is bonded on column.

Figure 3.19: Applying Final Coat on Column

7.**Binding of Column:** Column was bonded with oiled plywood with help of bonding wire and keep plywood size same as column side for full cover length of column.
8.**Curing:** water curing required for 28 days.

Following steps required for strengthening of column using SFRP:

- Grinding
- Applying of primer coat
- Cutting of SSWM-2
- Applying of epoxy
- Wrapping of SSWM-2
- Binding of column
- Applying of final Coat of Epoxy

1.**Grinding:-** Grinding of concrete surface after 28 period of concrete curing and grinding should be till aggregate appear on surface. And molding of corner radius up to 25 mm in square column. Grinding of columns as shown in figure: 3.20.

Figure 3.20: Grinding of Columns

2.**Applying of Primer Coat:-** Remove dust of grinding with water and keep surface dry. Then after apply primer coat on surface and leave it for 24 hours curing. The properties of primer and saturant are shown in table: 3.7. Primer and saturant are shown in figure: 3.21. Applying of primer coat on column as shown in figure 3.22.

Table 3.7: Epoxy Material Properties Provided by Manufacturer

BASF	Primer	Saturant
Brand name	MasterBrace 3500	MasterBrace 4500
Aspect	Free flowing liquid	Translucent blue liquid
Mixed density (kg/ltr)	1.07 ± 0.02	1.13 ± 0.03
Miixing ratio, by weight (A:B)	2:1	2.5:1
Coverage	4-6 sqm per kg	0.8-1.8 sqm per kg
Pot life	40 minutes at 25°c	25 minutes at 25°c

Figure 3.21: Primer (Part 1 and 2) and Saturant (Part 1 and 2)

Figure 3.22: Primer Coat on Columns

3.**Cutting of SSWM-2:-** Cutting of SSWM-2 as per dimension of column by use of seizer as shown in figure: 3.23. And the overlap in vertical joints should be considered 200mm by using debonding calculation. There was no requirement of horizontal overlaps.

Figure 3.23: Cutting of SSWM-2

4.**Applying of Epoxy:** Mix epoxy (Master Brace 4500) saturant part-1 and 2 in proportion 1:2 with and apply immediately before its setting.

Figure 3.24: Applying First Coat of Epoxy

5.**Wrapping of SSWM-2:-**After applying epoxy on column wrapped with SSWM and temporary bonded with binding wire. Also applied epoxy at the overlapping portion of SSWM. wrapping of SSWM as shown in figure: 3.25.

Figure 3.25: Wrapping of SSWM-2

6.**Binding of Column:** Column was bonded with oiled plywood with help of binding wire and keep plywood size same as column side for full cover length of column. Circular columns only bonded by binding wire and at joint of SSWM wooden strip was provided for proper joint of SSWM. In square column four side of column covered by full length of plywood with help of binding wires. Binding of square and circular column are shown in figure 3.26.

Figure 3.26: Binding of Columns

7.**Applying of Final Coat of Epoxy:** after setting of first coat plywood removed from column and applied final coat of epoxy saturant.7 days ambient curing required for gaining strength of epoxy.

Figure 3.27: Application of Final Coat

Figure 3.28: Final Coated All Columns

3.4.4 Test Set-up for Column

Testing of column was conducted on loading frame. The loads were applied using hydraulic Jack of 2000 kN capacity.Figure 3.29 shows arrangement of test setup for columns. The load was applied from the bottom of the column. Load was transferred from Jack to packing plate to column and finally on to the loading frame.

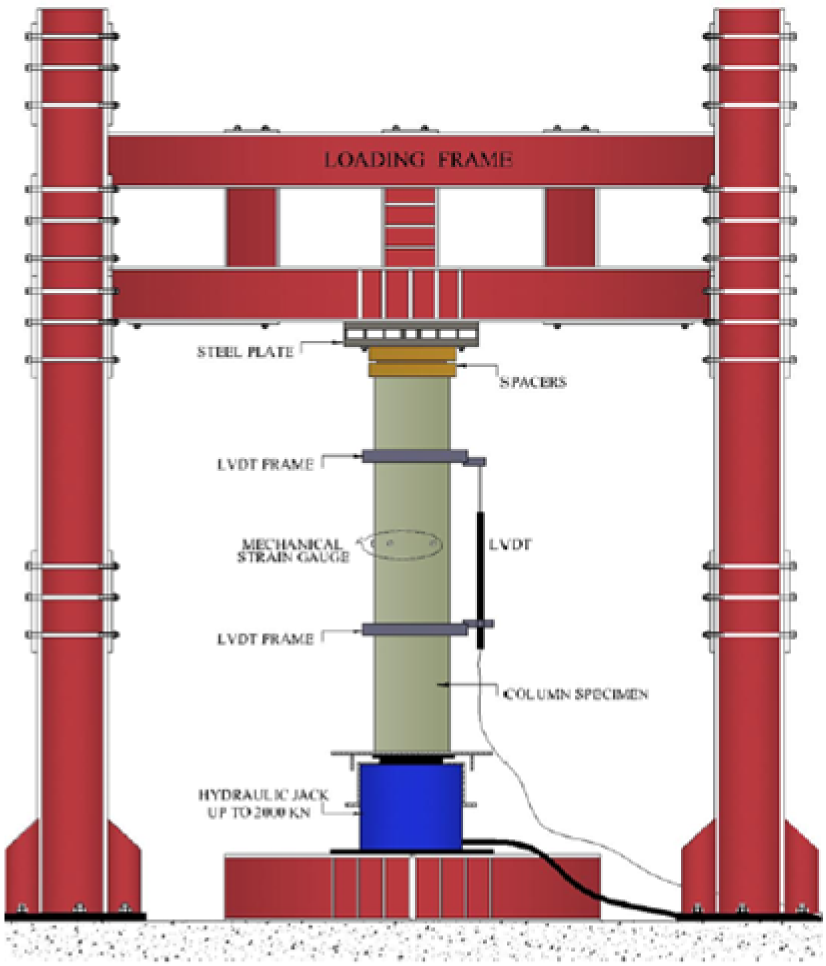

Figure 3.29: Test Setup for Column Specimen

3.4.5 Test Procedure

Load, displacement and lateral strain for column specimens are measured using hydraulic jack, LVDT and mechanical strain gauge, respectively. Various instruments used in experimental work are as follows:

1.**Hydraulic Jack**:-Hydraulic jack of capacity of 2000 kN is used and is working based on Pascal's principle. Basically, the principle states that the pressure in a closed container is the same at all points. Pressure is described mathematically by a Force divided by Area. Therefore if there are two cylinders connected together, a small one and a large one, and a small force is applied to the small cylinder, this would result in a given pressure.

2.**LVDT (Linear Variable Differential Transducer)**:-LVDT is Linear Variable Differential Transducer as shown in Figure: 3.30. It includes LVDT rod and Digital Displacement Indicator. LVDT is attached with indicator. LVDT is used to measure the vertical displacement. Least count of LVDT is 0.01mm. LVDT fixed with help of wooden frame for measuring axial shortening of column. When load of specimen reach that theoretical value it will be removed for safety purpose of instrument.

Figure 3.30: LVDT Rod and Digital Indicator

3.5 summary

In this chapter tensile test of SSWM, bond behavior of SSWM, axial strengthening of columns and test setup for column are given.

Chapter 4

Results and Discussion

4.1 General

This chapter deals with reporting of test results like: Axial compressive load, displacement and comparison of various types of columns results. Load is increased on the column at specific intervals and corresponding to every load, displacements are measured for the columns. Comparison of Ultimate failure load, experimental and theoretical results and displacements are presented in tabular as well as in graphical form. These parameters are very essential to understand the behavior of all the columns. Different parameters discussed in this chapter for columns are as follows:

- Estimation of strength of Columns
- Ultimate axial load
- Load vs. deflection

4.1.1 Notations for Columns

Table 4.1: Notations for Columns

CCP	Control Circular P.C.C.
CCR	Control Circular R.C.C.
CPEL1	Circular P.C.C Epoxy SSWM Layer 1
CPEL2	Circular P.C.C Epoxy SSWM Layer 2
CREL2	Circular R.C.C Epoxy SSWM Layer 2
CPPL1	Circular P.C.C Polymer SSWM Layer 1
CPPL2	Circular P.C.C Polymer SSWM Layer 2
CRPL2	Circular R.C.C Polymer SSWM Layer 2
CSP	Control Square P.C.C.
CSR	Control Square R.C.C.
SPEL1	Square P.C.C. Epoxy SSWM Layer 1
SPEL2	Square P.C.C. Epoxy SSWM Layer 2
SREL2	Square R.C.C. Epoxy SSWM Layer 2
SPPL1	Square P.C.C. Polymer SSWM Layer 1
SPPL2	Square P.C.C. Polymer SSWM Layer 2
SRPL2	Square R.C.C. Polymer SSWM Layer 2

4.2 Ultimate axial Strength of Columns

All Column specimens are subjected to axial load with both end partially fixed. The load was applied from Jack until the specimen failed. Ultimate failure load for all columns are given in table: 4.2 to 4.7. Ultimate axial load capacity of two specimens are measured for finding average ultimate axial strength. Table 4.2 represents ultimate axial strength of Control Circular P.C.C. column (CCP), Circular P.C.C. Epoxy SSWM layer1 (CPEL1) and Circular P.C.C. Epoxy SSWM layer2 (CPEL2) columns. Average ultimate axial strength of CCP (495 kN) increase with one layer of SFRP up to 600 kN and it further increase with two layers of SFRP up to 935 kN.

Table 4.2: Ultimate Axial Strength of CCP, CPEL1 and CPEL2 Columns

Name of Column	Length of column	Shape of Column	Bonding Agent	Type of column	No of layers	Ultimate Axial strength of column (kN)	Avg. Ulti. Axial strength of column (kN)
CCP	1200	Circular	Control	P.C.C.	0	500	495
						490	
CPEL1	1200	Circular	Epoxy	P.C.C.	1	600	600
						-	
CPEL2	1200	Circular	Epoxy	P.C.C.	2	920	935
						950	

Table 4.3 represents ultimate axial strength of Control Circular P.C.C. column (CCP), Circular P.C.C. Polymer SSWM layer1 (CPPL1) and Circular P.C.C. Polymer SSWM layer2 (CPPL2) columns. Average ultimate axial strength of CCP (495 kN) increase with one layer of SFRG up 615 kN and it further increase with two layers of SFRG up to 830 kN.

Table 4.3: Ultimate Axial Strength of CCP, CPPL1 and CPPL2 Columns

Name of Column	Length of column	Shape of Column	Bonding Agent	Type of column	No of layers	Ultimate Axial strength of column (kN)	Avg. Ulti. Axial strength of column (kN)
CCP	1200	Circular	Control	P.C.C.	0	500	495
						490	
CPPL1	1200	Circular	Polymer	P.C.C.	1	600	615
						630	
CPPL2	1200	Circular	Polymer	P.C.C.	2	800	830
						860	

Table 4.4 represents ultimate axial strength of Control Circular P.C.C. column (CCR), Circular R.C.C. Epoxy SSWM layer2 (CREL2) and Circular R.C.C. Polymer SSWM layer2 (CRPL2) columns. Average ultimate axial strength of CCR (565 kN) increase with two layer of SFRP up 1180 kN and similarly increase with two layers of SFRG up to 1010 kN.

Table 4.4: Ultimate Axial Strength of CCR, CREL2 and CRPL2 Columns

Name of Column	Length of column	Shape of Column	Bonding Agent	Type of column	No of layers	Ultimate Axial strength of column (kN)	Avg. Ulti. Axial strength of column (kN)
CCR	1200	Circular	Control	R.C.C.	0	550	565
						580	
CREL2	1200	Circular	Epoxy	R.C.C.	2	1200	1180
						1160	
CRPL2	1200	Circular	Polymer	R.C.C.	2	970	1010
						1050	

Table 4.5 represents ultimate axial strength of Control Square P.C.C. column (CSP), Square P.C.C. Epoxy SSWM layer1 (SPEL1) and Square P.C.C. Epoxy SSWM layer2 (SPEL2) columns. Average ultimate axial strength of CSP (495 kN) increase with one layer of SFRP up 635 kN and it further increase with two layers of SFRP up to 920 kN.

Table 4.5: Ultimate Axial Strength of CSP, SPEL1 and SPEL2 Columns

Name of Column	Length of column	Shape of Column	Bonding Agent	Type of column	No of layers	Ultimate Axial strength of column (kN)	Avg. Ulti. Axial strength of column (kN)
CSP	1200	Square	Control	P.C.C.	0	510	495
						480	
SPEL1	1200	Square	Epoxy	P.C.C.	1	650	635
						620	
SPEL2	1200	Square	Epoxy	P.C.C.	2	900	920
						940	

Table 4.6 represents ultimate axial strength of Control Square P.C.C. column (CSP), Square P.C.C. Polymer SSWM layer1 (SPPL1) and Square P.C.C. Polymer SSWM layer2 (SPPL2) columns. Average ultimate axial strength of CSP (495 kN) increase with one layer of SFRG up 655 kN and it further increase with two layers of SFRG up to 815 kN.

Table 4.6: Ultimate Axial Strength of CSP, SPPL1 and SPPL2 Columns

Name of Column	Length of column	Shape of Column	Bonding Agent	Type of column	No of layers	Ultimate Axial strength of column (kN)	Avg. Ulti. Axial strength of column (kN)
CSP	1200	Square	Control	P.C.C.	0	510	495
						480	
SPPL1	1200	Square	Polymer	P.C.C.	1	680	655
						630	
SPPL2	1200	Square	Polymer	P.C.C.	2	800	815
						830	

Table 4.7 represents ultimate axial strength of Control Square R.C.C. column (CSR), Square R.C.C. Epoxy SSWM layer2 (SREL@) and Square R.C.C. Polymer SSWM layer2 (SRPL2) columns. Average ultimate axial strength of CSR (635 kN) increase with two layers of SFRP up 1000 kN and similarly increase with two layers of SFRG up to 1025 kN.

Table 4.7: Ultimate Axial Strength of CSR, SREL2 and SRPL2 Columns

Name of Column	Length of column	Shape of Column	Bonding Agent	Type of column	No of layers	Ultimate Axial strength of column (kN)	Avg. Ulti. Axial strength of column (kN)
CSR	1200	Square	Control	R.C.C.	0	620	635
						650	
SREL2	1200	Square	Epoxy	R.C.C.	2	980	1000
						1020	
SRPL2	1200	Square	Polymer	R.C.C.	2	1050	1025
						1000	

Average ultimate axial strength considered for finding percentage increased strength with respect to control columns. Higher load carrying capacity of column is observed in circular SFRP wrapped columns. In single layer, the strength of SFRP and SFRG wrapped columns are similar but in double layers of SFRP, strength obtained are higher than SFRG columns. In most of the cases circular columns strength are higher than square columns. Estimation of strength of columns are shown in appendix- A. Comparison of experimental and theoretical results are shown in table: 4.8 to 4.11. Table 4.8 represents comparison of experimental ultimate axial strength with theoretical calculated ultimate axial strength of circular P.C.C. columns and SFRP/SFRG wrapped columns. In this table second last column presents percentage strength deviation with respect to theoretical value and last column presents percentage strength increase with respect to control column. Control circular P.C.C. column load carrying capacity increase with one layer of SFRP up to 21% and further increase with two layers of SFRP up to 89% similarly Control circular P.C.C. column load carrying capacity increase with one layer of SFRG up to 24% and further increase with two layers of SFRG up to 68%.

Table 4.8: Comparison of Circular P.C.C. Columns

Circular P.C.C. Column						
Name of column	No. of SSWM Layer	Bonding Agent	Experimental Value (KN)	Theoretical Value (KN)	(%) Strength Deviation	(%) Strength Increase
CCP	0	-	495	471	5	
CPEL1	1	epoxy	600	567	6	21
CPEL2	2	epoxy	935	925	1	89
CPPL1	1	polymer	615	726	-18	24
CPPL2	2	polymer	830	1243	-50	68

Table 4.9 represents comparison of circular R.C.C. columns. Control circular R.C.C. column load carrying capacity increase with two layers of SFRP up to 138% similarly two layers of SFRG up to 104%.

Table 4.9: Comparison of Circular R.C.C. Columns

Circular R.C.C. Column						
Sr.No.	No. of SSWM Layer	Bonding Agent	Experimental Value (KN)	Theoretical Value (KN)	(%) Strength Deviation	(%) Strength Increase
CCR	0	-	565	752	-33	
CREL2	2	epoxy	1180	1051	11	138
CRPL2	2	polymer	1010	1362	-35	104

Table 4.10 represents comparison of square P.C.C. columns. Control square P.C.C. column load carrying capacity increase with one layer of SFRP up to 28% and further increase with two layers of SFRP up to 86% similarly Control square P.C.C. column load carrying capacity increase with one layer of SFRG up to 32% and further increase with two layers of SFRG up to 65%.

Table 4.10: Comparison of Square P.C.C. Columns

Square P.C.C. Column						
Sr.No.	No. of SSWM Layer	Bonding Agent	Experimental Value (KN)	Theoretical Value (KN)	(%) Strength Deviation	(%) Strength Increase
CSP	0	-	495	600	-21	
SPEL1	1	epoxy	635	467	26	28
SPEL2	2	epoxy	920	669	27	86
SPPL1	1	polymer	655	557	15	32
SPPL2	2	polymer	815	848	-4	65

Table 4.11 represents comparison of square R.C.C. columns. Control square R.C.C. column load carrying capacity increase with two layers of SFRP up to 102% similarly two layers of SFRG up to 107%.

Table 4.11: Comparison of Square R.C.C. Columns

Square R.C.C. Column						
Sr.No.	No. of SSWM Layer	Bonding Agent	Experimental Value (KN)	Theoretical Value (KN)	(%) Strength Deviation	(%) Strength Increase
CSR	0	-	635	788	-24	
SPEL2	2	epoxy	1000	756	24	102
SRPL2	2	polymer	1025	932	9	107

Graphical presentation of comparison of experimental and theoretical results are shown in figure 4.1.

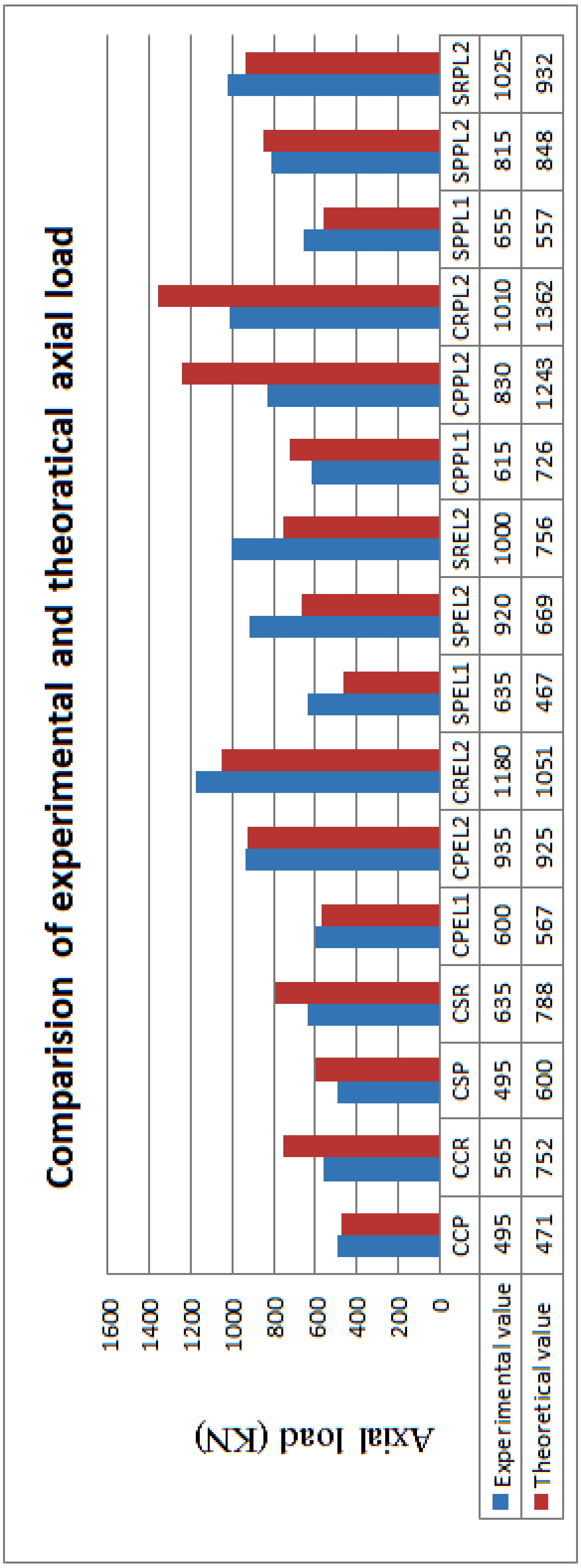

Figure 4.1: Comparison of Experimental and Theoretical Axial Load Results

Comparisons of axial load of circular P.C.C columns with respect to wrapping technics SFRP and SFRG given in figure 4.2.

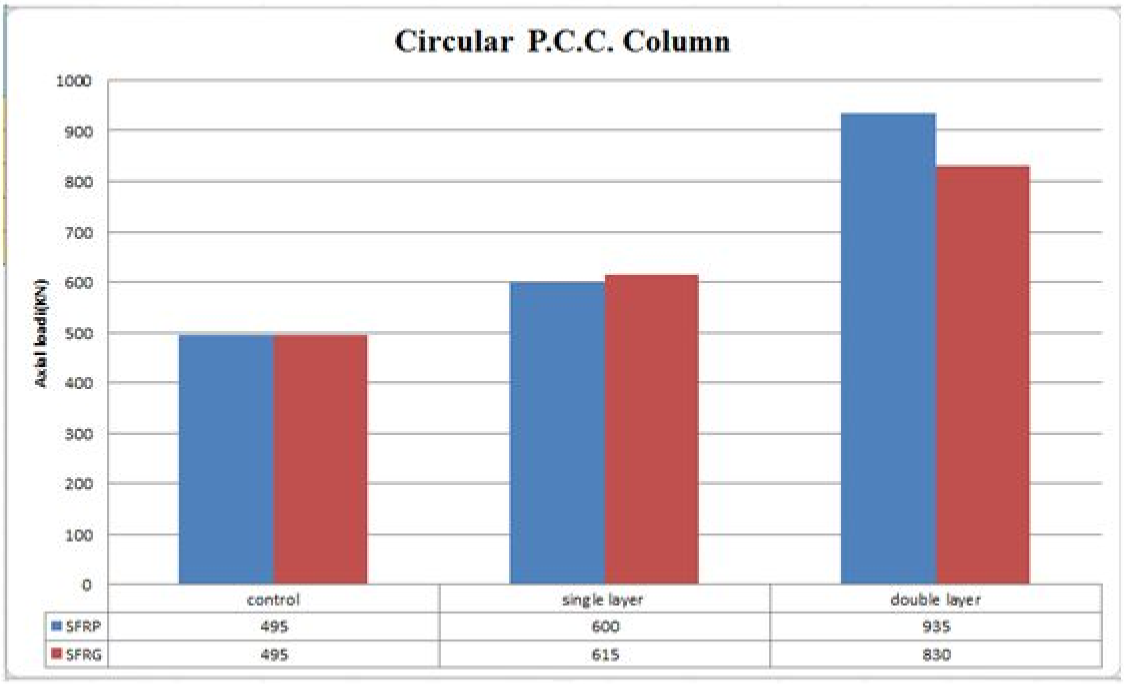

Figure 4.2: Comparison of Axial Load of Circular Column

Comparisons of axial load of Square P.C.C columns with respect to wrapping technics SFRP and SFRG given in figure 4.3.

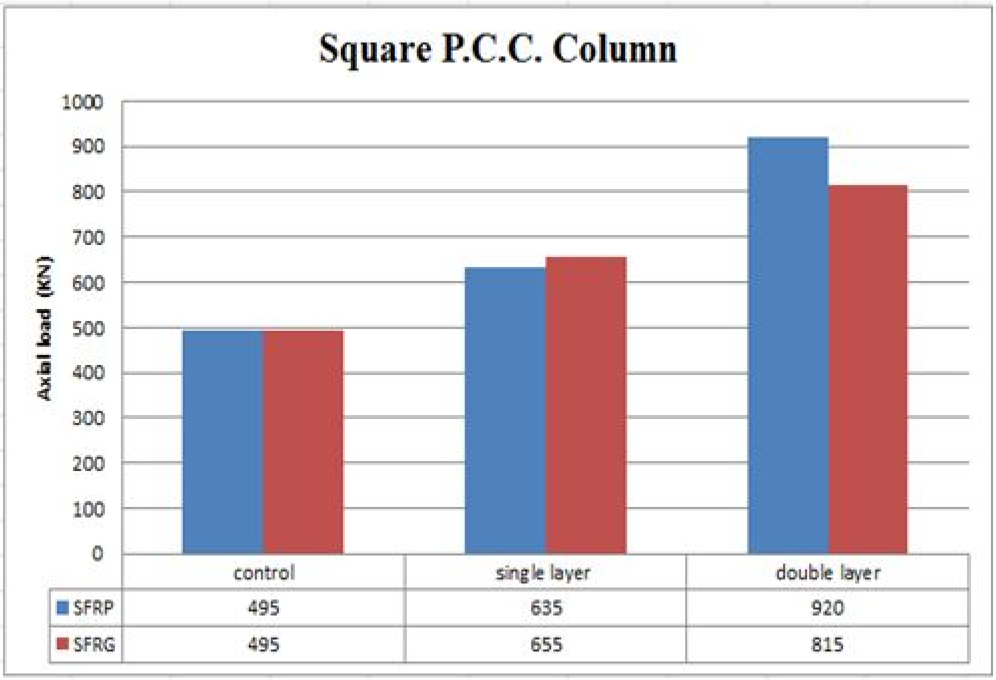

Figure 4.3: Comparison of Axial Load of Square Column

Comparisons of axial load of square and circular columns are shown in figure 4.4.

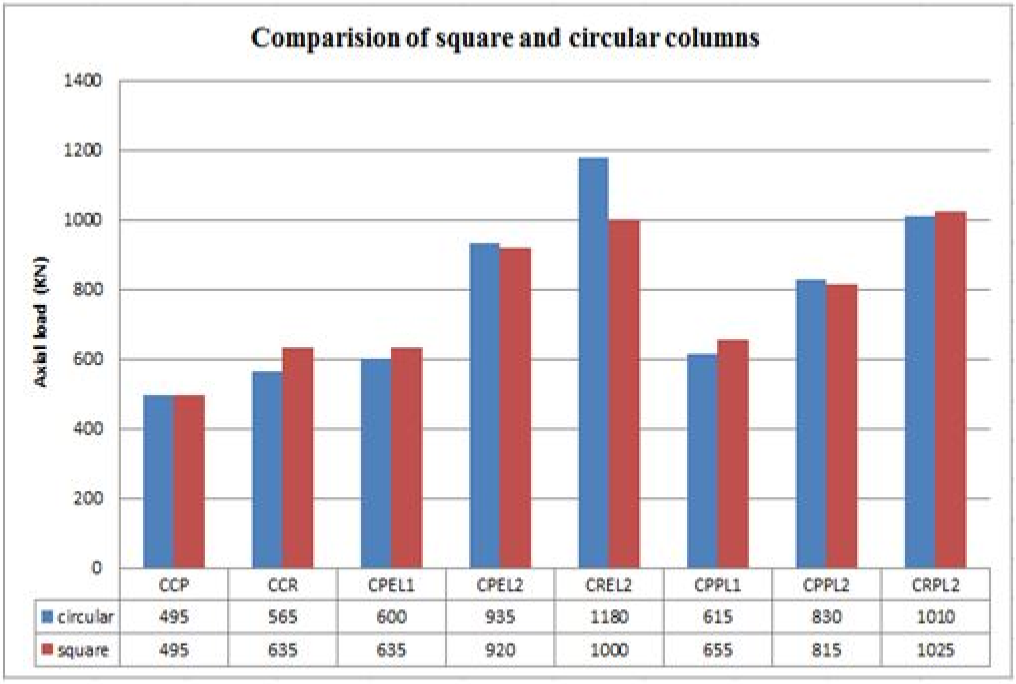

Figure 4.4: Comparison of Axial Load of Square and Circular Columns

4.3 Load vs. Deflection

Displacement is measured along the height of the column. To set the LVDT for measuring the displacement of column, wooden frame setup is developed. Displacement of all the columns is measured at an interval of every 20 KN load till the application of ultimate load. The column samples crushed at failure load displacement does not measured up to the failure of column due to Safety of LVDT. Axial deformation of all columns in presented in table:4.12 to table: 4.17.

Table 4.12: Deflection of CCP and CCR Columns

Control Circular P.C.C.				Control Circular R.C.C.			
Sample-1		Sample-2		Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)	Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00	0	0.00	0	0.00
10	0.00	10	0.00	10	0.00	10	0.00
20	1.00	20	0.00	20	1.00	20	0.00
30	1.00	30	1.00	30	1.00	30	0.00
40	1.00	40	1.00	40	2.00	40	0.00
50	1.00	50	1.00	50	3.00	50	0.00
60	2.00	60	1.00	60	4.00	60	1.00
70	2.00	70	1.00	70	5.00	70	1.00
80	3.00	80	2.00	80	8.00	80	1.00
90	3.00	90	2.00	90	9.00	90	2.00
100	4.00	100	2.00	100	9.00	100	2.00
110	4.00	110	2.00	110	9.00	110	2.00
120	5.00	120	3.00	120	10.00	120	3.00
130	5.00	130	3.00	130	10.00	130	4.00
140	5.00	140	3.00	140	10.00	140	4.00
150	6.00	150	3.00	150	11.00	150	5.00
160	6.00	160	3.00	160	11.00	160	5.00
170	6.00	170	4.00	170	11.00	170	6.00
180	7.00	180	4.00	180	12.00	180	6.00
190	7.00	190	4.00	190	12.00	190	6.00
200	7.00	200	4.00	200	13.00	200	6.00
210	8.00	210	5.00	210	13.00	210	6.00
220	8.00	220	5.00	220	13.00	220	7.00
230	8.00	230	5.00	230	14.00	240	7.00
240	9.00	240	5.00	240	15.00	250	8.00
250	9.00	250	6.00	250	15.00	260	8.00
260	9.00	260	6.00	260	16.00	270	9.00
270	9.00	270	6.00	270	16.00	280	9.00
280	10.00	280	6.00	280	17.00	290	10.00
290	10.00	290	6.00	290	17.00	300	10.00
300	10.00	300	6.00	300	17.00	320	10.00
500	-	490	-	550	-	580	-

Table 4.13: Deflection of CPEL1, CPEL2, CREL2 and CPPL1 Columns

Circular P.C.C Epoxy SSWM Layer 1			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	1.00	60	1.00
80	2.00	80	1.00
100	2.00	100	2.00
120	3.00	120	2.00
140	3.00	140	3.00
160	3.00	160	3.00
180	4.00	180	3.00
200	4.00	200	4.00
220	5.00	220	4.00
240	5.00	240	5.00
260	6.00	260	5.00
280	6.00	280	6.00
300	7.00	300	6.00
320	7.00	320	6.00
340	8.00	340	7.00
360	8.00	360	7.00
380	9.00	380	7.00
400	9.00	400	7.00
600	-	-	-

Circular P.C.C Epoxy SSWM Layer 2			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	1.00	60	1.00
80	1.00	80	1.00
100	2.00	100	2.00
120	2.00	120	2.00
140	3.00	140	3.00
160	3.00	160	3.00
180	4.00	180	3.00
200	4.00	200	4.00
220	4.00	220	4.00
240	5.00	240	4.00
260	5.00	260	5.00
280	6.00	280	5.00
300	6.00	300	6.00
320	6.00	320	6.00
340	7.00	340	6.00
360	7.00	360	7.00
380	7.00	380	7.00
400	8.00	400	7.00
920	-	950	-

Circular R.C.C Epoxy SSWM Layer 2			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	1.00	60	1.00
80	2.00	80	1.00
100	2.00	100	2.00
120	2.00	120	2.00
140	3.00	140	3.00
160	3.00	160	3.00
180	4.00	180	4.00
200	4.00	200	4.00
220	5.00	220	5.00
240	5.00	240	5.00
260	6.00	260	5.00
280	6.00	280	6.00
300	6.00	300	6.00
320	7.00	320	7.00
340	7.00	340	7.00
360	8.00	360	8.00
380	8.00	380	8.00
400	9.00	400	9.00
420	9.00	420	9.00
440	10.00	440	10.00
460	10.00	460	10.00
480	11.00	480	10.00
500	11.00	500	11.00
1200	-	1160	-

Circular P.C.C Polymer SSWM Layer 1			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	1.00	60	1.00
80	1.00	80	2.00
100	2.00	100	2.00
120	2.00	120	2.00
140	3.00	140	3.00
160	3.00	160	3.00
180	3.00	180	4.00
200	4.00	200	4.00
220	4.00	220	4.00
240	5.00	240	5.00
260	5.00	260	5.00
280	5.00	280	6.00
300	6.00	300	6.00
320	6.00	320	7.00
340	6.00	340	7.00
360	7.00	360	8.00
380	7.00	380	8.00
400	7.00	400	9.00
600	-	630	-

Table 4.14: Deflection of CPPL2 and CRPL2 Columns

Circular P.C.C Polymer SSWM Layer 2			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	1.00	60	1.00
80	2.00	80	1.00
100	2.00	100	2.00
120	3.00	120	2.00
140	3.00	140	3.00
160	3.00	160	3.00
180	4.00	180	4.00
200	4.00	200	4.00
220	5.00	220	4.00
240	5.00	240	5.00
260	6.00	260	5.00
280	6.00	280	5.00
300	7.00	300	6.00
320	7.00	320	6.00
340	8.00	340	7.00
360	8.00	360	7.00
380	8.00	380	8.00
400	9.00	400	8.00
800	-	860	-

Circular R.C.C Polymer SSWM Layer 2			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	1.00	60	1.00
80	1.00	80	2.00
100	2.00	100	2.00
120	2.00	120	2.00
140	3.00	140	3.00
160	3.00	160	3.00
180	4.00	180	4.00
200	4.00	200	4.00
220	4.00	220	5.00
240	5.00	240	5.00
260	5.00	260	5.00
280	6.00	280	6.00
300	6.00	300	6.00
320	6.00	320	7.00
340	7.00	340	7.00
360	7.00	360	8.00
380	8.00	380	8.00
400	8.00	400	8.00
420	9.00	420	9.00
440	9.00	440	9.00
460	9.00	460	10.00
480	10.00	480	10.00
500	10.00	500	10.00
970	-	1050	-

Table 4.15: Deflection of CSP and CSR Columns

Control Square P.C.C.			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
10	0.00	10	0.00
20	1.00	20	0.00
30	1.00	30	1.00
40	1.00	40	1.00
50	2.00	50	1.00
60	2.00	60	2.00
70	2.00	70	2.00
80	2.00	80	2.00
90	3.00	90	3.00
100	4.00	100	3.00
110	4.00	110	3.00
120	4.00	120	3.00
130	5.00	130	4.00
140	5.00	140	4.00
150	6.00	150	4.00
160	6.00	160	4.00
170	7.00	170	5.00
180	7.00	180	5.00
190	7.00	190	6.00
200	8.00	200	6.00
210	8.00	210	6.00
220	8.00	220	7.00
230	9.00	230	7.00
240	9.00	240	8.00
250	9.00	250	8.00
260	9.00	260	9.00
270	10.00	270	9.00
280	10.00	280	9.00
290	10.00	290	9.00
300	10.00	300	10.00
510	-	480	-

Control Square R.C.C.			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
10	0.00	10	0.00
20	1.00	20	0.00
30	1.00	30	1.00
40	2.00	40	1.00
50	2.00	50	1.00
60	2.00	60	1.00
70	3.00	70	2.00
80	4.00	80	2.00
90	5.00	90	2.00
100	6.00	100	2.00
110	6.00	110	3.00
120	7.00	120	3.00
130	8.00	130	4.00
140	9.00	140	4.00
150	10.00	150	5.00
160	10.00	160	5.00
170	11.00	170	6.00
180	11.00	180	6.00
190	11.00	190	6.00
200	12.00	200	6.00
210	12.00	210	6.00
220	12.00	220	7.00
230	12.00	230	7.00
240	13.00	240	7.00
250	13.00	250	8.00
260	14.00	260	9.00
270	14.00	270	9.00
280	14.00	280	10.00
290	15.00	290	10.00
300	15.00	300	10.00
310	15.00	310	11.00
320	15.00	320	11.00
330	16.00	330	11.00
340	16.00	340	11.00
350	16.00	350	11.00
620	-	650	-

Table 4.16: Deflection of SPEL1, SPEL2, SREL2 and SPPL1 columns

Square P.C.C Epoxy SSWM Layer 1			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	1.00	60	1.00
80	2.00	80	1.00
100	3.00	100	2.00
120	4.00	120	3.00
140	4.00	140	3.00
160	5.00	160	3.00
180	5.00	180	4.00
200	5.00	200	4.00
220	6.00	220	4.00
240	6.00	240	5.00
260	7.00	260	5.00
280	7.00	280	5.00
300	8.00	300	5.00
320	8.00	320	5.00
340	9.00	340	6.00
360	9.00	360	7.00
380	9.00	380	7.00
400	9.00	400	7.00
650	-	620	-

Square P.C.C Epoxy SSWM Layer 2			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	0.00	40	1.00
60	1.00	60	1.00
80	1.00	80	2.00
100	1.00	100	2.00
120	2.00	120	2.00
140	2.00	140	3.00
160	3.00	160	3.00
180	4.00	180	4.00
200	4.00	200	4.00
220	4.00	220	4.00
240	5.00	240	5.00
260	5.00	260	5.00
280	5.00	280	5.00
300	6.00	300	6.00
320	6.00	320	6.00
340	6.00	340	6.00
360	6.00	360	6.00
380	7.00	380	7.00
400	7.00	400	7.00
900	-	940	-

Square R.C.C Epoxy SSWM Layer 2			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	1.00	60	1.00
80	2.00	80	1.00
100	2.00	100	2.00
120	2.00	120	2.00
140	3.00	140	3.00
160	3.00	160	4.00
180	3.00	180	4.00
200	4.00	200	4.00
220	4.00	220	5.00
240	4.00	240	5.00
260	4.00	260	5.00
280	5.00	280	6.00
300	6.00	300	6.00
320	7.00	320	7.00
340	7.00	340	7.00
360	8.00	360	7.00
380	8.00	380	7.00
400	9.00	400	8.00
420	9.00	420	8.00
440	10.00	440	8.00
460	10.00	460	9.00
480	10.00	480	9.00
500	11.00	500	10.00
980	-	1020	-

Square P.C.C Polymer SSWM Layer 1			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	1.00	60	1.00
80	2.00	80	2.00
100	2.00	100	2.00
120	3.00	120	2.00
140	3.00	140	3.00
160	3.00	160	3.00
180	4.00	180	3.00
200	4.00	200	4.00
220	5.00	220	4.00
240	5.00	240	5.00
260	6.00	260	5.00
280	6.00	280	6.00
300	7.00	300	7.00
320	7.00	320	7.00
340	8.00	340	8.00
360	8.00	360	8.00
380	8.00	380	9.00
400	9.00	400	10.00
680	-	630	-

Table 4.17: Deflection of SPPL2 and SRPL2 columns

Square P.C.C Polymer SSWM Layer 2			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	2.00	60	1.00
80	2.00	80	1.00
100	2.00	100	2.00
120	3.00	120	2.00
140	3.00	140	2.00
160	4.00	160	3.00
180	4.00	180	4.00
200	5.00	200	4.00
220	5.00	220	4.00
240	5.00	240	5.00
260	6.00	260	5.00
280	6.00	280	5.00
300	7.00	300	6.00
320	8.00	320	6.00
340	8.00	340	7.00
360	9.00	360	7.00
380	9.00	380	7.00
400	9.00	400	7.00
800	-	830	-

Square R.C.C Polymer SSWM Layer 2			
Sample-1		Sample-2	
Load(KN)	Def (mm)	Load(KN)	Def (mm)
0	0.00	0	0.00
20	0.00	20	0.00
40	1.00	40	1.00
60	1.00	60	1.00
80	1.00	80	1.00
100	2.00	100	2.00
120	2.00	120	2.00
140	2.00	140	2.00
160	3.00	160	3.00
180	4.00	180	4.00
200	4.00	200	4.00
220	4.00	220	5.00
240	5.00	240	5.00
260	5.00	260	5.00
280	6.00	280	6.00
300	6.00	300	6.00
320	7.00	320	6.00
340	7.00	340	6.00
360	7.00	360	6.00
380	8.00	380	7.00
400	9.00	400	7.00
420	10.00	420	8.00
440	10.00	440	8.00
460	11.00	460	9.00
480	12.00	480	9.00
500	12.00	500	10.00
1050	-	1000	-

Graphical representation of load vs. deflection are shown in figure: 4.5 to 4.10

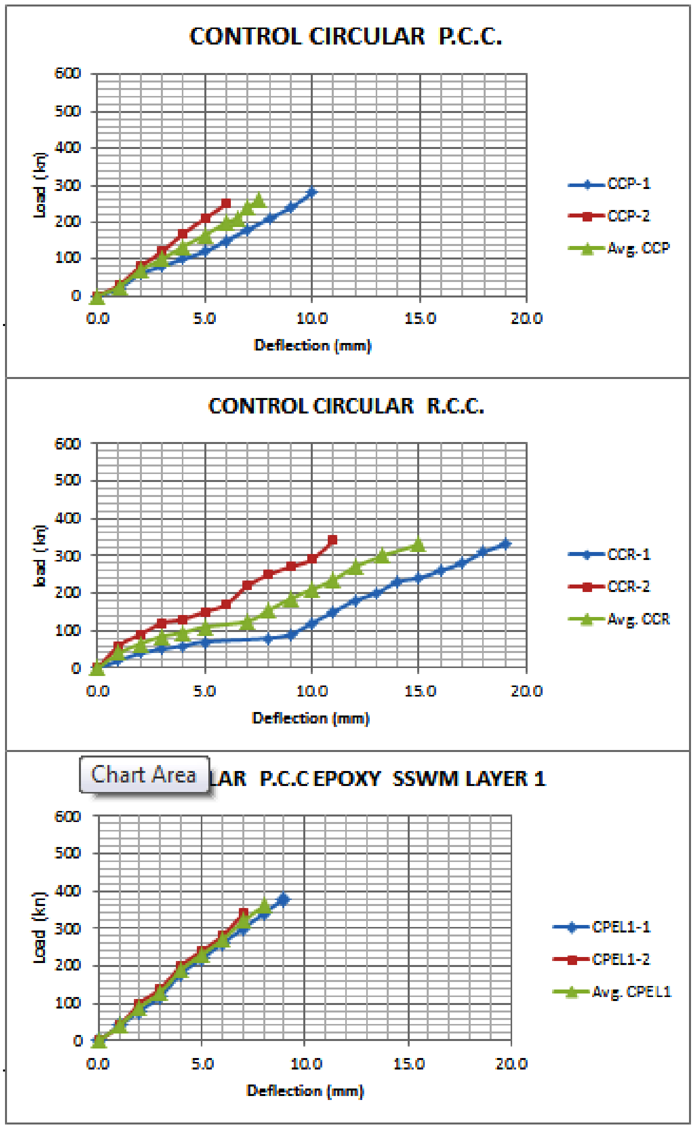

Figure 4.5: Load vs. Deflection of CCP, CCR and CPEL1 Columns

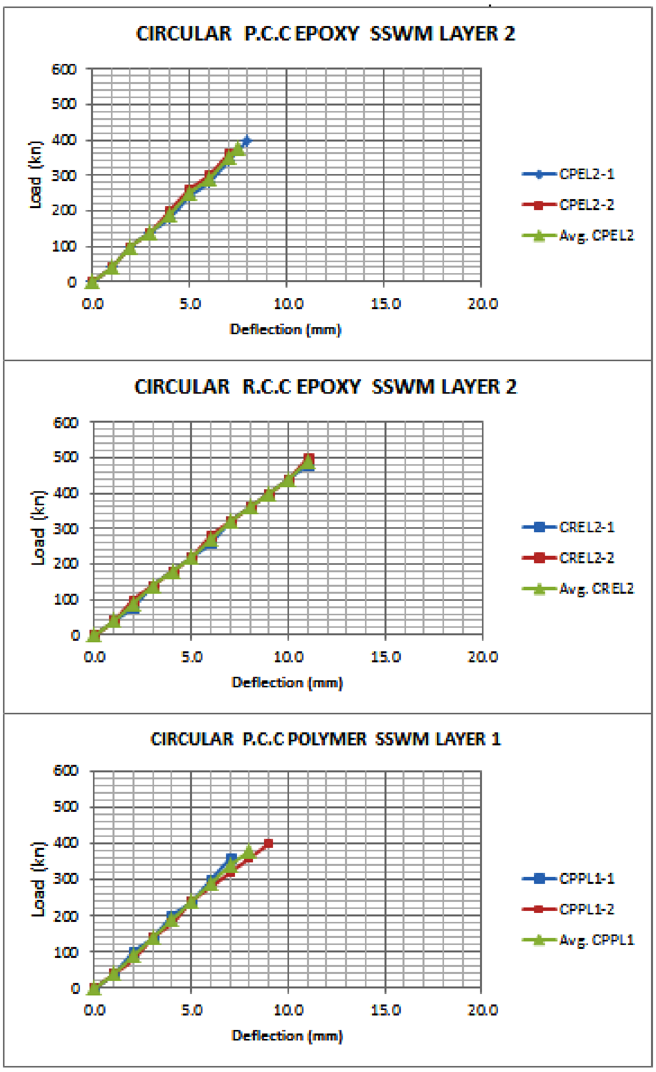

Figure 4.6: Load vs. Deflection of CPEL2, CREL2 and CPPL1 Columns

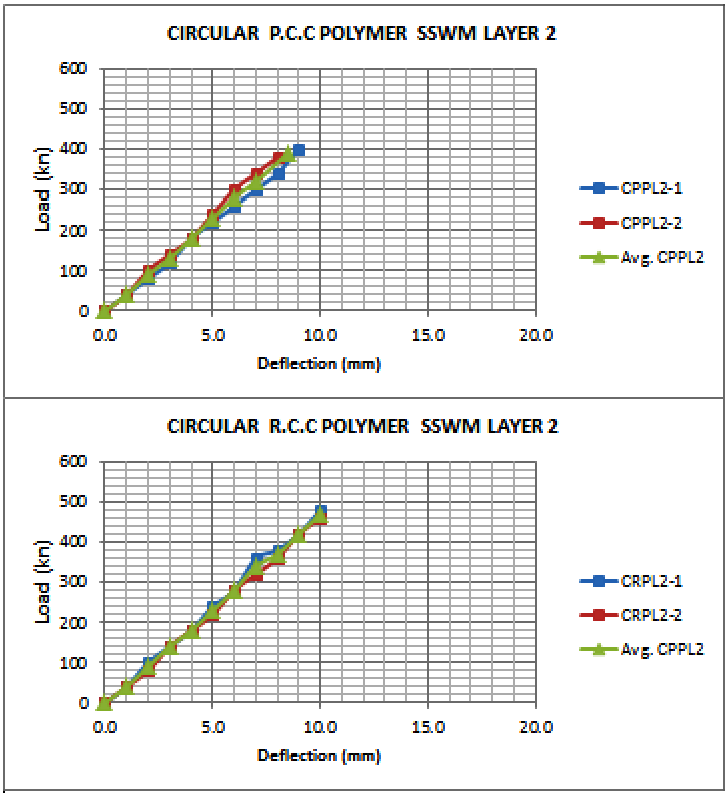

Figure 4.7: Load vs. Deflection of CPPL2 and CRPL2 columns

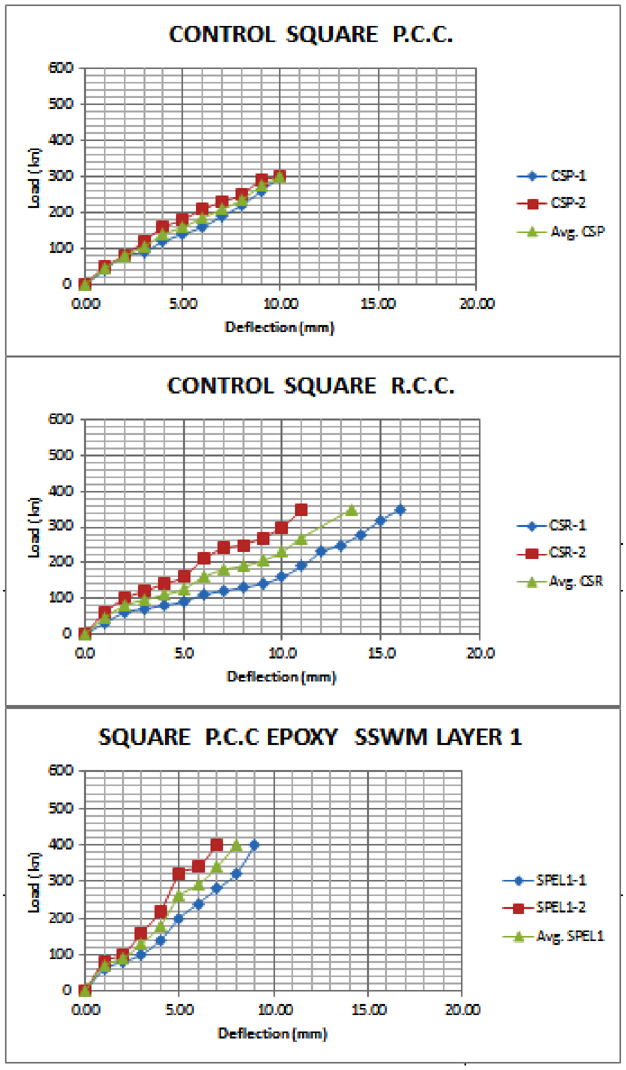

Figure 4.8: Load vs. Deflection of CSP, CSR and SPEL1 Columns

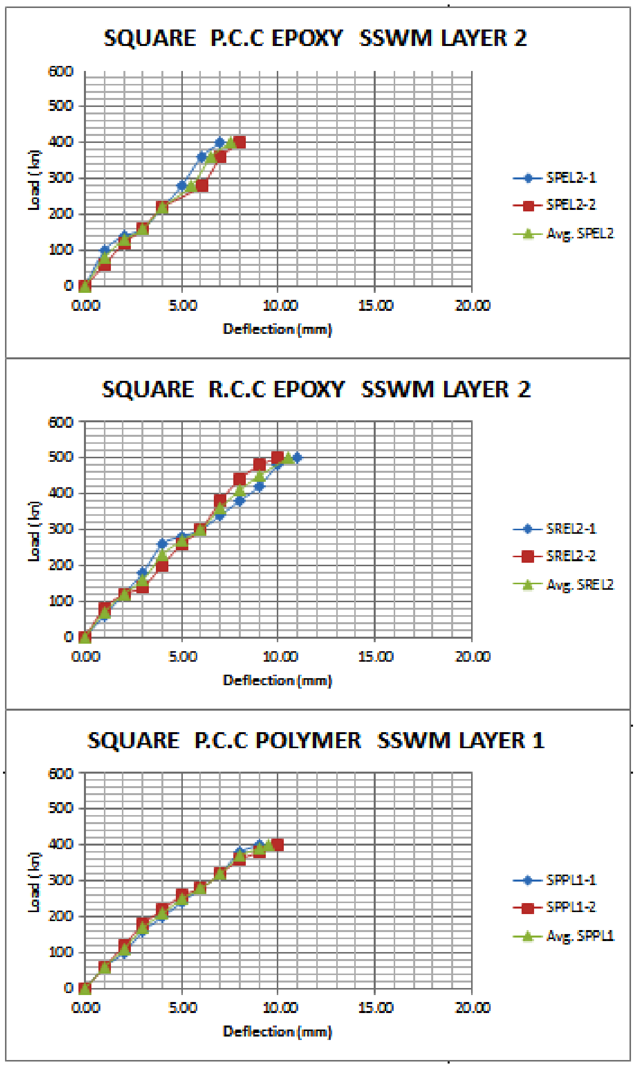

Figure 4.9: Load vs. Deflection of SPEL2, SREL2 and SPPL1 Columns

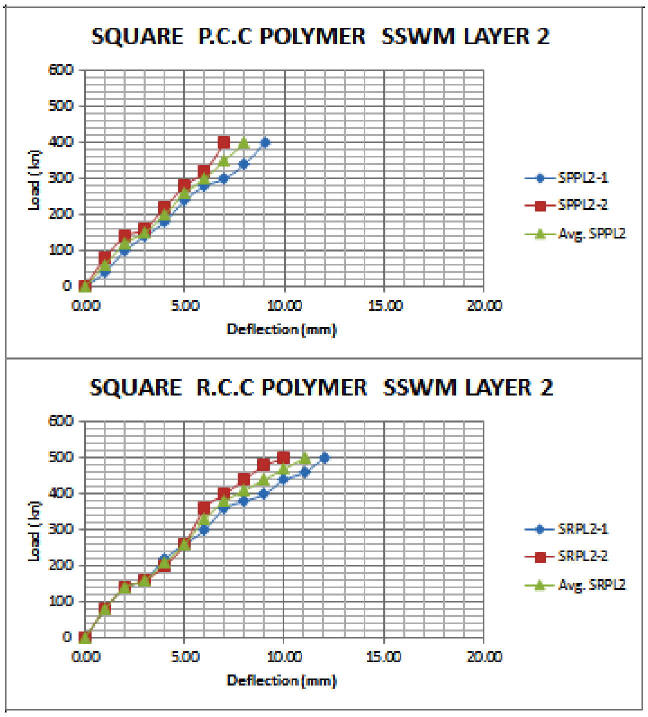

Figure 4.10: Load vs. Deflection of SPPL2 and SRPL2 Columns

Table 4.11 presents Comparison of load vs. deflection of circular P.C.C. columns.

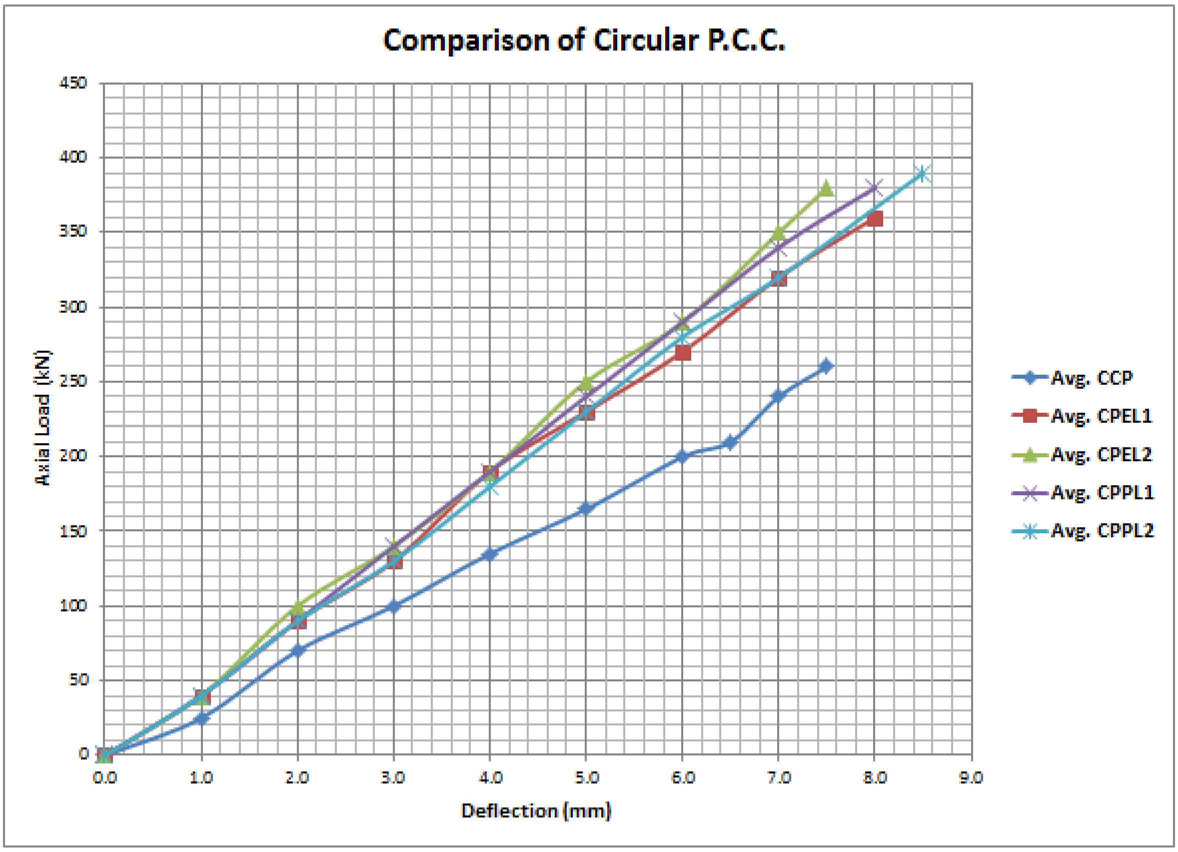

Figure 4.11: Load vs. Deflection of Circular P.C.C. Columns

Table 4.12 presents Comparison of load vs. deflection of circular R.C.C. columns.

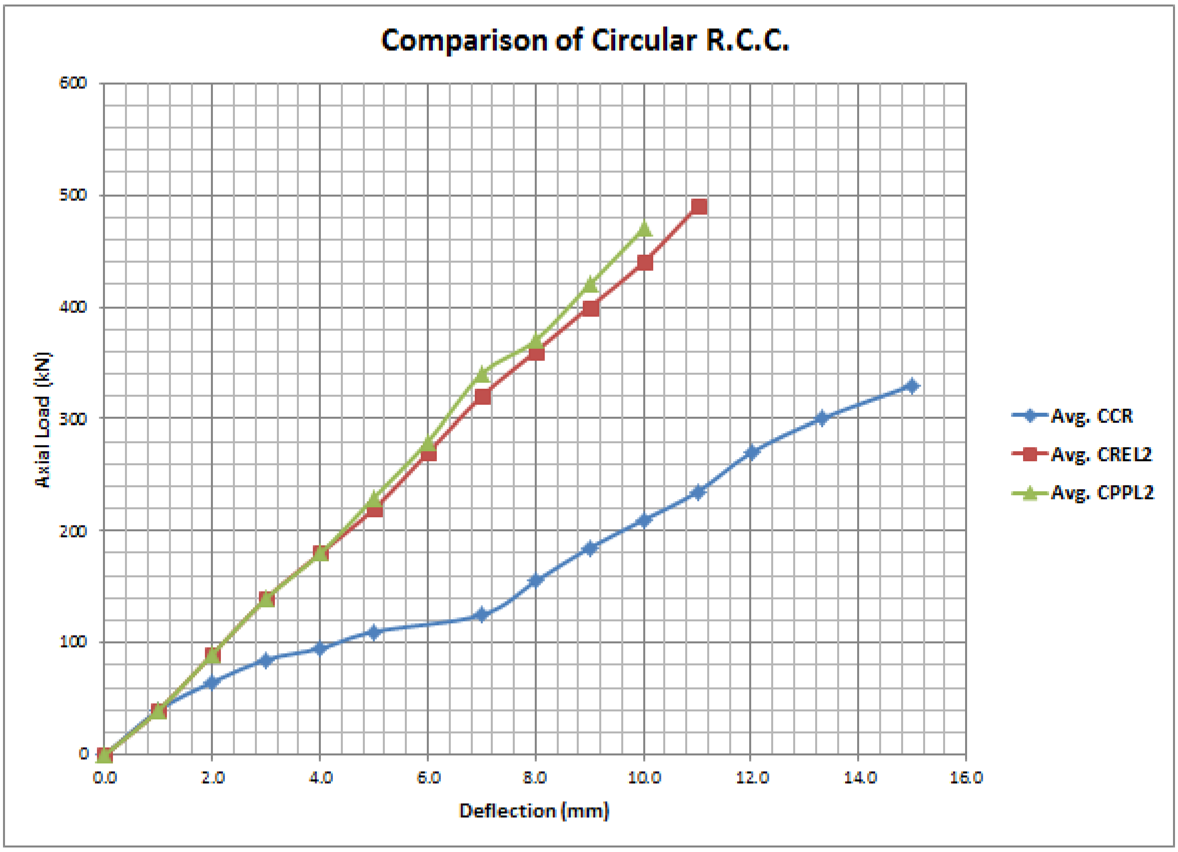

Figure 4.12: Load vs. Deflection of Circular R.C.C. Columns

Table 4.13 presents Comparison of load vs. deflection of square P.C.C. columns.

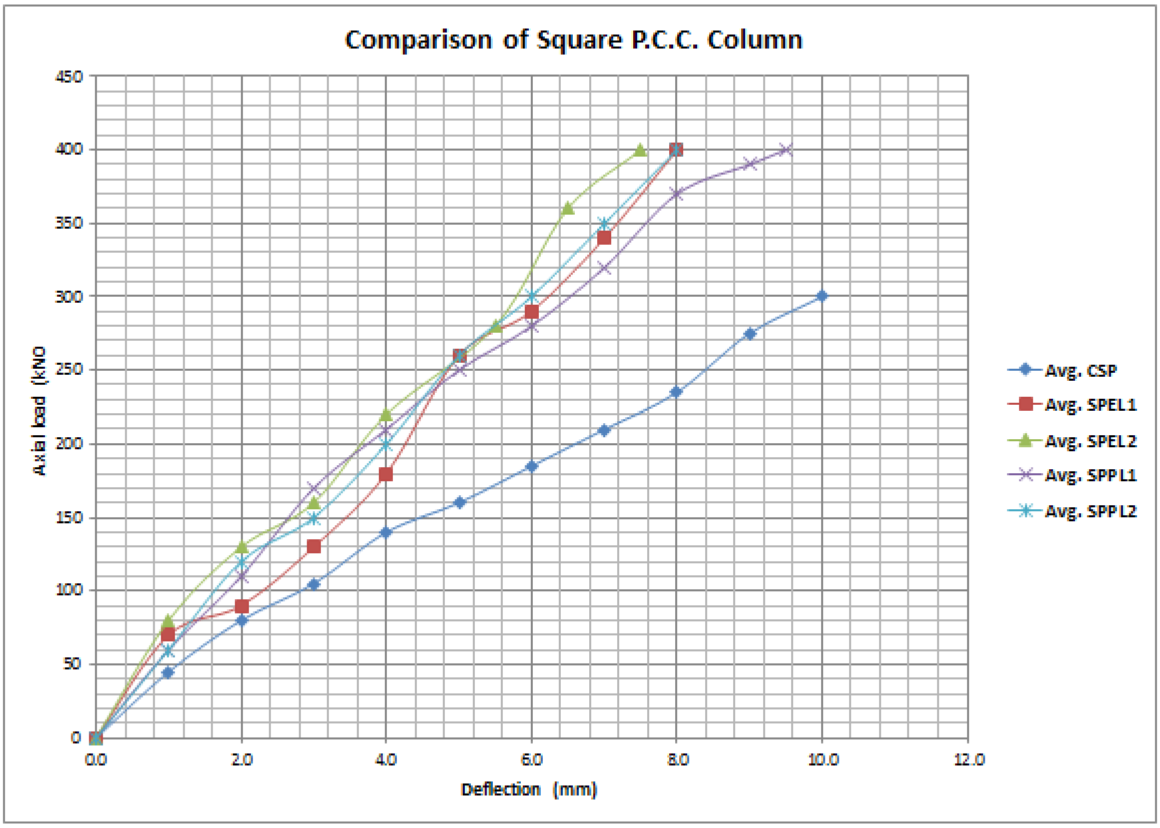

Figure 4.13: Load vs. Deflection of Square P.C.C. Columns

Table 4.14 presents Comparison of load vs. deflection of square P.C.C. columns.

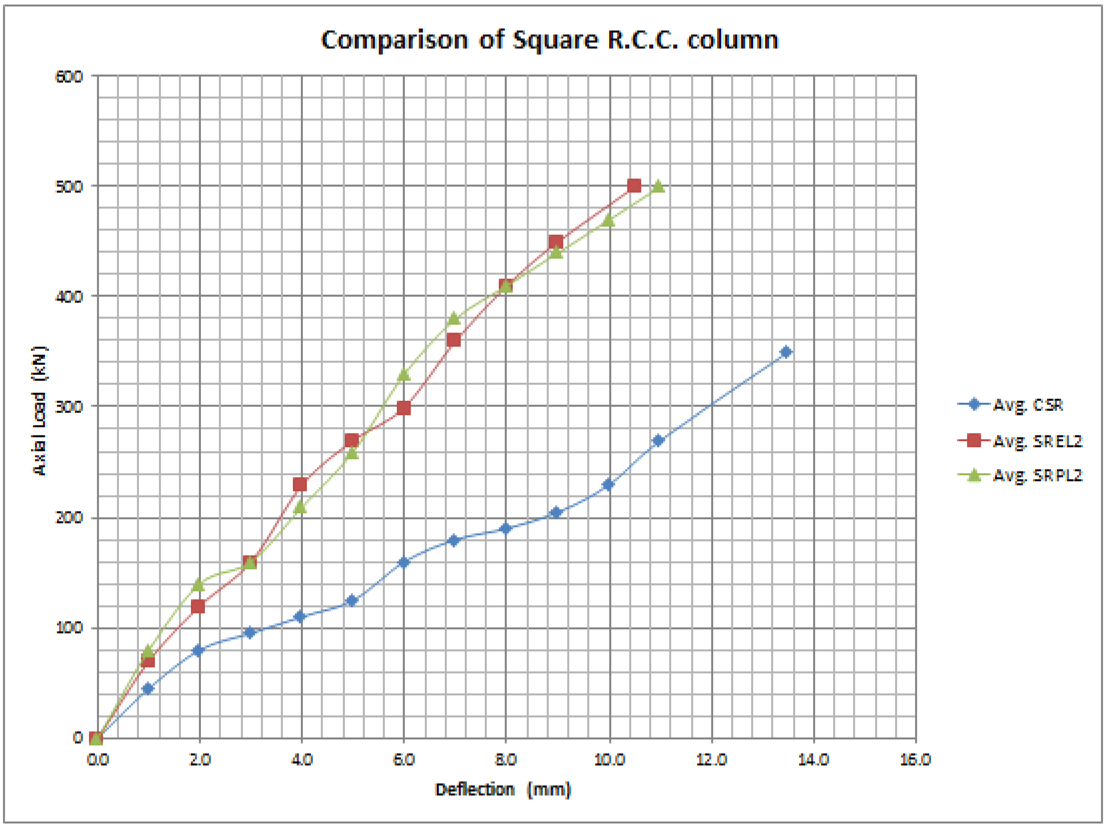

Figure 4.14: Load vs. Deflection of Square R.C.C. Columns

4.4 Failure Mode and Crack Patterns

Control columns are tested under axial load with both ends partially fixed. Control columns are failed when the ultimate compressive strength is increased, which causes splitting of concrete cover. Most of the all control specimens are brittle failure with blasting effect. Failure mode of control specimens have been discuss below.

(1) Control Circular R.C.C Control R.C.C. columns fail from top due to load concentration at ends. Cover of concrete was pulling out from specimen. There was no damage in reinforcements. Failures of columns are shown in figure: 4.15.

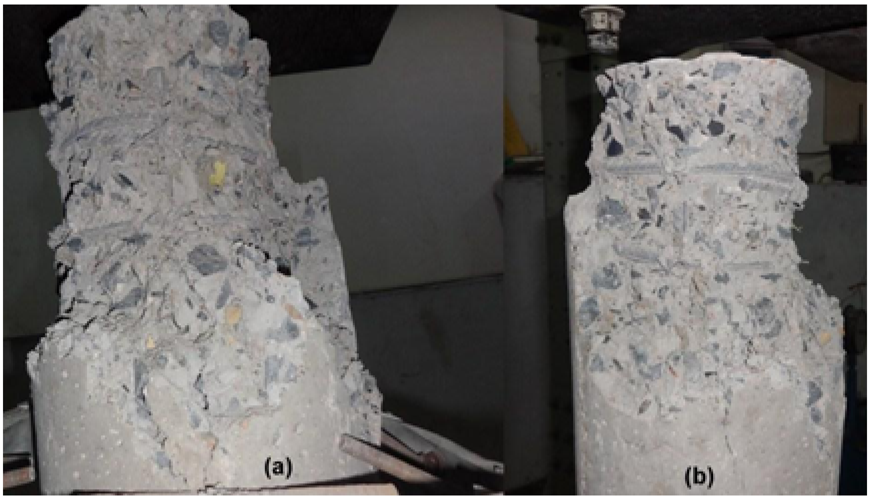

Figure 4.15: (a) and (b) Failure of Circular Column R.C.C.

(2) Control Circular P.C.C. Control circular P.C.C. columns fail from top and middle. The column failed with blasting effect. The columns failed in diagonal shear shape and upper part of column falling down at time of testing. Failure of columns are shown in figure: 4.16.

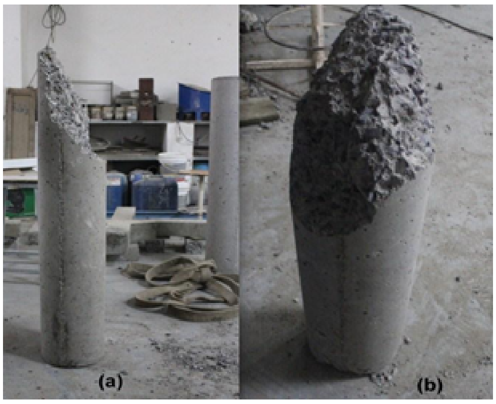

Figure 4.16: (a) and (b) Failure of Circular Column P.C.C.

(3) Control Square R.C.C. Control Square R.C.C. column failed from top and bottom. Concrete cover pulling out of specimen At time of loading minor cracks developed at top and bottom. After applying loads minor cracks are converted in to major cracks. Failure of columns are shown in figure: 4.17.

Figure 4.17: (a) and (b) Failure of Control Square R.C.C.

(4) Control Square P.C.C. Control Square P.C.C. columns are failed form top and longitudinal cracks were developed up to middle of columns. Totally crushing of concrete at top due to axial load on it. Failures of columns are shown in figure: 4.18.

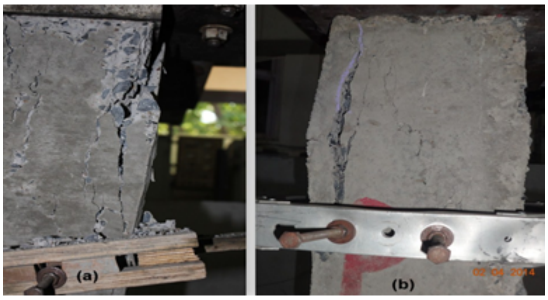

Figure 4.18: (a) and (b) Failure of Control Square P.C.C.

(5) Circular P.C.C Epoxy SSWM Layer 1 In this column, concrete crushed at top and column failed by sudden blasting. Layer of SFRP was broken from top of the column due to hoop tension. Both columns failed in same pattern. The failures of columns are shown in figure : 4.19.

Figure 4.19: (a) and (b) Failure of Circular P.C.C Epoxy SSWM Layer 1

(6) Circular P.C.C Epoxy SSWM Layer 2 Circular columns with two layers of SFRP fail from bottom where hinge generated in column and failed by splitting of SFRP layer. There is no debonding occurred in SFRP. The wires of SFRP were in uniform tension hence the vertical crack developed. Failures of columns are shown in figure: 4.20.

Figure 4.20: (a) and (b) Failure of Circular P.C.C Epoxy SSWM Layer 2

(7) Circular R.C.C Epoxy SSWM Layer 2 Due to lesser hoop tension on SFRP because of internal reinforcement of RC column the failure of SFRP crack developed slowly at bottom portion and propagated up to one forth part of column. Failures of columns are shown in figure: 4.21.

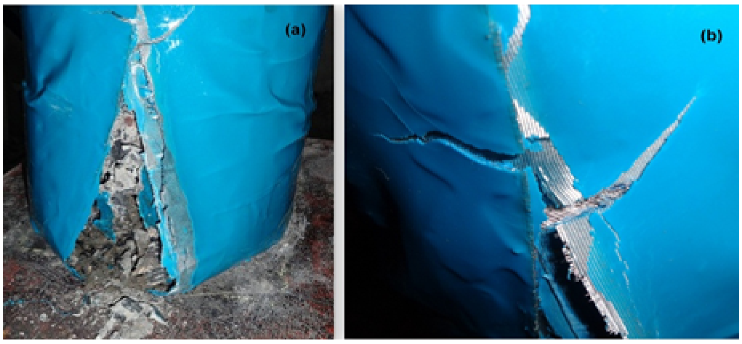

Figure 4.21: (a) and (b) Failure of Circular R.C.C Epoxy SSWM Layer 2

(8) Square P.C.C. Epoxy SSWM Layer 1 Square P.C.C. SFRP wrapped column failed from top and cracks developed at corner and prorogated up one third of column height. Due to crushing of concrete all four corner SFRP failed due to load concentration. Failures of columns are shown in figure: 4.22.

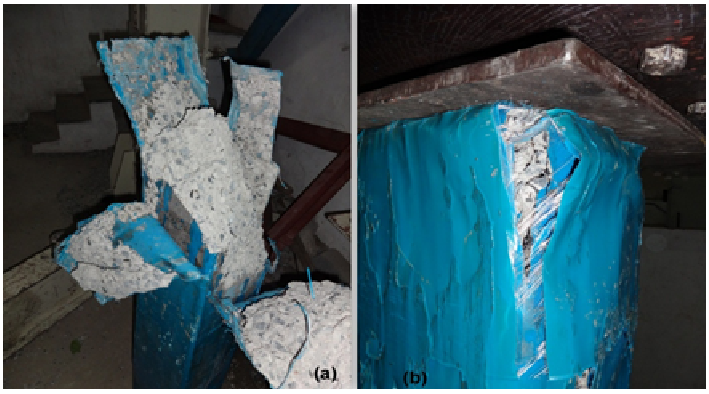

Figure 4.22: (a) and (b) Failure of Square P.C.C. Epoxy SSWM Layer 1

(9) Square P.C.C. Epoxy SSWM Layer 2 In this column concrete crushing and bulging of concrete at top and due to bulging of concrete the confinement pressure increased and SFRP failed by sudden crack sound. Failures of columns are shown in figure: 4.23.

Figure 4.23: (a) and (b) Failure of Square P.C.C. Epoxy SSWM Layer 2

(10) Square R.C.C. Epoxy SSWM Layer 2 Square R.C.C. column wrapped with 2 layers of SFRP failed in rapture of SFRP due load concentration and splitting of concrete cover. The failure of columns are shown in figure: 4.24.

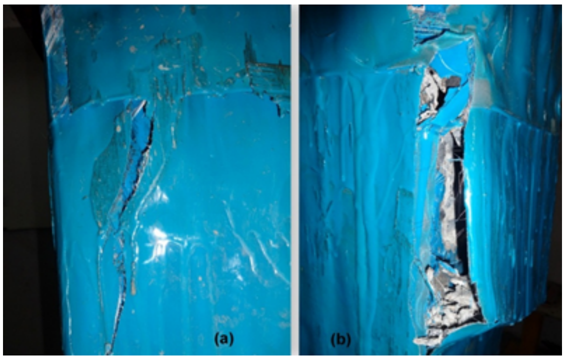

Figure 4.24: (a) and (b) Failure of Square R.C.C. Epoxy SSWM Layer 2

(11) Circular P.C.C Polymer SSWM Layer 1 Circular P.C.C. column wrapped with SFRG failed from top and middle respectively and the first column crushed from top with vertical crack near horizontal joint of SFRG and another column failed from middle due to bulging of concrete and vertical cracks developed in SFRG. The failure of columns are shown in figure: 4.25.

Figure 4.25: (a) and (b) Failure of Circular P.C.C Polymer SSWM Layer 1

(12) Circular P.C.C Polymer SSWM Layer 2 Circular P.C.C. column wrapped with two layer of SFRG which failed from top and the failure of column with sudden crack sound. Two layers of SFRP have good grip crushed concrete does not come out from it. The failure of columns are shown in figure: 4.26.

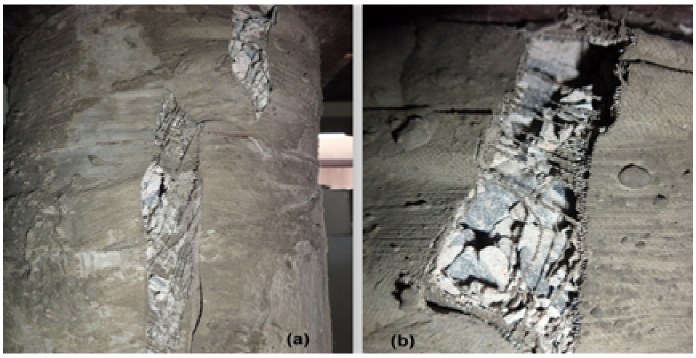

Figure 4.26: (a) and (b) Failure of Circular P.C.C Polymer SSWM Layer 2

(13) Circular R.C.C Polymer SSWM Layer 2 Circular R.C.C. column wrapped with 2 layer of SFRG failed due to splitting of SFRG at top and bulging of concrete. The failures of columns are shown in figure: 4.27.

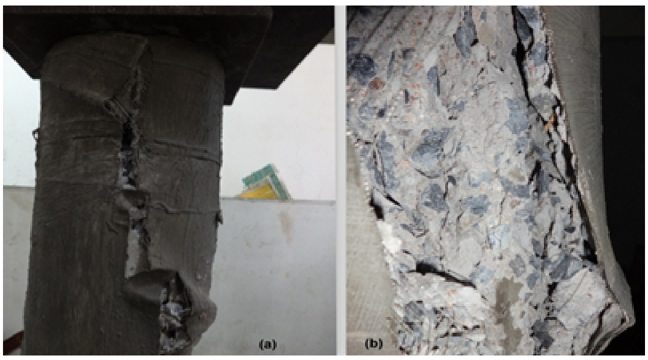

Figure 4.27: (a) and (b) Failure of Circular R.C.C Polymer SSWM Layer 2

(14) Square P.C.C. Polymer SSWM Layer 1 Square P.C.C. column wrapped with SFRG failed from bottom corner. Concrete bulging at bottom than confinement pressure increased than SFRG failed with vertical cracks. The failures of columns are shown in figure: 4.28.

Figure 4.28: (a) and (b) Failure of Square P.C.C. Polymer SSWM Layer 1

(15) Square P.C.C. Polymer SSWM Layer 2 Square P.C.C. column wrapped with 2 layers of SFRG failed in same pattern like SPPL2 columns. The failure of column is shown in figure: 4.29.

Figure 4.29: Failure of Square P.C.C. Polymer SSWM Layer 2

(16) Square R.C.C. Polymer SSWM Layer 2 Square R.C.C. columns wrapped with 2 layers of SFRG failed from top and bottom respectively and the column failed from corner due to splitting of concrete cover. The failures of columns are shown in figure: 4.30.

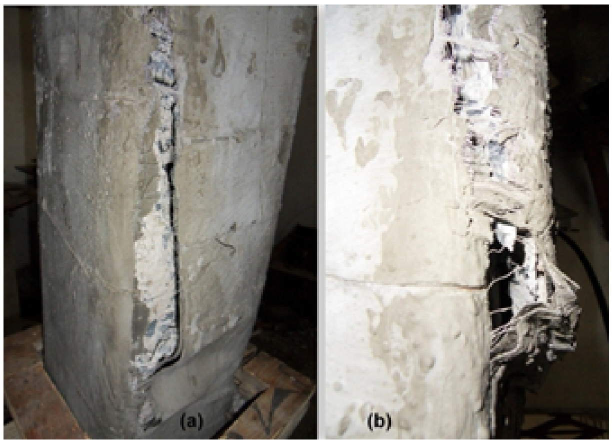

Figure 4.30: (a) and (b) Failure of Square R.C.C. Polymer SSWM Layer 2

4.5 Discussion

From Results of ultimate axial load, It is observed that the one layer of SFRP and SFRG results in almost similar performance. But with two layers of SFRP better results obtained as compared to SFRG wrapped columns. In RCC column two layers of SFRP results in two times increase in load carrying capacity of columns. and in SFRG wrapped R.C.C. column also give good results but not more than SFRP results. In terms of efficiency of wrapping two layers of SFRP give higher results than SFRG wrapped column and circular column give higher results than Square column. In R.C.C. column double confinement by external SFRP/SFRG and internal reinforcement, further enhance its axial load capacity. The theoretical results are more deviated from experimental results so new analytical model is required based on experimental data.

Chapter 5

Summary and Conclusion

5.1 Summary

Present investigation includes evaluation and effectiveness of SFRP and SFRG wrapped square and circular column along with different bonding agents. Tensile test and bond test were also conducted on SSWM samples. Three types of SSWMs and two types of bonding materials were used for preparation of bond specimen. And Square columns have size 200mm x 200mm x 1200m and circular have size of column have 200mm diameter and 1200mm length. All columns sample were of M15 grade of concrete. Two types of SSWM have used for wrapping of columns. Total 32 column specimens casted and tested under axial load.

5.2 Conclusion

Based on the analysis of experimental results, the following conclusions can be drawn:

a. In bond test, no debonding occurred in both types of bonding material.

b. Experimental results clearly demonstrate the wrapping efficiency of circular column is better as compared with square column.

Circular Column

c. There are 21% and 24% increase in axial strength of 1 layer of SFRP and SFRG as compared to control P.C.C. circular column.

d. There are 89% and 68% increase in axial strength of 2 layers of SFRP and SFRG respectively as compared to control P.C.C. circular column.

e. There are 109% and 79% increase in axial strength of 2 layers of SFRP and SFRG R.C.C. columns respectively as compared to control R.C.C. circular column.

Square Column

f. There are 28% and 32% increase in axial strength of 1 layer of SFRP and SFRG as compared to control P.C.C. square column.

g. There are 86% and 65% increase in axial strength of 2 layers of SFRP and SFRG respectively as compared to control P.C.C. square column.

h. There are 57% and 61% increase in axial strength of 2 layers of SFRP and SFRG R.C.C. columns respectively as compared to control R.C.C. square column.

i. Load vs. deflection curve approximately straight-line because of plain concrete columns.

Note: Due to the difference in reinforcements in square and circular columns the strength are different therefore no comparison can be made between square and circular R.C.C. columns.

5.3 Future Scope of Work

The present study can be extended further to include following aspects:

a. Experimental work can be extended further for different types of loading condition.

b. Experimental work can be extended further for different corner radius.

c. Development of the confinement model for SFRP wrapped concrete column subjected to axial load.

d. Experimental work can be extended further for long term durability tests.

Appendix A

Estimation of Strength of Column

Appendix A include estimation of strength of columns. The strength of Control columns are calculated as per Is 456: 2000 and strength of wrapped columns are calculated as per ACI 440.2R-08 [15]. All columns are short columns. Estimation of strength of columns are shown in table: A.1. Detailed calculation of all columns are given as per table:A.2 to A.13.

Control column are calculated as per IS 456:2000 equation.

Design Parameters

$Fck = 15\ MPa$

$Fy = 415\ MPa$

Asc of Circular column = 6 No of 12mm bar

Asc of Circular column = 678 mm^2

Asc of Square column = 4 No of 12mm bar

Asc of Square column = 452 mm^2

Ac of Circular column = $\pi/4 \times 200^2$

Ac of Circular column = $34000mm^2$

Ac of Square column = 200×200

Ac of Square column = $40000 mm^2$

In calculation of ultimate axial load no factor of safety considered.

Square R.C.C. Column

P = $Ac \times Fck + Asc \times Fy$

P = $40000 \times 15 + 452 \times 415$

p = 788 kN

Square P.C.C. Column

P = $Ac \times Fck$

P = 40000×15

p = 600 kN

Circular R.C.C. column

P = $Ac \times Fck + Asc \times Fy$

P = $34000 \times 15 + 678 \times 415$

p = 752 kN

Circular P.C.C. column

P = $Ac \times Fck$

P = 34000×15

p = 471 kN

In ACI method the environmental reduction factor (CE) taken as 1 instead of 0.95 because of controlled environment and other factor ø, ka taken as per CFRP wrapped column design. Design of Square and circular columns same method will be applied. Only shape factor Ka will be one in circular column.

Table A.1: Estimation of strength of columns

Column Notation	Estimation of Strength of column (KN)
Control Circular P.C.C.	471
Control Circular R.C.C.	752
Circular P.C.C Epoxy SSWM Layer 1	567
Circular P.C.C Epoxy SSWM Layer 2	925
Circular R.C.C Epoxy SSWM Layer 2	1051
Circular P.C.C Polymer SSWM Layer 1	726
Circular P.C.C Polymer SSWM Layer 2	1243
Circular R.C.C Polymer SSWM Layer 2	1362
Control Square P.C.C.	600
Control Square R.C.C.	788
Square P.C.C. Epoxy SSWM Layer 1	467
Square P.C.C. Epoxy SSWM Layer 2	669
Square R.C.C. Epoxy SSWM Layer 2	756
Square P.C.C. Polymer SSWM Layer 1	557
Square P.C.C. Polymer SSWM Layer 2	848
Square R.C.C. Polymer SSWM Layer 2	932

Table A.2: Estimation of Strength of CPEL1 Column

Strengthening of a Circular P.C.C. Column Using one layer of SFRP (CPEL1)	
DESIGN PARAMETERS	
Diameter of Column (mm)	200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	-
Ast (mm^2)	0
Ag (mm^2)	31400
P_n without SFRP (kN)	495
P_{n1} with SFRP(kN)	567

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.22
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	310
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.034
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	**CALCULATIONS**
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}{}^*$ $f_{fu} = 1 \; x \; 310 = 310$ $\varepsilon_{fu} = c_E \varepsilon_{fu}{}^*$ $\varepsilon_{fu} = 1 \; x \; 0.034 = 0.034$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 310 MPa ε_{fu} = 0.034
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ ψ = 0.95 $K\varepsilon$ = 0.57 n = 1.0 $\varepsilon_{fe} = 0.57 \; x \; 0.034$ $f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{D}$ $f_l = \frac{0.95 \; x \; 2 \; x \; 1 \; x193000 \; x \; 0.22 \; x \; 0.019}{200}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.019 f_l = 7.82 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $f'_{cc} = 3.3 \; x \; ka \; x \; f_l + fc'$ *ka = 1 for circular column* $f'_{cc} = 3.3 \; x \; 1 \; x \; 7.82 + 15$	Ka = 1 f'_{cc} = 40.80 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8 \, \phi \, ((0.85 \; f'_{cc} (Ag - Ast)) + fy \; Ast)$ $Pn1 = 0.8 \; x \; 0.65 \; ((0.85 \; x \; 40.8 \; (31400 - 0)) + 415 \; x \; 0)$	$Pn1$= 567 kN

Table A.3: Estimation of Strength of CPEL2 Column

Strengthening of a Circular P.C.C. Column Using Two layers of SFRP (CPEL2)	
DESIGN PARAMETERS	
Diameter of Column (mm)	200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	-
Ast (mm^2)	0
Ag (mm^2)	31400
P_n without SFRP (kN)	495
P_{n1} with SFRP(kN)	925

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.22
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	310
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.034
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	**CALCULATIONS**
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}^{*}$ $f_{fu} = 1 \; x \; 310 = 310$ $\varepsilon_{fu} = c_E \varepsilon_{fu}^{*}$ $\varepsilon_{fu} = 1 \; x \; 0.034 = 0.034$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 310 MPa ε_{fu} = 0.034
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ ψ = 0.95 $K\varepsilon$ = 0.57 $\varepsilon_{fe} = 0.57 \; x \; 0.034$ n = 2 $f_l = \frac{\psi_f 2 n E_f t_f \varepsilon_{fe}}{D}$ $f_l = \frac{0.95 \; x \; 2 \; x \; 2 \; x 193000 \; x \; 0.22 \; x \; 0.019}{200}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.019 f_l = 15.63 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $f'_{cc} = 3.3 \; x \; ka \; x \; f_l + fc'$ *ka = 1 for circular column* $f'_{cc} = 3.3 \; x \; 1 \; x \; 15.63 + 15$	*Ka* = 1 f'_{cc} = 66.59 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8 \, \phi \, ((0.85 \; f'_{cc} (Ag - Ast)) + fy \; Ast)$ $Pn1 = 0.8 \; x \; 0.65 \; ((0.85 \; x \; 66.59 \; (31400 - 0)) + 415 \; x \; 0)$	$Pn1$= 925 kN

Table A.4: Estimation of Strength of CREL2 Column

Strengthening of a Circular R.C.C. Column Using Two layers of SFRP (CREL2)	
DESIGN PARAMETERS	
Diameter of Column (mm)	200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	-
Ast (mm^2)	678
Ag (mm^2)	31400
P_n without SFRP (kN)	565
P_{n1} with SFRP(kN)	1051

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.22
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	310
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.034
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	**CALCULATIONS**
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}^*$ $f_{fu} = 1\ x\ 310 = 310$ $\varepsilon_{fu} = c_E \varepsilon_{fu}^*$ $\varepsilon_{fu} = 1\ x\ 0.034 = 0.034$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 310 MPa ε_{fu} = 0.034
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ ψ = 0.95 $K\varepsilon$ = 0.57 $\varepsilon_{fe} = 0.57\ x\ 0.034$ n = 2 $f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{D}$ $f_l = \frac{0.95\ x\ 2\ x\ 2\ x 193000\ x\ 0.22\ x\ 0.18}{200}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.019 f_l = 15.63 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $f'_{cc} = 3.3\ x\ ka\ x\ f_l + fc'$ *ka = 1 for circular column* $f'_{cc} = 3.3\ x\ 1\ x\ 15.63 + 15$	Ka = 1 f'_{cc} = 66.59 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8\ \phi\ (0.85\ f'_{cc}(Ag - Ast) + fy\ Ast$ $Pn1 = 0.8\ x\ 0.65\ (0.85\ x\ 39.51\ (31400 - 678) + 415\ x\ 678$	$Pn1$= 1051 kN

Table A.5: Estimation of Strength of CPPL1 Column

Strengthening of a Circular P.C.C. Column Using one layer of SFRG (CPPL1)	
DESIGN PARAMETERS	
Diameter of Column (mm)	200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	-
Ast (mm^2)	0
Ag (mm^2)	31400
P_n without SFRP (kN)	495
P_{n1} with SFRP(kN)	726

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.27
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	236
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.04
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	**CALCULATIONS**
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}^*$ $\quad f_{fu} = 1\ x\ 236 = 236$ $\varepsilon_{fu} = c_E \varepsilon_{fu}^*$ $\quad \varepsilon_{fu} = 1\ x\ 0.04 = 0.04$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 236 MPa ε_{fu} = 0.040
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ $\quad \psi$ = 0.95 $K\varepsilon$ = 0.57 $\varepsilon_{fe} = 0.57\ x\ 0.034$ $\quad$ n = 1 $f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{D}$ $\quad f_l = \frac{0.95\ x\ 2\ x\ 1\ x 193000\ x\ 0.27\ x\ 0.023}{200}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.023 f_l = 11.29 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $f'_{cc} = 3.3\ x\ ka\ x\ f_l + fc'$ $\quad$ *ka = 1 for circular column* $f'_{cc} = 3.3\ x\ 1\ x\ 11.29 + 15$	Ka = 1 f'_{cc} = 52.25 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8\ \phi\ ((0.85\ f'_{cc}\ (Ag - Ast)) + fy\ Ast)$ $Pn1 = 0.8\ x\ 0.65\ ((0.85\ x\ 52.25\ (31400 - 0)) + 415\ x\ 0)$	$Pn1$= 726 kN

Table A.6: Estimation of Strength of CPPL2 Column

Strengthening of a Circular P.C.C. Column Using Two layers of SFRG (CPPL2)	
DESIGN PARAMETERS	
Diameter of Column (mm)	200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	-
Ast (mm^2)	0
Ag (mm^2)	31400
P_n without SFRP (kN)	495
P_{n1} with SFRP(kN)	1243

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.27
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	236
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.04
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	**CALCULATIONS**
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}{}^*$ $\quad f_{fu} = 1\ x\ 236 = 236$ $\varepsilon_{fu} = c_E \varepsilon_{fu}{}^*$ $\quad \varepsilon_{fu} = 1\ x\ 0.04 = 0.04$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 236 MPa ε_{fu} = 0.040
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ ψ = 0.95 $K\varepsilon$ = 0.57 $\varepsilon_{fe} = 0.57\ x\ 0.034$ n = 2 $f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{D}$ $\quad f_l = \frac{0.95\ x\ 2\ x\ 2\ x 193000\ x\ 0.27\ x\ 0.023}{200}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.023 f_l = 22.57 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $f'_{cc} = 3.3\ x\ ka\ x\ f_l + fc'$ $\quad$ *ka = 1 for circular column* $f'_{cc} = 3.3\ x\ 1\ x\ 22.57 + 15$	*Ka* = 1 f'_{cc} = 89.49 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8\ \phi\ ((0.85\ f'_{cc}\ (Ag - Ast)) + fy\ Ast)$ $Pn1 = 0.8\ x\ 0.65\ ((0.85\ x\ 89.49\ (31400 - 0)) + 415\ x\ 0)$	*Pn*1= 1243 kN

Table A.7: Estimation of Strength of CRPL2 Column

Strengthening of a Circular R.C.C. Column Using Two layers of SFRG (CRPL2)	
DESIGN PARAMETERS	
Diameter of Column (mm)	200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	-
Ast (mm^2)	678
Ag (mm^2)	31400
P_n without SFRP (kN)	565
P_{n1} with SFRP(kN)	1362

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.27
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	236
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.04
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	**CALCULATIONS**
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}^*$ $f_{fu} = 1\ x\ 236 = 236$ $\varepsilon_{fu} = c_E \varepsilon_{fu}^*$ $\varepsilon_{fu} = 1\ x\ 0.04 = 0.04$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 236 MPa ε_{fu} = 0.040
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ ψ = 0.95 $K\varepsilon$ = 0.57 $\varepsilon_{fe} = 0.57\ x\ 0.034$ n = 2 $f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{D}$ $f_l = \frac{0.95\ x\ 2\ x\ 2\ x 193000\ x\ 0.27\ x\ 0.023}{200}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.023 f_l = 22.57 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $f'_{cc} = 3.3\ x\ ka\ x\ f_l + fc'$ *ka = 1 for circular column* $f'_{cc} = 3.3\ x\ 1\ x\ 22.57 + 15$	Ka = 1 f'_{cc} = 89.49 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8\ \phi\ (0.85\ f'_{cc}\ (Ag - Ast) + fy\ Ast$ $Pn1 = 0.8\ x\ 0.65\ (0.85\ x\ 89.49\ (31400 - 678) + 415\ x\ 678$	$Pn1$= 1362 kN

Table A.8: Estimation of Strength of SPEL1 Column

Strengthening of a Square P.C.C. Column Using one layer of SFRP (SPEL1)	
DESIGN PARAMETERS	
Size of Column (mm)	200 x 200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	25
Ast (mm^2)	0
Ag (mm^2)	40000
P_n without SFRP (kN)	495
P_{n1} with SFRP(kN)	467

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.22
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	310
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.034
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	**CALCULATIONS**
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}{}^*$ $f_{fu} = 1\ x\ 310 = 310$ $\varepsilon_{fu} = c_E \varepsilon_{fu}{}^*$ $\varepsilon_{fu} = 1\ x\ 0.034 = 0.034$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 310 MPa ε_{fu} = 0.034
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ ψ = 0.95 $K\varepsilon$ = 0.57 n = 1 $\varepsilon_{fe} = 0.57\ x\ 0.032$ $f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{\sqrt{b^2+h^2}}$ $f_l = \frac{0.95\ x\ 2\ x\ 1\ x 193000\ x\ 0.22\ x\ 0.019}{\sqrt{200^2+200^2}}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.019 f_l = 5.53 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $\frac{Ae}{Ac} = \frac{1 - \left[\frac{\left(\frac{b}{h}\right)(h-2rc)^2 + \left(\frac{h}{b}\right)(b-2rc)^2}{3Ag}\right] - \rho_g}{1-\rho_g}$ $k_a = \frac{Ae}{Ac}\left(\frac{b}{h}\right)^2$ $f'_{cc} = 3.3\ x\ ka\ x\ f_l + fc'$	rc = 25 mm Ag = 40000 mm^2 ρ_g = 0 % Ae / Ac = 0.625 *Ka* = 0.63 f'_{cc} = 26.40 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8\ \phi\ ((0.85\ f'_{cc}(Ag - Ast)) + fy\ Ast)$ $Pn1 = 0.8\ x\ 0.65\ ((0.85\ x\ 26.4\ (40000 - 0)) + 415\ x\ 0)$	$Pn1$= 467 kN

Table A.9: Estimation of Strength of SPEL2 Column

Strengthening of a Square P.C.C. Column Using Two layers of SFRP (SPEL2)	
DESIGN PARAMETERS	
Size of Column (mm)	200 x 200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	25
Ast (mm^2)	0
Ag (mm^2)	40000
P_n without SFRP (kN)	495
P_{n1} with SFRP(kN)	669

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.22
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	310
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.034
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	CALCULATIONS
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}{}^*$ $\quad f_{fu} = 1\ x\ 310 = 310$ $\varepsilon_{fu} = c_E \varepsilon_{fu}{}^*$ $\quad \varepsilon_{fu} = 1\ x\ 0.034 = 0.034$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 310 MPa ε_{fu} = 0.034
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ $\quad \psi$ = 0.95 $K\varepsilon$ = 0.57 $\varepsilon_{fe} = 0.57\ x\ 0.032$ $\quad$ n = 2 $f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{\sqrt{b^2 + h^2}}$ $\quad f_l = \frac{0.95\ x\ 2\ x\ 2\ x 193000\ x\ 0.22\ x\ 0.019}{\sqrt{200^2 + 200^2}}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.019 f_l = 11.06 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $\frac{Ae}{Ac} = \frac{1 - \left[\frac{\left(\frac{b}{h}\right)(h-2rc)^2 + \left(\frac{h}{b}\right)(b-2rc)^2}{3Ag}\right] - \rho_g}{1 - \rho_g}$ $k_a = \frac{Ae}{Ac}\left(\frac{b}{h}\right)^2$ $\quad f'_{cc} = 3.3\ x\ ka\ x\ f_l + fc'$	Ag = 40000 mm^2 ρ_g = 0 % Ae / Ac = 0.625 *Ka* = 0.63 f'_{cc} = 37.80 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8\ \phi\ ((0.85\ f'_{cc}\ (Ag - Ast)) + fy\ Ast)$ $Pn1 = 0.8\ x\ 0.65\ ((0.85\ x\ 37.8\ (40000 - 0)) + 415\ x\ 0)$	*Pn*1= 669 kN

Table A.10: Estimation of Strength of SREL2 Column

Strengthening of a Square R.C.C. Column Using one layer of SFRP (SREL2)	
DESIGN PARAMETERS	
Size of Column (mm)	200 x 200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	25
Ast (mm^2)	452
Ag (mm^2)	40000
P_n without SFRP (kN)	635
P_{n1} with SFRP(kN)	756

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.22
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	310
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.034
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	**CALCULATIONS**
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}{}^*$ $f_{fu} = 1 \ x \ 310 = 310$ $\varepsilon_{fu} = c_E \varepsilon_{fu}{}^*$ $\varepsilon_{fu} = 1 \ x \ 0.034 = 0.034$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 310 MPa ε_{fu} = 0.034
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ ψ = 0.95 $K\varepsilon$ = 0.57 $\varepsilon_{fe} = 0.57 \ x \ 0.032$ n = 2 $f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{\sqrt{b^2+h^2}}$ $f_l = \frac{0.95 \ x \ 2 \ x \ 2 \ x 193000 \ x \ 0.22 \ x \ 0.019}{\sqrt{200^2+200^2}}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.019 f_l = 11.06 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $\frac{Ae}{Ac} = \frac{1 - \left[\frac{\left(\frac{b}{h}\right)(h-2rc)^2 + \left(\frac{h}{b}\right)(b-2rc)^2}{3Ag}\right] - \rho_g}{1-\rho_g}$ $k_a = \frac{Ae}{Ac}\left(\frac{b}{h}\right)^2$ $f'_{cc} = 3.3 \ x \ ka \ x \ f_l + fc'$	Ag = 40000 mm^2 ρ_g = 1.13 % Ae / Ac = 0.6207 *Ka* = 0.62 f'_{cc} = 37.65 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8 \phi \ ((0.85 \ f'_{cc} (Ag - Ast)) + fy \ Ast)$ $Pn1 = 0.8 \ x \ 0.65 \ ((0.85 \ x \ 37.65 \ (40000 - 452)) + 415 \ x \ 452)$	$Pn1$= 756 kN

Table A.11: Estimation of Strength of SPPL1 Column

Strengthening of a Square P.C.C. Column Using one layer of SFRG(SPPL1)	
DESIGN PARAMETERS	
Size of Column (mm)	200 x 200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	25
Ast (mm^2)	0
Ag (mm^2)	40000
P_n without SFRP (kN)	495
P_{n1} with SFRP(kN)	557

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.27
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	236
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.04
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	**CALCULATIONS**
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}^*$ $\quad f_{fu} = 1 \times 236 = 236$ $\varepsilon_{fu} = c_E \varepsilon_{fu}^*$ $\quad \varepsilon_{fu} = 1 \times 0.04 = 0.04$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 236 MPa ε_{fu} = 0.040
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ $\quad \psi$ = 0.95 $K\varepsilon$ = 0.57 $\varepsilon_{fe} = 0.57 \times 0.032$ $\quad$ n = 1 $f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{\sqrt{b^2+h^2}}$ $\quad f_l = \frac{0.95 \times 2 \times 2 \times 193000 \times 0.27 \times 0.023}{\sqrt{200^2+200^2}}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.023 f_l = 7.98 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $\frac{Ae}{Ac} = \frac{1 - \left[\frac{\left(\frac{b}{h}\right)(h-2rc)^2 + \left(\frac{h}{b}\right)(b-2rc)^2}{3Ag}\right] - \rho_g}{1-\rho_g}$ $k_a = \frac{Ae}{Ac}\left(\frac{b}{h}\right)^2$ $f'_{cc} = 3.3 \times ka \times f_l + fc'$	Ag = 40000 mm^2 ρ_g = 0 % Ae / Ac = 0.625 *Ka* = 0.63 f'_{cc} = 31.46 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8\,\phi\,((0.85\ f'_{cc}(Ag - Ast)) + fy\ Ast)$ $Pn1 = 0.8 \times 0.65\ ((0.85 \times 31.46\ (40000 - 0)) + 415 \times 0)$	*Pn*1= 557 kN

Table A.12: Estimation of Strength of SPPL2 Column

Strengthening of a Square P.C.C. Column Using Two layers of SFRG (SPPL2)	
DESIGN PARAMETERS	
Size of Column (mm)	200 x 200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	25
Ast (mm^2)	0
Ag (mm^2)	40000
P_n without SFRP (kN)	495
P_{n1} with SFRP(kN)	848

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.27
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	236
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.04
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE | **CALCULATIONS**

Step 1—Calculate the FRP system design material properties

$$f_{fu} = C_E f_{fu}^{*} \qquad f_{fu} = 1\ x\ 236 = 236$$

$$\varepsilon_{fu} = c_E \varepsilon_{fu}^{*} \qquad \varepsilon_{fu} = 1\ x\ 0.04 = 0.04$$

C_E = 1

FROM TABLE-9.1 ACI 440.2R

Calculations: f_{fu} = 236 MPa; ε_{fu} = 0.040

Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l

$$\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$$

ψ = 0.95

$K\varepsilon$ = 0.57

n = 2

$$\varepsilon_{fe} = 0.57\ x\ 0.032$$

$$f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{\sqrt{b^2+h^2}} \qquad f_l = \frac{0.95\ x\ 2\ x\ 1\ x 193000\ x\ 0.22\ x\ 0.019}{\sqrt{200^2+200^2}}$$

Checking for minimum confinement ratio: $\frac{f_l}{f_c'} \geq 0.08$

Calculations: ε_{fe} = 0.023; f_l = 15.96 MPa; *CHECK* **O.K.**

Step 3—Determine the required maximum compressive strength of confined concrete f 'cc

$$\frac{Ae}{Ac} = \frac{1 - \left[\frac{\left(\frac{b}{h}\right)(h-2rc)^2 + \left(\frac{h}{b}\right)(b-2rc)^2}{3Ag}\right] - \rho_g}{1-\rho_g}$$

$$k_a = \frac{Ae}{Ac}\left(\frac{b}{h}\right)^2$$

$$f'_{cc} = 3.3\ x\ ka\ x\ f_l + fc'$$

Calculations: Ag = 40000 mm^2; ρ_g = 0 %; Ae / Ac = 0.625; Ka = 0.63; f'_{cc} = 47.92 MPa

Step 4—Axial Load Carrying Capacity (Pn1)

ϕ = 0.65

$$Pn1 = 0.8\ \phi\ ((0.85\ f'_{cc}(Ag - Ast)) + fy\ Ast)$$

$$Pn1 = 0.8\ x\ 0.65\ ((0.85\ x\ 47.42\ (40000 - 0)) + 415\ x\ 0)$$

Calculations: $Pn1$= 848 kN

Table A.13: Estimation of Strength of SRPL2 Column

Strengthening of a Square R.C.C. Column Using one layer of SFRG (SRPL2)	
DESIGN PARAMETERS	
Size of Column (mm)	200 x 200
f_c' (MPa)	15
f_y (MPa)	415
rc (mm)	25
Ast (mm^2)	452
Ag (mm^2)	40000
P_n without SFRP (kN)	495
P_{n1} with SFRP(kN)	932

SSWM PROPERTIES	
THICKNESS PER PLY, t_f (mm) =	0.27
ULTIMATE TENSILE STRENGTH, f_{fu} (N/mm^2) =	236
REPTURE STRAIN ,ε_{fu} (mm/mm) =	0.04
MODULUS OF ELASTICITY OF SFRP LAMINATES E_f (N/mm^2) =	193000

PROCEDURE	**CALCULATIONS**
Step 1—Calculate the FRP system design material properties $f_{fu} = C_E f_{fu}^*$ $f_{fu} = 1 \times 236 = 236$ $\varepsilon_{fu} = c_E \varepsilon_{fu}^*$ $\varepsilon_{fu} = 1 \times 0.04 = 0.04$ C_E = 1 FROM TABLE-9.1 ACI 440.2R	f_{fu} = 236 MPa ε_{fu} = 0.040
Step 2—Determine the maximum confining pressure due to the SFRP jacket, f_l $\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ ψ = 0.95 $K\varepsilon$ = 0.57 $\varepsilon_{fe} = 0.57 \times 0.032$ n = 2 $f_l = \frac{\psi_f 2nE_f t_f \varepsilon_{fe}}{\sqrt{b^2+h^2}}$ $f_l = \frac{0.95 \times 2 \times 2 \times 193000 \times 0.27 \times 0.023}{\sqrt{200^2+200^2}}$ *Checking for minimum confinement ratio:* $\frac{f_l}{f_c'} \geq 0.08$	ε_{fe} = 0.023 f_l = 15.96 MPa *CHECK* ***O.K.***
Step 3—Determine the required maximum compressive strength of confined concrete f 'cc $\frac{Ae}{Ac} = \frac{1 - \left[\frac{\left(\frac{b}{h}\right)(h-2rc)^2 + \left(\frac{h}{b}\right)(b-2rc)^2}{3Ag}\right] - \rho_g}{1-\rho_g}$ $k_a = \frac{Ae}{Ac}\left(\frac{b}{h}\right)^2$ $f'_{cc} = 3.3 \times ka \times f_l + fc'$	Ag = 40000 mm^2 ρ_g = 1.13 % Ae / Ac = 0.621 *Ka* = 0.62 f'_{cc} = 47.70 MPa
Step 4—Axial Load Carrying Capacity (Pn1) ϕ = 0.65 $Pn1 = 0.8\,\phi\,((0.85\ f'_{cc}(Ag - Ast)) + fy\ Ast)$ $Pn1 = 0.8 \times 0.65\,((0.85 \times 47.7\,(40000 - 452)) + 415 \times 452)$	*Pn*1= 932 kN

Appendix B

List of Papers Published/Communicated

- Nikunj M. Patel, Mr. Varinder. K. Singh, Dr. Paresh. V. Patel Experimental Investigation of compressive behavior of stainless steel wire mesh (SSWM) wrapped concrete circular and square columns" Proceedings of the Structural Engineering Convention 2014 (SEC 2014), Department of Civil engineering, IIT Delhi, (Abstract circulated).

- Nikunj M. Patel, Mr. Varinder. K. Singh, Dr. Paresh. V. Patel Study of SFRP and SFRG retrofitting of column." Proceedings of the International Conference on Sustainable Civil Infrastructure 2014, American Society of Civil Engineering-Indian section (ASCE Indian section), Department of Civil engineering, IIT Hyderabad, (Abstract circulated).

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