Experimental Study of SFRP in Retrofitting of Column

By

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13MCLC09

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Major Project

Submitted in Partial Fulfillment of the Requirements

For the degree of

Master of Technology in Civil Engineering

(Computer Aided Structural Analysis & 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 and has not been submitted elsewhere for a degree.

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

Deven P. Patel

Certificate

This is to certify that Major Project entitled **"Experimental Study of SFRP in Retrofitting of Column"** submitted by **Deven P. Patel (13MCLC09)**, towards the partial fulfillment of the requirements for the degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis & Design) of Nirma University of Science and Technology, Ahmedabad is the Record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

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Abstract

Fiber Reinforce Polymer (FRP) composites are emerging as an important construction material for increasing capacity of existing structure. Presently, carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymer (GFRP) are being used as external reinforcement for strengthening of structure.

Steel fiber reinforced polymer (SFRP) composite materials have been recently introduced as an alternative to glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) composite materials. In SFRP steel fibers in form of mesh is applied on concrete surface using epoxy as grout material. The objective of present project is to evaluate axial strength of Steel Fiber Reinforced Polymer (SFRP) wrapped column specimens.

Three specimens of locally available stainless steel wire mesh (SSWM) were selected and tested for finding the tensile strength. The average ultimate tensile strength of wire was found to be 758.91 N/mm^2. To check the bond strength between concrete and SSWM (Stainless steel wire mesh), 6 dumbbell shaped concrete specimens were prepared and tested. Ultimate bond strength was found to be more than 837.75 N/mm^2 because the wire mesh strip got fractured but there was no bond failure between concrete and wire mesh.For experimental evaluation of axial load carrying capacity of concrete columns, total 54 cylindrical column specimens of 200 mm diameter were cast. Variation parameters considered for experimental study are: concrete grade M15,M20 and M25, height of column 400mm, 800mm and 1200mm and number of wrapping layers one and two. Axial load carrying capacity of strengthened column is compared with that without wrapping. Total 18 columns were cast in each grade of concrete. For each grade, 6 specimens were prepared for the same height but with different number of wrapping.

Based on experimental work it has been found that for column having **M15** grade concrete and 400 mm height with one layer of SSWM and two layers of SSWM compressive strength is increased by 19% and respectively by 49%. In case of column with 800 mm height with one layer of SSWM and two layers of SSWM compressive strength is increased by 61% and respectively by 71%. In case of column with 1200 mm height with one layer of SSWM and two layers of SSWM compressive strength

is increased by 61% and respectively by 86%.

In **M20** grade concrete and 400 mm height with one layer of SSWM and two layers of SSWM compressive strength is increased by 15% and respectively by 47%. In case of column with 800 mm height with one layer of SSWM and two layers of SSWM compressive strength is increased by 47% and respectively by 67%. In case of column with 1200 mm height with one layer of SSWM and two layers of SSWM compressive strength is increased by 54% and respectively by 70%.

In **M25** grade concrete and 400 mm height with one layer of SSWM and two layers of SSWM compressive strength is increased by 15% and respectively by 39%. In case of column with 800 mm height with one layer of SSWM and two layers of SSWM compressive strength is increased by 30% and respectively by 52%. In case of column with 1200 mm height with one layer of SSWM and two layers of SSWM compressive strength is increased by 34% and respectively by 57%.

Based on experimental work carried out in this study it is formed that SSWM can be used for structural strengthening of RCC column successfully. There are other benefits of using SFRP are inherent ductility, good bond with concrete surface, resistance to corrosion being of stainless steel, lightweight in comparison to steel plates and above all much cost effective.

Acknowledgement

I would like to thank my guide Dr. Paresh V. Patel, 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.

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I further extend my thanks to Dr. K. Kotecha, Director, Institute of Technology, Nirma University, Ahmedabad.

Last but not the least, I would like to thank the Almighty, to my parents for their blessings, my all friends and classmates for their continuous support and encouragement in all possible ways.

-Deven P. Patel

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Chapter 1

Introduction

1.1 General

Repair and Retrofit of concrete structure has been an increasingly important issue as infrastructure continues to age and deteriorate. More options are becoming available for such structures for which it is more economical to retrofit than to demolish.

Over the years, various repair methods have been proposed such as concrete and steel jacketing. The main problem with these materials is that they have the same deterioration potential as the damaged structure.

Reinforced concrete structures often have to face modification and improvement of their performance during their service life. The main contributing factors are change in their use, new design standards, deterioration due to corrosion in the steel caused by exposure to an aggressive environment and accident events such as earthquakes. In such circumstances there are two possible solutions: replacement or retrofitting. Full structure replacement might have disadvantages such as high costs for material and labor. So, it is often better to repair or upgrade the structure by retrofitting.[15]

In the last decade, the development of strong epoxy glue has led to a technique which has great potential in the field of upgrading structures. Basically the techniques involve gluing steel plates or fiber reinforced polymer (FRP) plates or sheets to the surface of the concrete. Each material has its specific advantages and disadvantages. Steel plates have been used for many years and are very effective to use as bonding reinforcement. However, they are heavy to transport and install, prone to corrosion and delivery length of plates are limited. FRP can therefore be convenient compared to other techniques. These materials have higher ultimate strength and lower density than steel. The installation is easier and require temporary support until the adhesive gains its strength. The plates or sheets then act compositely with the concrete and help to carry the loads. Plates are rigid FRP strips that are manufactured using a process called pultrusion. FRP sheets are flexible fabrication of raw fibers. In both of FRP plates and sheets, the FRP materials used are usually unidirectional (with all fibers oriented along the length of the sheet).

Fiber reinforced polymer (FRP) composite materials have come to the forefront as promising materials and systems for structural retrofit. Fiber Reinforced Polymer (FRP) Composites are defined as "A matrix of polymeric material that is reinforced by fibers or other reinforcing materials." Fiber Reinforced Polymers FRP composites comprise fibers of high tensile strength within a polymer matrix such as epoxy. FRP's present various advantages such as light weight, high confinement strength, high strength-to-weight ratio, easier installation and maintenance and also durable. The role of FRP for strengthening of existing or new structures is growing at an extremely rapid pace because of the ease and speed of construction, and the possibility of application without disturbing the existing functionality of the structure.[14]

Thus, a non-corrosive and durable material such as Fiber Reinforced Polymers (FRP) are considered as an ideal substitute to conventional materials such as concrete and steel for repair and rehabilitation of concrete structures. The common types of FRP materials used are Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and Aramid Fiber Reinforced Polymer (AFRP) shown in Fig. 1.1 and 1.2. Various researches concerning the durability, slenderness, and size effects of concrete specimens confined with the conventionally used FRP materials have been studied.

Recently, a new type of FRP materials termed Steel Fiber Reinforced Polymer (SFRP) and Steel Fiber Reinforced Grout (SFRG) have been proposed for repair and strengthening applications of concrete.[8]

Figure 1.1: CFRP and GFRP sheet

Figure 1.2: SFRP and AFRP sheet

Although confining concrete columns with SFRP sheets using the epoxy bonded wet-layup installation procedure is similar to the CFRP or GFRP sheets, when cementitious grout is used rather than epoxy as the bonding agent, the SFRG can exhibit excellent fire endurance properties.

1.2 Steel Fiber Reinforced Polymer (SFRP)

Hardwire is a family of reinforcements made from ultrahigh strength twisted steel wires. It is a material that affords end users the ability to put ultrahigh tensile strength steel (11-times stronger than typical steel plate) inside or outside just about any material[16].

Hard Wire (3×2 and 3×2 tape)

The 3×2 Hardwire is a high carbon steel cord with a micro-fine brass coating. The 3×2 wire cord is made by twisting 5 individuals wires together - 3 straight filaments wrapped by 2 filaments at a high twist angle as shown in Fig. 1.3. The result is an easy to handle cord that combines the best engineering values with great economics. Properties of cord is given in Table 1.1 and 1.2.

Characteristics

- Excellent mix of engineering properties - Up to 8 kip/inch.
- Great stiffness, instant wet-ability and excellent conformability.
- Works in all resins.
- Asymmetric shape acts like a screw and gives great mechanical bonding characteristics.
- Excellent fatigue properties in tension and in high-flex situations.
- Great choice for extrusion and pultrusion applications.

Figure 1.3: 3×2 Tape and 3×2 Cord

Table 1.1: Single Roving (Cord) Properties

Single Roving (Cord) Properties				
Description	Filament Diameter(mm)	Cord Dia(mm)	Break(kN)	Strain to failure
3×2	All filaments are 0.35	0.889	1.539	2.10%

Table 1.2: Tape Properties

Single Roving (Cord) Properties			**Tape Properties**		
Density	Hardwire item number	Standard Cord Coating	Tape Density (wire/in)	Tensile load (kN/m)	Tape thickness (mm)
Low	3×2-4-12	Brass	4	241.66	1.2
Medium	3×2-12-12	Brass	12	726.47	1.2
High	3×2-20-12	Brass	20	1217.08	1.2

Advantages of SFRP 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.[4]

- The cords used to make the SFRP sheets have some inherent ductility unlike carbon fibers, so SFRP is expected to show more ductile behavior than the CFRP.

- In comparison of confinement both SFRP and CFRP confinement is same, than SFRP confinement would be prefer more because of SFRP sheet is 56% less than CFRP.

- The steel cords of the SFRP sheets are formed from high tensile strength steel, up to eleven times stronger than typical steel plate. So, SFRP is expected to exhibit superior behavior.

- The steel cords of the SFRP sheets are coated with brass or galvanized coating to protect them from corrosion, and making the SFRP sheets suitable for various types of environmental exposures, so the corrosion is not an issue for SFRP sheets.

1.3 SSWM (Stainless Steel Wire Mesh)

SSWM is a locally available material of different wire thicknesses and opening size and manufactured for versetile use in the market. Out of so many varieties of wire mesh manufactured the mesh of 40×32 having wire thickness 0.25 mm and opening size 0.365 mm has been selected for strengthening of circular concrete column by 1-2 numbers of wrapping.

1.4 Research Significance

All literature related to FRP-confined concrete columns considered either CFRP or GFRP systems. Steel plates and CFRP/GFRP are more popular but steel plate handling is very difficult at site and CFRP/GFRP are non ductile and costly. Very less research has been performed using SFRP sheets for retrofitting concrete columns. As such, the effectiveness of SFRP as strengthening material to confine concrete columns needs to be addressed and studied extensively.

1.5 Need of Study

The main need of this study is to experimentally found out the effects of upgrading the load carrying capacity of columns subjected to axial compression by confining with SSWM wraps, due to

- High cost of CFRP and GFRP.
- High density of steel plate.
- Corrosion of steel plates.
- Inherent ductility of SFRP.
- Excellent fire resistant properties of SFRG.

1.6 Objective of Study

The purpose of this study is to investigate and gather more information regarding the behavior of surface bonded retrofit method for columns subjected to axial loading. The other objectives are as:

- To understand bond behavior between SSWM and concrete.
- To understand stress strain relationship of stainless steel wire meshes (SSWM).
- To understand the behavior of SSWM wrapped column under axial load.
- To increase the axial load carrying capacity of the column.

1.7 Scope of Work

To achieve above objectives, the scope of present study is decided as follows:

- Find the Tensile strength of SSWM.
- Find the bond strength from dumbbell shaped specimens of stainless steel wire mesh (SSWM).
- Casting circular column of M15, M20 and M25 grade of concrete with different slenderness ratio.
- Wrapping of circular column with one and two wraps of SSWM.
- Testing of circular PCC specimens and understand the failure pattern.
- Comparison with control specimen results to find the increase in compressive strength of column specimen by wrapping.

1.8 Organization of Report

This study is related to increase the axial load carrying capacity of the column by wrapping the column with SSWM. The organization of report is as follows:

Chapter-1 gives general introduction of the project. Introduction to SFRP , Advantages of SFRP, along with need of study, objectiveof study and scope of the project are included in this chapter.

The literature review related to the experimental study of SFRP strengthened concrete, is presented in chapter 2.

Chapter 3 describes the details about the experimental program which includes casting of specimens, application of SSWM and preparation of test set-up to evaluate tensile strength of SSWM and bond strength of SSWM.

Chapter-4 includes results and discussion of experimental work, Load vs Linear deflection, Load vs Lateral deflection and failure pattern of columns are presented in this chapter.

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

Chapter 2

Literature Survey

2.1 General

Reinforced concrete (RC) structures built according to older generation of codes present deficiencies related to structural integrity issues. Retrofitting is deemed necessary in order for this category of structures to survive future earthquake events by avoiding premature failure modes. When the retrofit strategy requires local intervention measures (at member level) to be taken or when the objective is the enhancement of the ductility level, then one of the most widely applied methods is wrapping with composite fabrics (carbon, glass or aramid). Within this framework, in the last decade ,a new material has been introduced, the steel reinforced fabric combined with either polymer (SRP) or grout (SRG). This type of fabric consists of high strength steel cords embedded in epoxy resin or grout matrix. Most of the applications concern the use of SRP as externally bonded longitudinal reinforcement in flexural members. The use of the steel reinforced fabric as a jacketing device was investigated experimentally to pre-damaged cantilever specimens of old type detailing for the first time in 2007 by Thermou and Pantazopoulou.

As per the current scenario, the load demand continues to increase, so both rehabilitation and strengthening of the structure are more demanding. 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. In this chapter literature related to steel fiber reinforced polymer (SFRP) for strenthening of concrete member is presented. Various aspect like bond behaviour of SSWM and concrete as well as improvement in axial load carrying capacity are reviewed from literature.

2.2 Bond Behavior

Matana et al. [1] presented the results of an experimental study to evaluate the bond between SRP/SRG and concrete substrate using direct shear test. For SRP, polymeric resin was sikadur 330 and for SRG, grout was SikaTop 121 PLUS. 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 as shown in Fig. 2.1. The existence of the effective bond length after which the load can no longer increase was proved 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. Effective bond length was calculated for SRP specimens and was found to be about 127 mm, which is somewhat large than in FRP specimens, where it is reported to be about 102 mm. For SRG, the effective bond length is large than 305 mm.

SRP Specimen - Concrete shearing   SRG Specimen - grout shearing

Figure 2.1: Direct shear tested specimens- Failure mode

Figeys et al. [9] studied with the new material that can be used as external reinforcement: steel cord reinforced polymer (SCRP). It consists of thin high-strength steel fibres embedded in a polymer matrix. This innovative material combines the advantages of steel and carbon fibres. The material cost of SCRP was relatively low and the laminate preserves the flexibility. To determine the strength and Youngs modulus, different tensile tests were carried out on the material. The individual cords, the laminate itself and an impregnated laminate were tested. Also 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 as shown in Fig. 2.2.

(a) single cord (b) not-impregnated laminate (c) impregnated laminate

Figure 2.2: Tensile test on steel cord reinforecement

2.3 Axial Strengthening

Alper et al. [10] studied the CFRP jacketing of columns under different design parameters. 68 reinforced concrete columns were tested under uniaxial compression after being jacketed externally with carbon fiber reinforced polymer (CFRP) sheets. Forty specimens were cast using low strength concrete and inadequate internal transverse reinforcement, while 28 specimen were east with medium strength concrete and adequate internal transverse reinforcement. Thickness of the CFRP jacket, cross-section shape, concrete strength amount of internal transverse reinforcement, corner radius, existence of pre damage, loading type (monotonic or cyclic) and the bonding pattern (orientation, spacing anchorage details, additional corner supports) of CFRP sheets were the main test parameters of the extensive experimental work. Test results showed that external confinement of columns with CFRP sheets resulted in an increase in ultimate axial deformations without a substantial loss in strength. The efficiency of retrofitting was much more pronounced in the case of relatively lower strength concrete. The proposal model, together with two other available models, were used for predicting the strength and corresponding axial deformation of more than 300 specimens tested by other researchers, as well as more than 100 specimens tested by the writers during this study and before. It was shown that the predicted results by the proposed model were in reasonable agreement with this extensive database of experimental studies.

Raafat El-Hacha and Mohammad A. Mashrik [4] analysed circular and square specimens confined with SFRP sheets. The experimental program was conducted in three phases. In Phase I, 36 circular specimens (150 mm diameter and 300 mm height) and in Phase II, 36 square specimens (150 × 150 mm cross-section and 300 mm height, with corner radius of 0 mm) were tested. In Phase III, 12 square specimens of same size but rounded at the corner with radii of 3, 6, 10, and 25 mm (representing 2%, 4%, 6.7%, and 16.7% of the side length of the square specimens) were tested. Testing frame setup shown in Fig. 2.3.

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. Rounding the corners improved the axial capacity and ductility of the SFRP wrapped square specimens. The capacity and ductility increased with increasing corner radius.

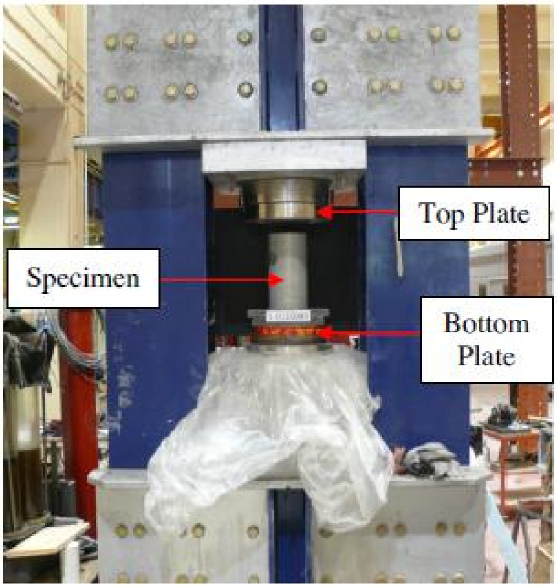


Figure 2.3: Testing frame

Khaled Abdelrahman and Raafat El-Hacha [3] Common types of fibers used for wrapping are carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), and aramid fiber reinforced polymer (AFRP). Recently, steel FRP (SFRP) has been introduced as a new class of composites for strengthening applications. They studied the behavior of large scale column with SFRP sheets. Non-reinforced and reinforced large-scale columns (300 × 1200) mm wrapped with CFRP and SFRP sheets were examined and compared with that of unwrapped columns. The experimental results included stress-strain behavior, ultimate stress, ultimate strain, dilation, and ductility of large-scale columns. This study presents the first ever insight into the strain variation of large-scale circular columns wrapped with CFRP and SFRP sheets using the digital image correlation technique (DICT) as shown in Fig. 2.4. This technique is a photogrammetric technique that allows capturing strains from the surface of FRP-confined concrete. Results from DICT were used to analyze the strain efficiency of the SFRP sheets. Results indicated that the overall performance of the SFRP- wrapped concrete columns were 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 SFRP sheets provided a higher percentage contribution toward the total ductility of the columns than the CFRP sheets. Thus, the columns wrapped with SFRP sheets showed a higher percentage increase in the total ductility of the columns compared to the CFRP-wrapped columns. The dilation response of the columns wrapped with the SFRP sheets showed behavior similar to that of the columns wrapped with CFRP sheets. Wrapping the columns with one layer of CFRP and SFRP sheets was not sufficient enough to curtail the dilatation tendency of the concrete. The strain efficiency analysis based on the DICT data as shown in Fig. 2.4 and the readings from the conventional foil strain gauges for non-reinforced and reinforced concrete columns showed that the columns wrapped with the SFRP sheets achieved higher strain efficiencies than the columns wrapped with the CFRP sheets.

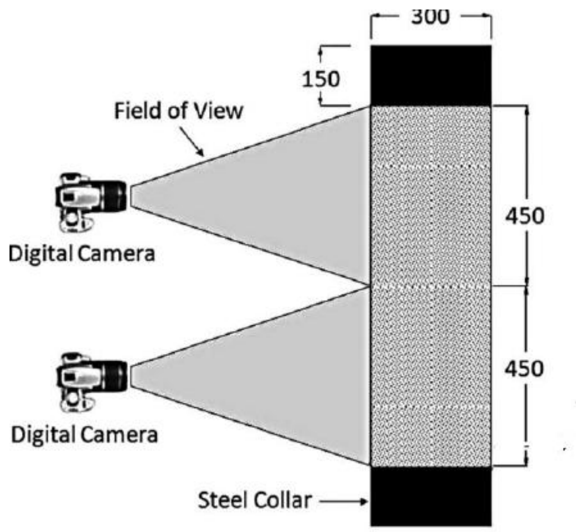


Figure 2.4: DICT test setup

Khaled Abdelrahman and Raafat EL-HACHA [5] conducted experimental program of cylinder divided into two groups. The specimens in Group A consisted of nine small-scale plain concrete cylinders with dimensions of 150 mm in diameter and 300 mm in height. The specimens were divided in category like unwrapped, CFRP wrapped and SFRP wrapped. The specimens in Group B consisted of three large-scale plain concrete columns with dimensions of 300 mm in diameter and 1200 mm in height. One column was left unwrapped to act as the control specimen, the second column was wrapped with CFRP sheets, and the third column was wrapped with SFRP sheets.

These results clearly indicated that increasing the size of the specimen had a significant effect on the performance of the unwrapped, CFRP wrapped, and SFRP wrapped specimens. The ultimate axial strength, axial strain, and hoop strain of the FRP wrapped columns were reduced significantly compared to the FRP wrapped cylinders.

Mashrik et al., [6] presented the results of an experimental investigation that evaluated the effectiveness of using Steel Fiber Reinforced Polymer (SFRP) sheets to confine small scale plain concrete circular columns. Different parameters were investigated including: number of SFRP layers (1, 2 and 3) and concrete compressive strength (25, 30, and 35 MPa). A total of 35 circular specimens (150 mm diameter × 300 mm height) were tested and divided into three groups according to concrete compressive strength. In each group, two/three specimens were tested without wrapping for comparison purposes, and two/three specimens for each number of layers.

All the unwrapped circular specimens failed in shear failure. The specimens wrapped with one layer of SFRP sheet ruptured right at the beginning of the overlap. The specimens wrapped with two layers of SFRP sheets showed a combination of rupture and debonding. The specimens wrapped with three layers of SFRP sheets debonded at the overlap completely without rupture. When the SFRP sheets ruptured, failure was sudden and in a brittle manner with loud crushing sound without any prior warning except for some creeping sound of concrete cracking. Increasing the number of SFRP layers for the same concrete strength increased the axial concrete compressive strengths.

Khoa Tran et al. [2] investigated on circular specimens confined with SFRP sheets. The SFRP sheet is a new type of material recently introduced for strengthening applications of concrete structures. Thus, the main aim of this investigation was to quantify and access the axial strength, axial strain hoop strain, dilation and ductility performance of SFRP confined concrete with the increase in the slenderness of the specimen. 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. 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.

All specimens were loaded in uniaxial compression until failure. The specimens were also instrumented with a photogrammetric method termed Digital Image Correlation Technique as shown in Fig. 2.5 to measure the hoop strains from the surface of the SFRP confined concrete specimens. Increasing the slenderness of the specimens reduced the percentage increase of the ultimate axial strength, axial and hoop strains, and strain efficiency of the SFRP wrapped specimens. This indicated the reduced effectiveness of the SFRP confinement due to the slenderness effects.

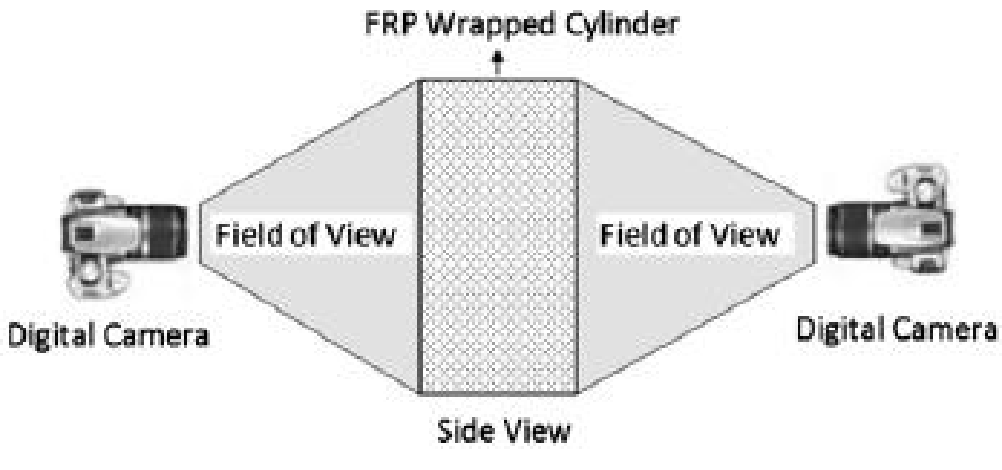


Figure 2.5: Schematic view

Thermou et al. [11] conducted an experimental study to investigate the efficiency of GFRP (Glass FRP), CFRP and SRP in upgrading the seismic behaviour of substandard R/C prismatic members. Sixteen specimens, representative of a typical building column, were tested. After the initial tests, specimens were repaired/strengthened with the aforementioned materials and then retested. The potential of SRP as a strengthening/repair material emerged from the experimental evidence. In most cases retrofitted specimens attained increased strength and deformation capacity with respect to their initial properties. Comparison with the performance enhancement imparted by the FRP jackets (glass and carbon) demonstrated the higher efficiency of the SRPs.

G.J. Mitolidis et al. [12] studied the mechanical and bond characteristics of SRP and CFRP reinforcement. The work presented tensile tests of SRP (Steel Reinforced Polymer) and CFRP (Carbon Fibre Reinforced Polymer) strips, with and without epoxy resin, as well as bond tests of polymer strips glued on rectangular concrete prisms. Various configurations of SRP and CFRP strips were bonded to ten rectangular concrete prisms using epoxy resin. The main parameters of the tests were the fibre type (steel, carbon), strip length, and strip width. For each specimen the deformation law (bond strength vs. total slip) up to maximum strength and elongation at failure, was recorded. Tested materials were classified according to their debonding strength and deformation capacity. For SRP strips the stress strain relationship includes a short inelastic branch, while CFRP strips are characterised by a linear elastic, stress strain relationship up to failure. The fracture elongation was almost the same for the SRP and CFRP specimens that were tested. From the tests conducted on reinforced polymer strips bonded on concrete prisms, it was found that CFRP strips had a higher debonding strength than SRP strips; this conclusion was subject to the limitation that only 2 CFRP specimens were tested. The width of the composite material strip was found to affect the debonding strength, however the ratio of the ultimate loads was not exactly proportional to the width of the strips, which is an indication of the complex bond stress distribution. The different length of strips (300mm and 150mm), being always larger than the effective anchorage length, was not found to affect the debonding strength.

Thermou et al. [11] studied the influence of the loading rate on the axial compressive behavior of concrete specimens confined with SRG jackets. An experimental study was carried out where the main objective was to investigate the favorable confinement characteristics of steel reinforced grout (SRG) jackets on the compressive behavior of unreinforced concrete prisms under monotonic and cyclic axial loading. SRG jackets were made by applying steel fiber reinforced fabrics of reduced density combined with cementitious grout that serves as the connecting matrix. For one layer of the novel jacketing system was applied to a number of unreinforced concrete prismatic specimens constructed for a moderate concrete cylindrical compressive strength of 25 MPa. The parameters of this investigation were: a) the density of the fabric used in the steel reinforced concrete jackets and b) the rate of axial loading. The density of the fabric was either medium (2 cords/cm) or relatively low (1 cord/cm). The specimens were subjected to monotonic concentric uni-axial compression load applied either in a slow rate reaching the maximum load in 400 secs or at a axial load rate 10 times faster. Both the slow rate load and the fast rate load were applied in the following manner. Initially, approximately 50% of the maximum load was reached in 3 load-unload cycles that were followed by 3 load unload cycles at approximately 75% of the maximum load before the specimen reached the maximum load and failure at a final loading cycle.

Hadi and Zhao [13] investigated in this study to reduce the cover spalling of high strength concrete columns. Three materials were choosen for the study: fiberglass fly mesh, standard aluminum fly mesh and galvanised steel wire mesh. A total 16 cylindrical specimens with the length of 925 mm and a diameter 205 mm were cast and tested under concentric, eccentric and pure bending loading. From the test, they concluded that the galvanised steel wire mesh(S12.7WM) significantly increases the load carrying capacity of the column specimens for both concentric loading and eccentric loading. Columns confined with other two materials outperformed their counterparts confined with S12.7WM in ductility under both concentric loading and eccentric loading, but the significance decreased with the increase of eccentricity. The ductility values of columns confined with FGFM and SAFM were close to one another.

2.4 Summary

According to the present invention SSWM is used for the strenthening of column. When SSWM wrapping is done on column, it increases the confinement of columns and increases the axial load carrying capacity of the columns.

Chapter 3

Experimental Program

3.1 General

The SFRP sheet is a new type of material recently introduced for strengthening applications of concrete structures. Thus, the main aim of this investigation is to quantify and access the axial strength, axial strain, hoop strain of SSWM confined concrete with the increase in the slenderness of the specimens. The experimental program includes eighteen specimens with varying slenderness ratios (height-to-diameter ratio) of 6 specimens (200 mm × 400 mm), 6 specimens (200 mm × 800 mm), and 6 specimens (200 mm × 1200 mm) for each grade of M15, M20 and M25. All specimens are tested in uniaxial compression until failure. Detailed specifications and test setup are discussed in this chapter.

3.2 Material for Axial Strengthening

Material properties used for axial strengthening of columns using stainless steel wire mesh is presented in this section.

- **Stainless Steel Wire Mesh** For retrofitting of column different types of stainless steel wire mesh are available like (40×32 , 80×40 , 50×250). But in this investigation 40×32 type wire mesh has been used due to its high tensile strength and low cost. The properties of this wire mesh are shown in Table 3.1.

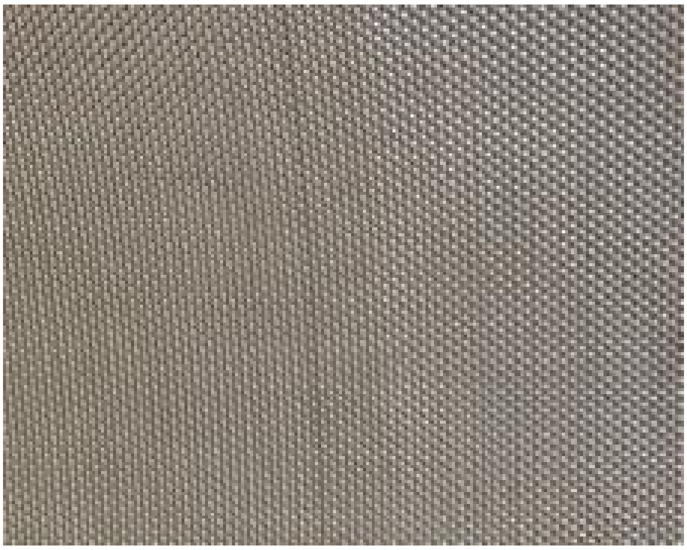


Figure 3.1: Wire mesh 40x32

Table 3.1: Typical wire mesh Properties

Woven type	Mesh per Inch	SWG	Diameter of wire (mm)	Size of Opening (mm)
Square	40	32	0.25	0.365

- **Bonding Material**
  - **MasterBrace**

    For MasterBrace 3500 (Primer) and MasterBrace 4500 (Saturant) material is used for the CFRP. There are two parts in each Primer and Saturant (Part A and Part B) as shown in Fig. 3.2 and 3.3.

Figure 3.2: MasterBrace 3500

Figure 3.3: MasterBrace 4500

Table 3.2: MasterBrace Properties

BASF	Primer	Saturant
Material	MasterBrace 3500	MasterBrace 4500
Aspect	Free flowing liquid	Translucent Blue liquid
Part A	Amber	Blue
Part B	Clear	Clear
Mixed Density (kg/ltr)	1.07 ± 0.02	1.13± 0.03
Mixing Ration (A:B)	1.67:1	2:1
Coverage	4-6 Sq.m/kg	0.8-1.8 Sq.m/kg
Pot life	70 min	30 min
Flexure Strength(MPa)	55	54
Compressive Strength(MPa)	73	86.2

– **Sikadur 30 LP**

For Strengthening of column, Sikadur 30 LP material is used for the wrapping of CFRP and steel plate. There are two parts (Part A and Part B) as shown in Fig. 3.4.

Figure 3.4: Sikadur 30 LP (Part A and Part B)

Table 3.3: Sikadur 30 LP Properties

Material	Sikadur 30 LP
Part A	White
Part B	Black
Mixed Density(kg/ltr)	1.8 ± 0.1
Mixing Ration (A:B)	3:1
Pot life	60 min
Flexure Strength(MPa)	42
Compressive Strength(MPa)	17-21
Bond Strength(MPa)	1 day Concrete Fracture

3.3 Tensile Strength of SSWM

For finding the tensile strength of stainless steel wire mesh, tension test on SSWM was done in the universel testing machine (UTM). The test procedure step by step as shown following.

3.3.1 Specimen Preparation

- Stainless Steel Wire Mesh strip cut in 100 mm×500 mm in size. SSWM strip is fixed at the end by 100 mm wide and 150 mm long steel plate.

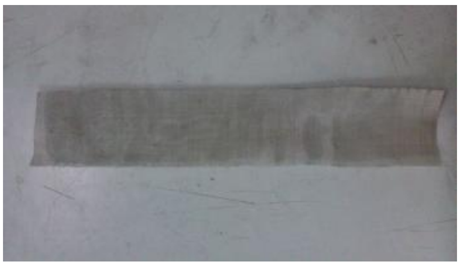


Figure 3.5: Mesh for Tensile test

- The Bond between mesh and steel plate is done by Epoxy MasterBrace (4500-Saturent). MasterBrace 4500 Part A and Part B in ratio of 2:1 (A:B). Apply 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 Fig. 3.6. 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 as shown in Fig. 3.8.

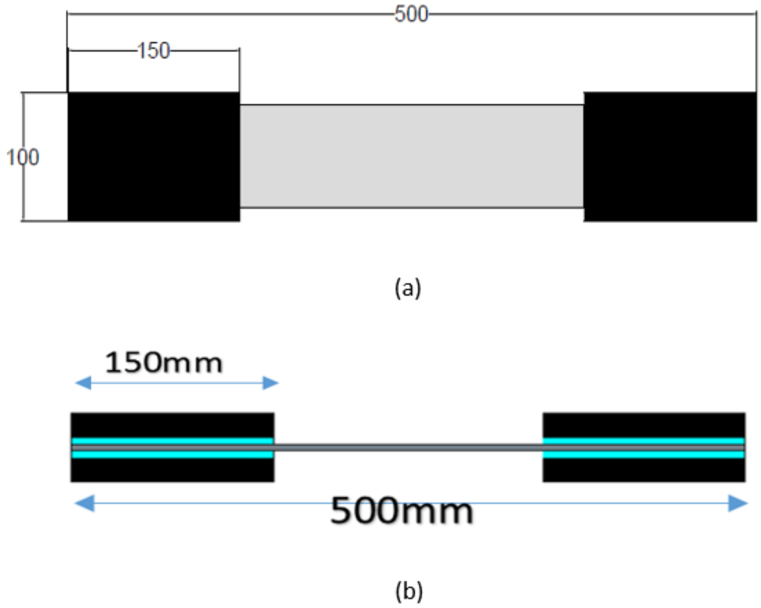


Figure 3.6: Schematic Diagram

Figure 3.7: Tension test Sample

Figure 3.8: Test Setup for SSWM

3.3.2 Result and Discussion

The tensile test result calculation is shown in Table 3.4 and the Stress vs Strain and Load vs Deflection graph are shown in Fig. 3.9 and 3.10.

Table 3.4: Calculation of Tensile Test

No.	Wire mesh Properties	SSWM		Unit	Remarks
1	Wire mesh type	40		-	
2	Width of mesh	100		mm	
3	Thickness of mesh	0.25		mm	
4	No. of wires	158			
5	C/s of wire	0.049		mm^2	
6	Total C/s area mesh	7.75		mm^2	4×5
7	Load Reading	Specimen-1 570	Specimen-2 630	kgf kgf	
8	Load Reading	Specimen-1 5591.7	Specimen-2 6180.3	N N	
9	Average Load	5886		N	
10	Average Ultimate tensile strength of wire	758.91		N/mm^2	9/6
11	Average Ultimate tensile strength of mesh	235.4		N/mm^2	9/(2×3)
12	Average elongation of wire mesh	13.58		mm	
13	Rupturee strain	0.048		mm/mm	

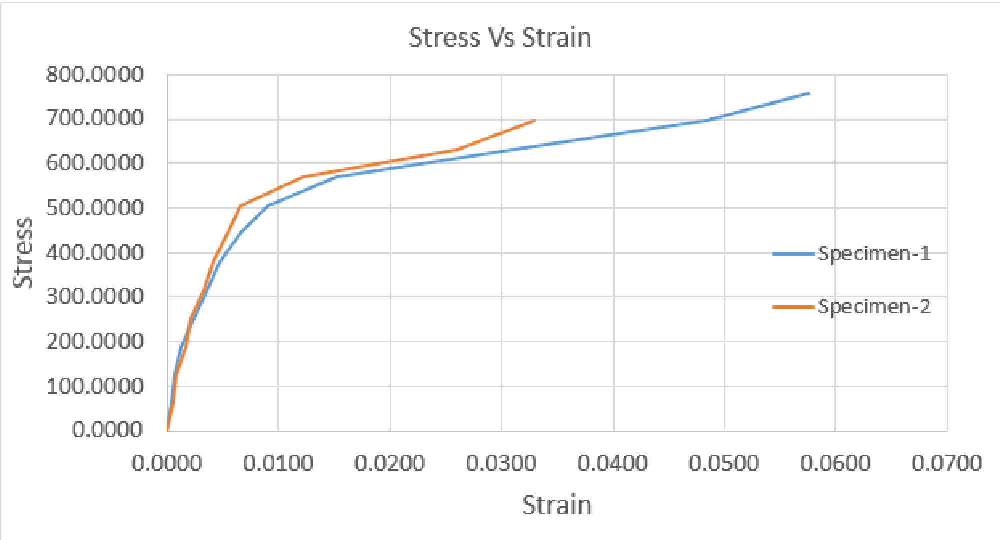


Figure 3.9: Stress Vs Strain

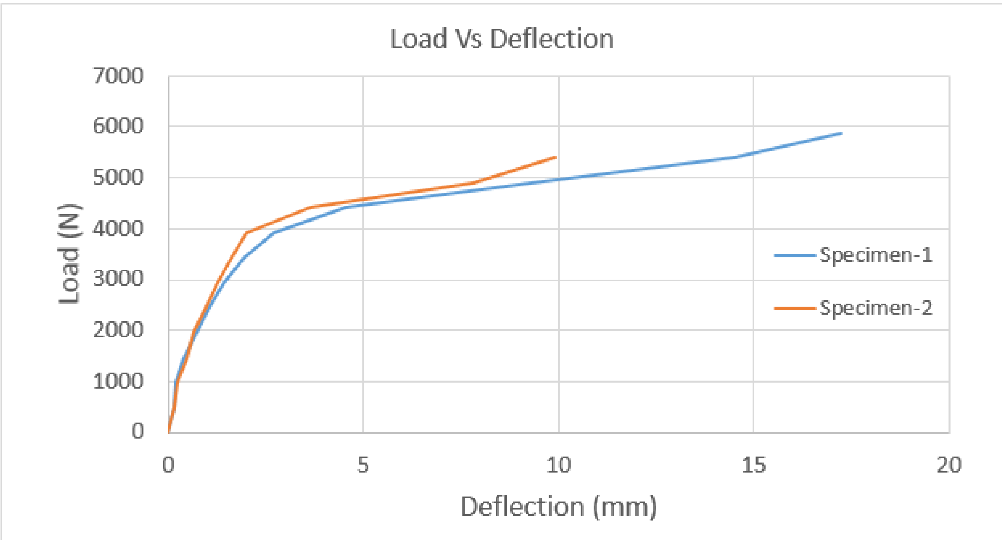


Figure 3.10: Load Vs Deflection

Composite Wire Mesh (CWM):

For making of Composite wire mesh, the mesh in the size of 10 mm × 500 mm was cut. Mixed of the Sikadur 30 LP in the proper proportion. Coated the both side of the mesh with Sikadur 30 LP with uniform thickness. After the setting of material on the mesh, fixed the two ends in the steel plates with the same Sikadur 30 LP material. The test result has shown in following Table 3.5 and Stress vs Strain and Load vs Deflection graph are shown in Fig. 3.11 and 3.12.

Table 3.5: Tensile Test of Composite Wire Mesh

1	Type of Mesh	**40 x 32**		Units	Remarks
2	Size of opening	0.365		mm	
3	Dia of wire	0.25		mm	
4	Width of mesh	100		mm	
5	No of wires	158		No.	
6	C/s Area of one wire	0.049087385		mm^2	
7	Thickness of mesh	1.61	1.34	mm	
8	Total c/s Area	161	134	mm	4×7
		Specimen-1	Specimen-2		
9	Load (kgf)	610	560	kgf	
10	Load (N)	5984.1	5493.6	N	
11	Avg ultimate TS of CWM	37.2	41.0	N/mm^2	10/7
12	Avg elongation of CWM	14.68		mm	
13	Repture strain (l/L)	0.073		mm/mm	

The Composite wrap was tested for tensile strength in UTM. The results shown in Table 3.5. It has been found that average ultimate tensile strength of composite is found less than SSWM due to increase in thickness of composite wire mesh but Epoxy thickness has not contributed to tensile strength of SSWM. It has been used only to bond the wire mesh to the concrete surface.

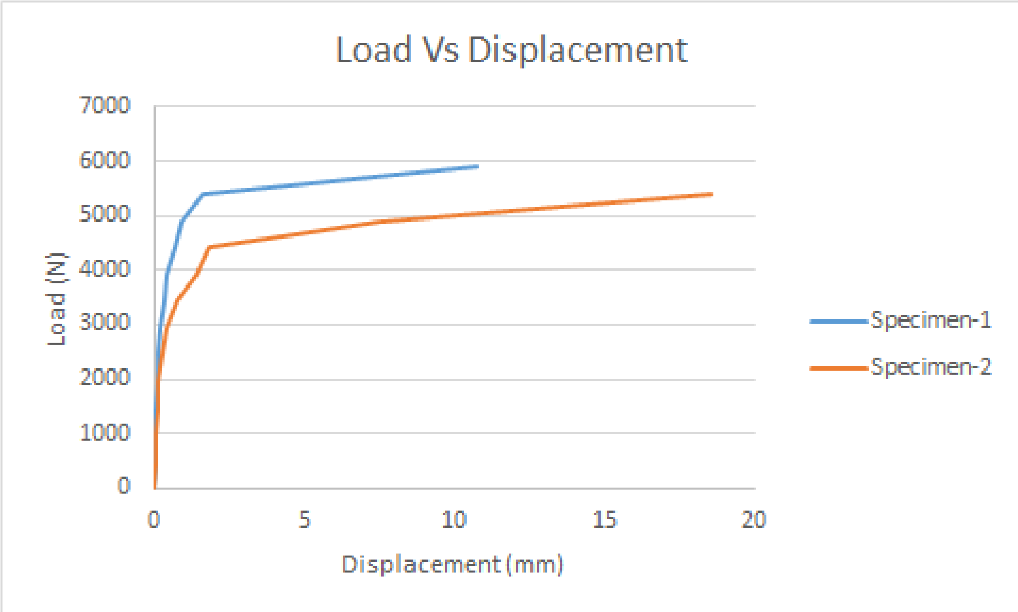


Figure 3.11: Load Vs Displacement (Composite Wire Mesh)

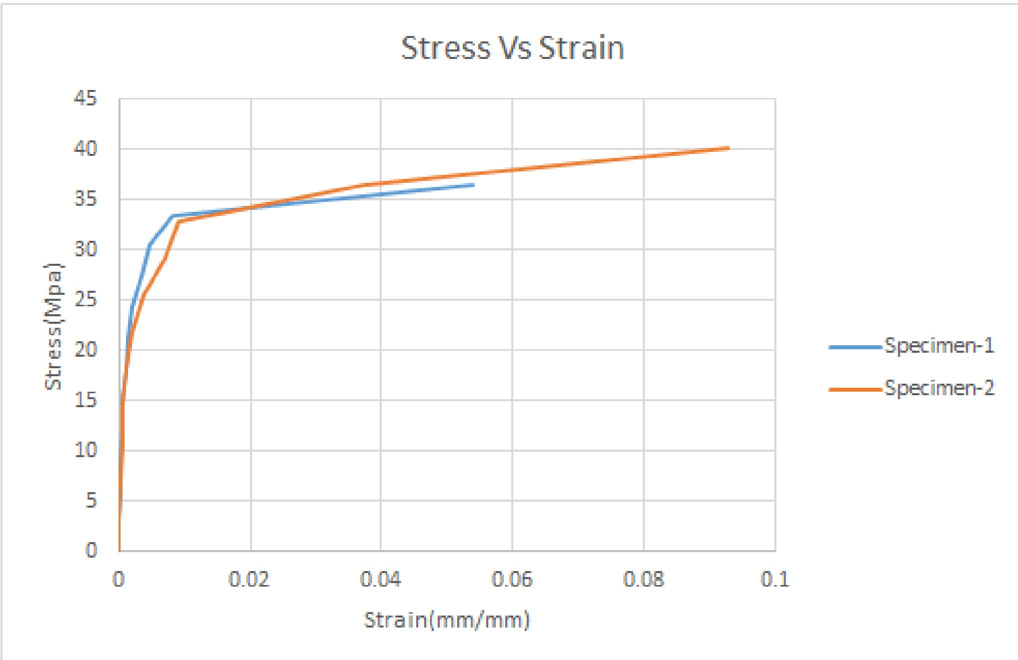


Figure 3.12: Stress Vs Strain (Composite Wire Mesh)

3.4 Bond behaviour of SSWM

Direct tension test gave behavior of wrapping and how it fail either in tension failure or de-bonding of wrapping. A loading frame was fabricated to apply direct tension on the specimen. Universal Testing Machine (UTM) was 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. Due to two individual specimens concrete tensile strength did not come in the picture.

3.4.1 Specimen Preparation

From tensile test of dumbbell shaped specimen, the bond between SSWM and Concrete surface can be found out. Total 3 specimens of M25 grade of concrete were cast for the Bond test of SSWM as shown in Fig. 3.14. MasterBrace [3500 & 4500] and Sikadur 30LP are used for bonding mesh to the dumbbell shaped concrete specimens. Formwork of Dumbbell shape specimen is shown in Fig. 3.13.

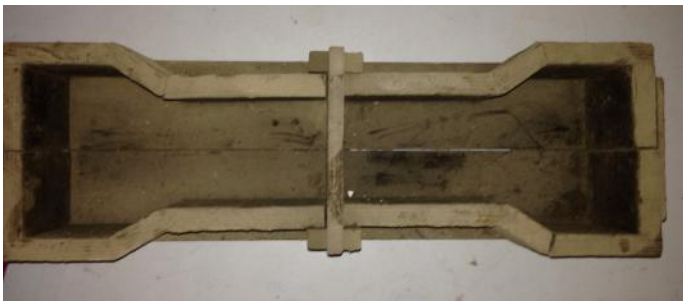


Figure 3.13: Dumbbell Shape Mould

3.4.2 MasterBrace 3500 and MasterBrace 4500

The dumbbell shape specimen were tested under compression loads which was converted into tensile load by the special equipment used. The test results are shown in Table 3.6. The stress vs strain and load vs deflection diagram of the test were shown in Fig. 3.16 and 3.17.

a. First grinding the surface of dumbbell shape concrete specimens.

b. Applied of MasterBrace 3500 (Part A and Part B) in proportion of 1.67 : 1 by weight on Dumbbell surface as shown in Fig. 3.14. Followed by one day curing.

c. After a day, applied coat of saturant MasterBrace 4500 (Part A and Part B) in proportion of 2 :1 by weight followed by 7 days curing time.

Figure 3.14: Coat of Primer

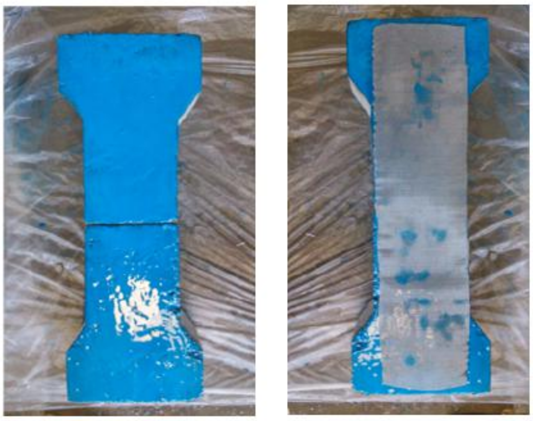


Figure 3.15: Coat of Saturant

Table 3.6: Calculation of Bond Strength with MasterBrace

1	Wire mesh type	40×32		
2	Size of Opening	0.365		mm
3	Diameter of Opening	0.25		mm
4	Width of Mesh	100		mm
5	No. of wires	158		
6	C/s of wire	0.0491		mm^2
7	Total C/s area of mesh	7.76		mm^2
		Specimen-1	**Specimen-2**	
8	Load	1150	1050	kgf
9	Load	11281.5	10300.5	N
10	Half Load on each side of Dumbbell	5640.75	5150.25	N
11	Bond Strength	727.11	663.88	N/mm^2
12	Average TS	695.49		N/mm^2

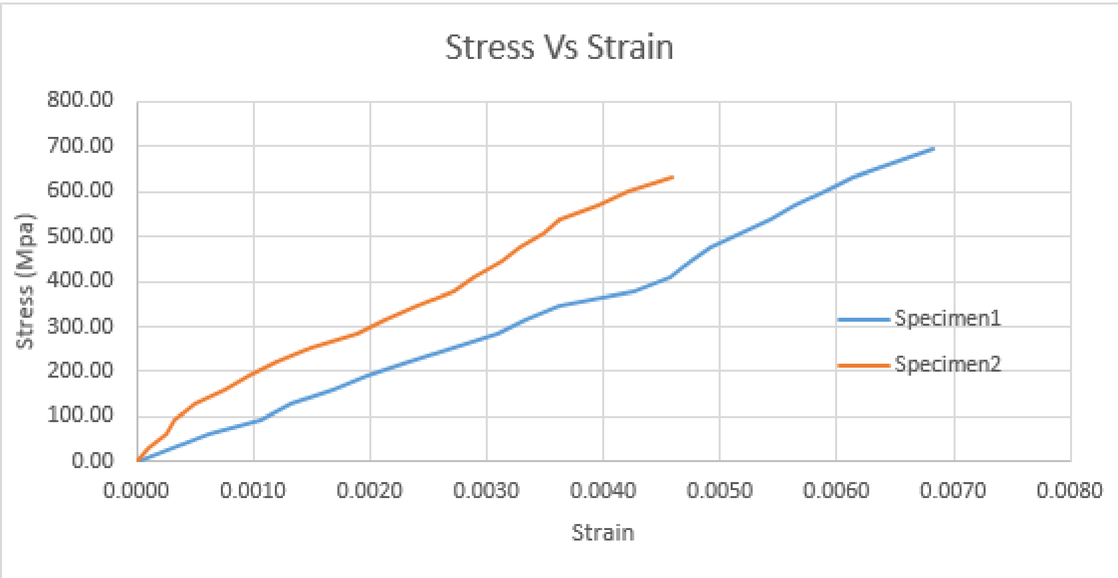


Figure 3.16: Stress Vs Strain (Bond Test)[MasterBrace]

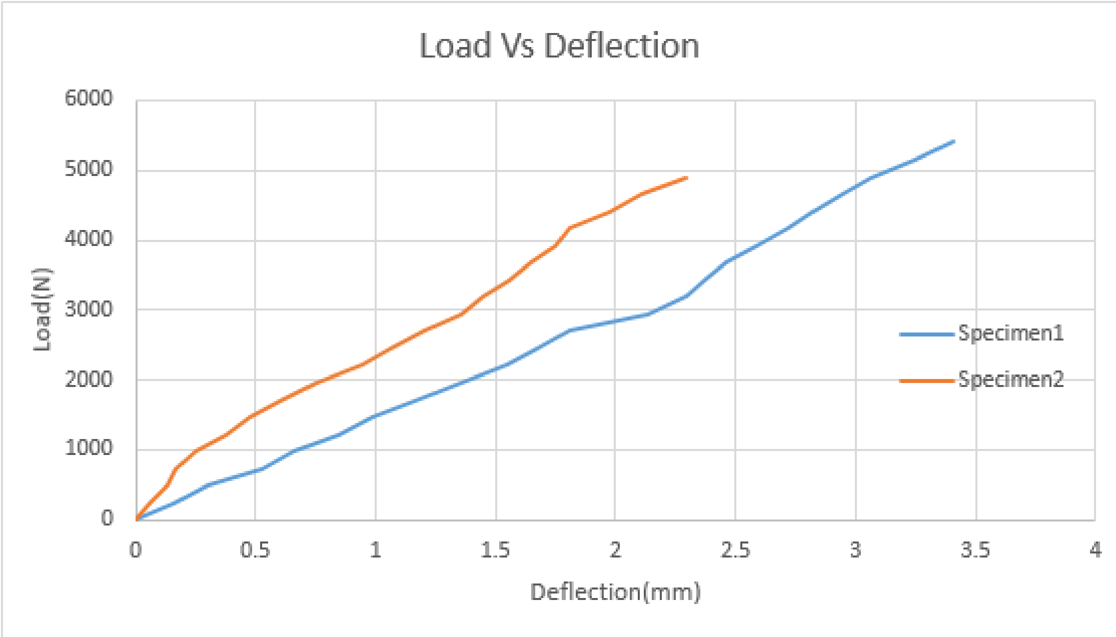


Figure 3.17: Load Vs Deflection(Bond Test)[MasterBrace]

3.4.3 Sikadur 30LP

The dumbbell shaped specimen were also prepared using Sikadur 30LP and tested in UTM. The results are shown in Table 3.7. The stress vs strain and load vs deflection diagram of the test were shown in Fig. 3.19 and 3.20.

a. First grinding the surface of dumbbell shape concrete specimen.

b. Now apply of Sikadur 30LP (Part A and Part B) in proportion of 3 : 1 by weight mixing and apply coat of mixture on Dumbbell surface. And place for seven days ambient curing.

Figure 3.18: Dumbbell wraped with Sikadur 30LP

Table 3.7: Calculation of Bond Strength with Sikadur 30LP

1	Wire mesh No.	40X32		type
2	Size of Opening	0.365		mm
3	Diameter of Wire	0.25		mm
4	Width of mesh	100		mm
5	No. of wire	158		
6	C/s of one wire	0.0491		mm^2
7	Total c/s area	7.7578		mm^2
		Specimen-1	**Specimen-2**	
8	Load	1250	1400	kgf
9	Load	12262.5	13734	N
10	Half load on each side	6131.25	6867	N
11	Tensile strength	790.33	885.17	N/mm^2
12	Average TS	837.75		N/mm^2

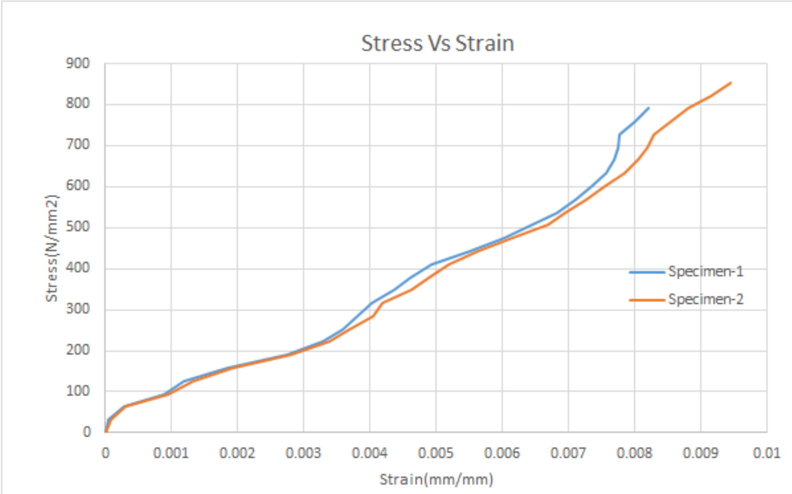


Figure 3.19: Stress Vs Strain (Bond Test)[Sikadur 30LP]

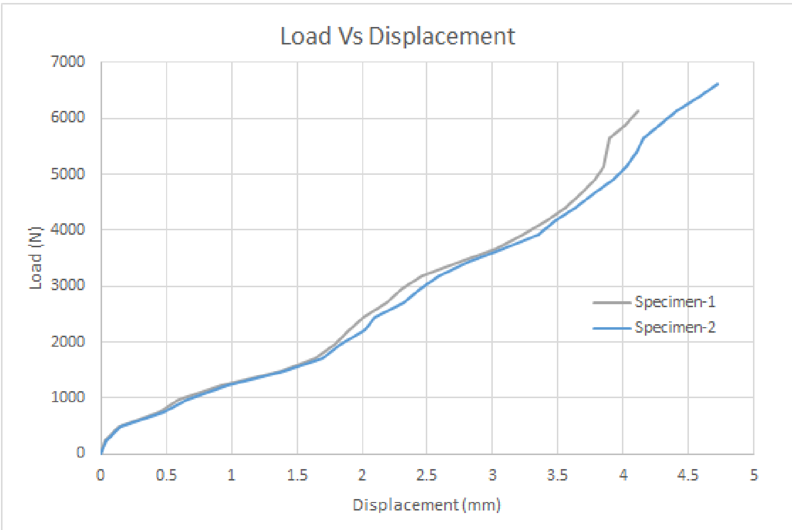


Figure 3.20: Load Vs Deflection(Bond Test)[Sikadur 30LP]

From the bond test carried out with MasterBrace and Sikadur 30 LP, it has been found that failure strength is 790.33 MPa and 885.1 MPa for repectively two specimens in case of Sikadur 30LP, corrosponding failure strength 727.11 MPa and 663.88 MPa in case of MaterBrace. It was also observed that failure of MasterBrace was due to debonding and not due to failure of mesh in both specimens. On this basis it was decided to use Sikadur 30 LP as bonding material to wrap column specimens due to its high bond strength.

3.5 Concrete Mix Design

Cylinder columns specimens were cast in three different grades of concrete (M15, M20 and M25). The mix design of concrete as shown in table. The mix design of concrete done as per IS 10262: 2009. Three cubes of 150mm x 150mm x 150mm were prepared for each batch of concrete prepare for casting of column specimens.

3.5.1 M15 Grade

In Table 3.8 the mix design of M15 grade concrete was shown. For finding the compressive strength of M15 grade concrete, 3 cubes were cast and test. The results of the compressive strength was shown in Table 3.9. In Fig. 3.21 the CTM was shwon, in which cubes were tested.

Figure 3.21: 28 Days Strength M-15 Grade Concrete

Table 3.8: Mix Design of M15 grade Concrete

Spevific Gravity of Cement	3.15
Spevific Gravity of C.A	2.71
Spevific Gravity of F.A	2.66
Zone of Aggregate	2
Cement OPC-53	318 kg/m^3
Fine Aggregate	715.9 kg/m^3
Coarse Aggregate	1190 kg/m^3
Water	191 $liter/m^3$
W/C Ratio	0.6

Table 3.9: Cube Strength (M-15)

Strength (MPa)	Cube-1	Cube-2	Cube-3	Average
28-days	21.78	22.22	21.78	21.92

3.5.2 M20 Grade

In Table 3.10 the mix design of M20 grade concrete was shown. For finding the compressive strength of M20 grade concrete, 3 cubes were cast and test. The results of the compressive strength was shown in Table 3.11. In Fig. 3.22 the CTM was shwon, in which cubes were tested.

Figure 3.22: 28 Days Strength of M-20 Grade

Table 3.10: Mix Design of M20 grade

Spevific Gravity of Cement	3.15
Spevific Gravity of C.A	2.71
Spevific Gravity of F.A	2.66
Zone of Aggregate	2
Cement OPC-53	346.45 kg/m^3
Fine Aggregate	688.41 kg/m^3
Coarse Aggregate	1194.19 kg/m^3
Water	191 $liter/m^3$
W/C Ratio	0.55

Table 3.11: Cube Strength (M-20)

Strength (MPa)	Cube-1	Cube-2	Cube-3	Average
28-days	26.67	27.1	26.67	26.81

3.5.3 M25 Grade

In Table 3.12 the mix design of M25 grade concrete was shown. For finding the compressive strength of M25 grade concrete, 3 cubes were cast and test. The results of the compressive strength was shown in Table 3.13. In Fig. 3.23 the CTM was shwon, in which cubes were tested.

Figure 3.23: 28 days Cube Strength (M25)

Table 3.12: Mix Design of M25 grade

Spevific Gravity of Cement	3.15
Spevific Gravity of C.A	2.71
Spevific Gravity of F.A	2.66
Zone of Aggregate	2
Cement OPC-53	383.16 kg/m^3
Fine Aggregate	657.66 kg/m^3
Coarse Aggregate	1191.15 kg/m^3
Water	191.58 $liter/m^3$
W/C Ratio	0.50

Table 3.13: Cube Strength (M-25)

Strength (MPa)	Cube-1	Cube-2	Cube-3	Average
28-days	31.78	31.55	31.11	31.48

3.6 Casting of Specimens

Total 54 Column Specimens were cast in the laboratory. Three different heights of column specimens were cast 400 mm,800 mm and 1200 mm with all of 200 mm diameter column.

3.6.1 Column Specimens

The following Flowchart shows the various aspects that consider in casting shown in Fig. 3.24.

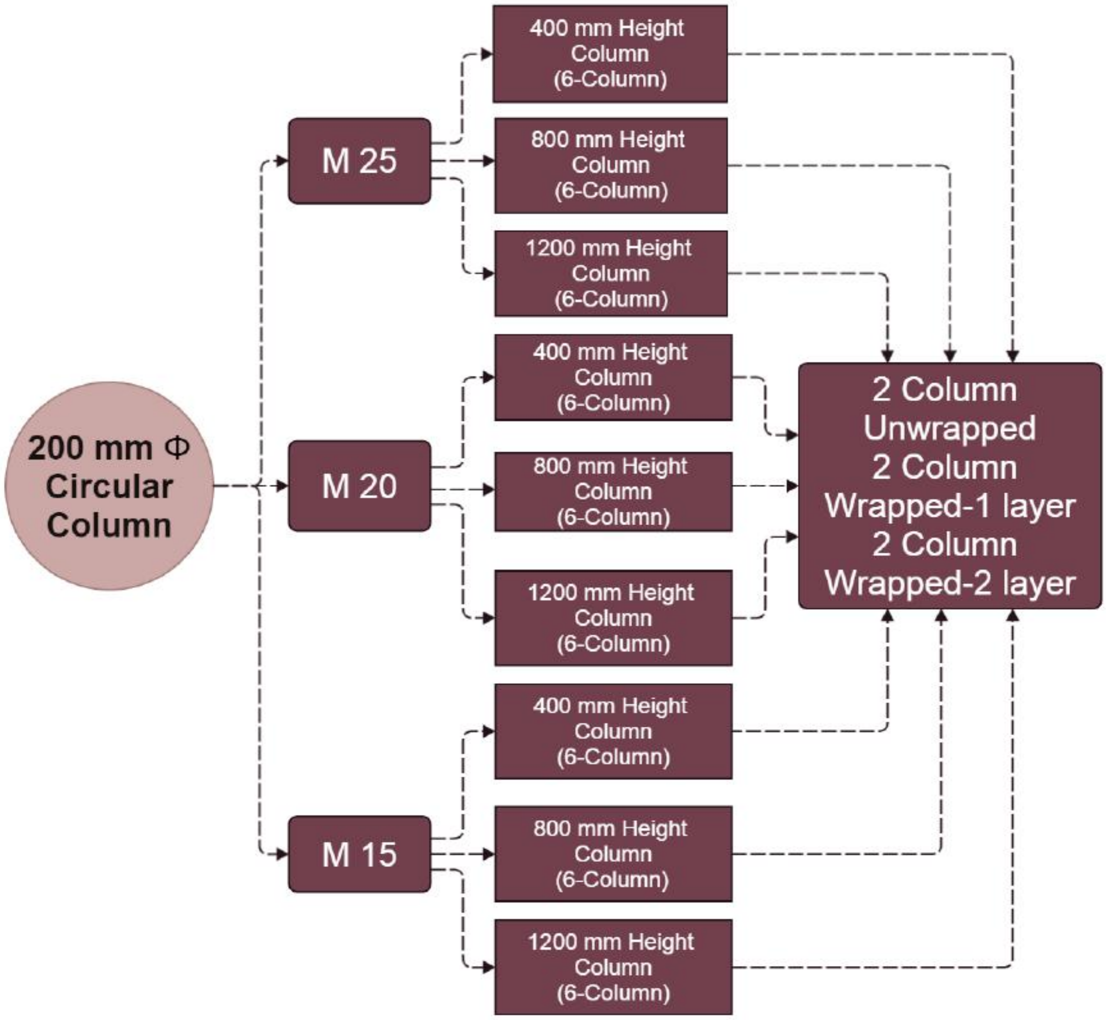


Figure 3.24: Flowchart of Column Specimens

3.6.2 Procedure for Strengthening of Column

Strengthening of column was done by wrapping of SSWM on column with the Sikadur 30 LP material. According the Bond test, the bond strength of Sikadur 30LP material with concrete was more as compared to the MasterBrace 3500 and MasterBrace 4500 material. So, Sikadur 30LP was used as the Bonding material. SSWM was wrapped on concrete columns after 28 days of curing. The step by step procedure of SSWM wrapping of column has been discussed below.

- Preparation of Surface
- Mixing of Material
- Cutting of Wire Mesh
- Applying of first coat
- Wrapping of SSWM
- Applying of Final Coat

a. **Preparation of Surface:** The most important required for any type of external strengthening is, that the surface of the specimens should be cleaned, smooth and even. Before application of SSWM proper surface preparation is required to have a good bond between the Concrete surface and SSWM as shown in Fig. 3.25. After 28 days of curing the concrete surface was cleaned with wire brush to remove all the loose dust particles.Grinding machine is used for grinding and cleaning the surface of column. Any voids on the surface of concrete are filled by the epoxy.

Figure 3.25: Cleaning of Surface and Grinding of Column

b. **Mixing of Material:** Sikadur 30LP is comes in two parts (A & B). The rasin and hardener is mixed in proportion of 3:1 (A:B). Mix parts A+B together for at least 3 minutes with a mixing spindle attached to a slow speed electric drill (max. 600 rpm) until the material becomes smooth in consistency and a uniform grey colour in Fig. 3.26. The potlife begins when the resin and hardener are mixed (Potlife-60 minute). It is shorter at high temperatures and longer at low temperatures. The greater the quantity mixed, the shorter the potlife.

Figure 3.26: Mixing of material

c. **Cutting of Wire Mesh:** The wire mesh was cut as per dimension of column with the help of scissor. For 400 mm height column, the wire mesh is cut in one piece,400 mm in height and in circumferential direction it is 629 mm in length plus 150 mm overlap length. For 800 mm height column, the wire mesh is cut in two piece of 400 mm in height and in circumferential direction it is 629 mm in length plus 150 mm overlap length. For 1200 mm height column, the wire mesh is cut in three piece, two piece of 500 mm in height and one piece of 200 mm in height, and in circumferential direction it is 629 mm in length plus 150 mm overlap length.

d. **Applying of First Coat:** Sikadur 30LP is now applied over the concrete surface with the help of plates as shown in Fig. 3.27.

Figure 3.27: Applying First Coat

e. **Wrapping of SSWM:** After the applying of first coat of Sikadur 30LP, wrapping of SSWM is done as shown in Fig. 3.28. For the best contact between wiremesh and concrete, the SSWM is held tight to concrete with the help of binding wire to make the contact proper without the air gaps in between wire mesh and concrete surface.

Figure 3.28: Wrapping of Mesh and Binding of Mesh

f. **Applying of Final Coat:** After binding of mesh some epoxy material comes out from the SSWM. For proper bond, a second coat of Sikadur 30LP was applied on mesh and finished smooth shown in Fig. 3.29.

Figure 3.29: FInal Coat

Figure 3.30: Wrapped Column Specimens

3.7 Test Setup and Instrumentation

Testing of columns were conducted on loading frame. The load was applied on columns by using hydraulic Jack of 2000 kN capacity. Figure 3.31 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. Main components of the test setup were as follows Fig. 3.31:

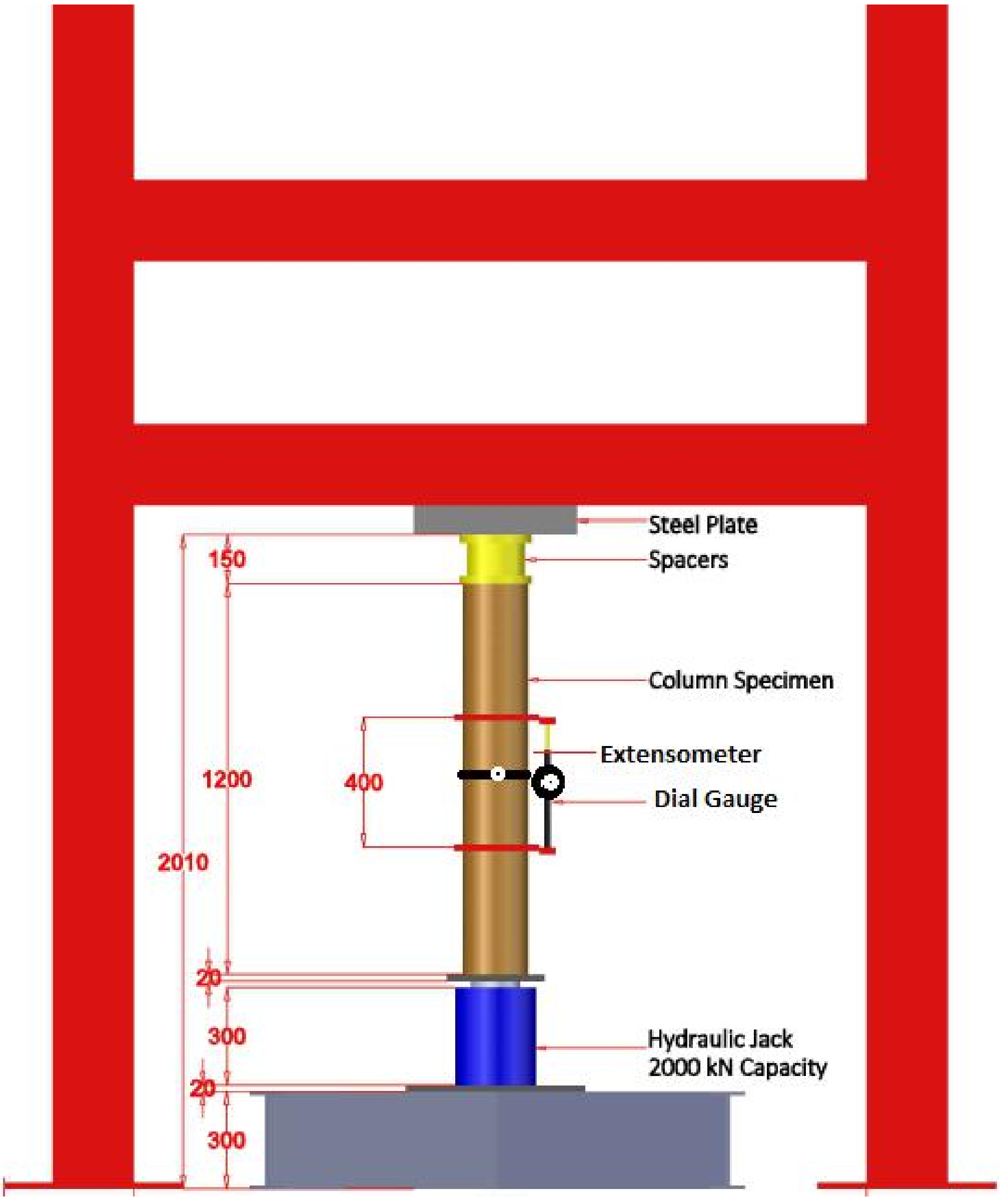


Figure 3.31: Test Setup

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

- **Hydraulic Jack:** Hydraulic jack of capacity of 2000 kN is used and its working is 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 ratio of Force to the 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 check. The following figure shows that the Hydraulic jack used for the appling axial load. Fig. 3.32

(a) Hydraulic Jack (b) Dial of 2000 kN

Figure 3.32: Hydraulic Jack

- **Linear Deflection Measurement:** It includes the stand on which we place the dial gauge to find the vertical deflection as seen in following Fig. 3.33. Least count of dial gauge is 0.01mm. The dial gauge fixed to the column with the help of steel frame for measuring axial deformation of column.

Figure 3.33: Dial gauge for vertical displacement

- **Lateral Strain Measurement:** In circular columns, the confinement of concrete is done by wrapping of SSWM on columns. So, for finding the confinement pressure lateral strain is required for measuring lateral strain extensometer as shown in the following Fig. 3.34 was used. When the axial load is applied on the column, the column tries to expand in the lateral direction. This leads to the expansion of circular ring. This increases the distance between the two wings which are connected to the circular ring. This increased distance is measured by the dial gauge.

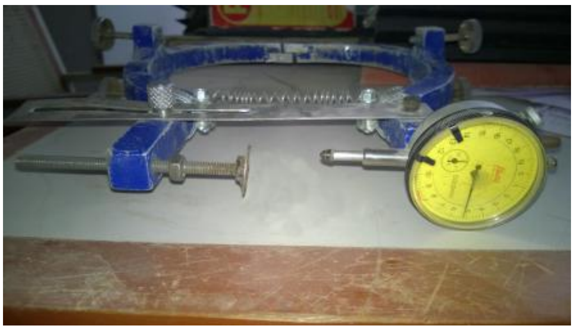


Figure 3.34: Extensometer

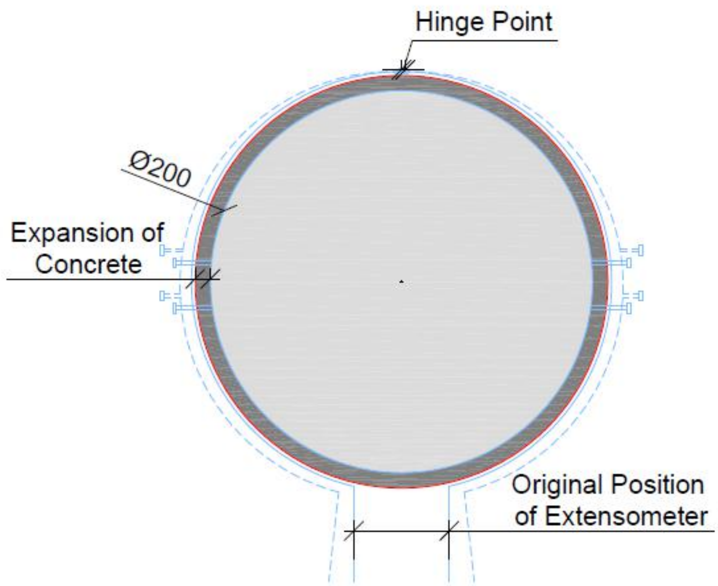


Figure 3.35: Extensometer Working Procedure

If the distances of the pivot hinge and the gauge from the vertical plane passing through the support points of the rotations are equal, the deformation of the specimen is equal to one-half the gauge reading [ASTM C 409-02]. If these distances are not equal, calculate the deformation as follows:

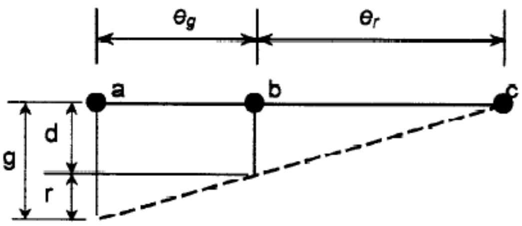


Figure 3.36: Graphical Presentation of working Extensometer

From figure,

d = $ge_r/(e_r + e_g)$

d = displacement due to specimen deformation

r = displacement due to rotation about the pivot rod

a = location of gauge

b = support point of the rotation

c = location of pivot rod

g = gauge reading

3.8 Summary

This Chapter contains the experimental setup with casting of column specimens and testing setup. Also tesnsile strength and bond strength of SSWM were considered in this chapter. Total 54 Column Specimens were cast. The variations were considered as grade of concrete (M15,M20 and M25), height of column (400mm, 800mm and 1200mm) and number of wrapping layers(unwrapped,1-layer and 2-layer).

Chapter 4

Result and Discussion

4.1 General

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

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

4.2 Notation of Columns

For discription of the columns, the following Table 4.1 shows the notation that given to the columns.

Table 4.1: Notation of Column

C400M15W0	Circular 400 mm Height M15 Grade Without Wrap
C400M15W1	Circular 400 mm Height M15 Grade 1-Layer Wrap
C400M15W2	Circular 400 mm Height M15 Grade 2-Layer Wrap
C800M15W0	Circular 800 mm Height M15 Grade Without Wrap
C800M15W1	Circular 800 mm Height M15 Grade 1-Layer Wrap
C800M15W2	Circular 800 mm Height M15 Grade 2-Layer Wrap
C1200M15W0	Circular 1200 mm Height M15 Grade Without Wrap
C1200M15W1	Circular 1200 mm Height M15 Grade 1-Layer Wrap
C1200M15W2	Circular 1200 mm Height M15 Grade 2-Layer Wrap
C400M20W0	Circular 400 mm Height M20 Grade Without Wrap
C400M20W1	Circular 400 mm Height M20 Grade 1-Layer Wrap
C400M20W2	Circular 400 mm Height M20 Grade 2-Layer Wrap
C800M20W0	Circular 800 mm Height M20 Grade Without Wrap
C800M20W1	Circular 800 mm Height M20 Grade 1-Layer Wrap
C800M20W2	Circular 800 mm Height M20 Grade 2-Layer Wrap
C1200M20W0	Circular 1200 mm Height M20 Grade Without Wrap
C1200M20W1	Circular 1200 mm Height M20 Grade 1-Layer Wrap
C1200M20W2	Circular 1200 mm Height M20 Grade 2-Layer Wrap
C400M25W0	Circular 400 mm Height M25 Grade Without Wrap
C400M25W1	Circular 400 mm Height M25 Grade 1-Layer Wrap
C400M25W2	Circular 400 mm Height M25 Grade 2-Layer Wrap
C800M25W0	Circular 800 mm Height M25 Grade Without Wrap
C800M25W1	Circular 800 mm Height M25 Grade 1-Layer Wrap
C800M25W2	Circular 800 mm Height M25 Grade 2-Layer Wrap
C1200M25W0	Circular 1200 mm Height M25 Grade Without Wrap
C1200M25W1	Circular 1200 mm Height M25 Grade 1-Layer Wrap
C1200M25W2	Circular 1200 mm Height M25 Grade 2-Layer Wrap

4.3 Ultimate Axial Strength of Column

All Column specimens are subjected to axial load with both end partially fixed. The load was applied from Jack until the specimen failed. During the loading linear deflection and lateral deflection were measured. Ultimate failure load for all columns are given in Tables 4.2 to 4.10. Ultimate axial load carrying capacity of two specimens are measured for finding average ultimate axial strength of columns.

M15 Grade Columns:

Table 4.2 represents the ultimate axial strength of C400M15W0 columns, C400M15W1 columns and C400M15W2 columns. Average ultimate axial strength of C400M15W0 column specimen increase from 530 kN to 630 kN with one layer of SSWM and further increase to 790kN with two layers of SSWM P.C.C.

Table 4.2: Ultimate Axial Strength of 400 mm Height M-15 Grade Column

Name of Column	Height of Column(mm)	No. of layers	Ultimate Axial Strenth of Column (kN)	Avg. Ultimate Axial Strenth of Column (kN)
C400M15W0	400	0	560	530
			500	
C400M15W1	400	1	620	630
			640	
C400M15W2	400	2	780	790
			800	

Table 4.3 represents the ultimate axial strength of C800M15W0 columns, C800M15W1 columns and C800M15W2 columns. Average ultimate axial strength of C800M15W0 column specimen increase from 480 kN to 760 kN with one layer of SSWM and further increase to 830kN with two layers of SSWM P.C.C.

Table 4.3: Ultimate Axial Strength of 800 mm Height M-15 Grade Column

Name of Column	Height of Column(mm)	No. of layers	Ultimate Axial Strenth of Column (kN)	Avg. Ultimate Axial Strenth of Column (kN)
C800M15W0	800	0	480	485
			490	
C800M15W1	800	1	800	760
			760	
C800M15W2	800	2	820	830
			840	

Table 4.4 represents the ultimate axial strength of C1200M15W0 columns, C1200M15W1 columns and C1200M15W2 columns. Average ultimate axial strength of C1200M15W0 column specimen increase from 500 kN to 805 kN with one layer of SSWM and further increase to 930kN with two layers of SSWM P.C.C.

Table 4.4: Ultimate Axial Strength of 1200 mm Height M-15 Grade Column

Name of Column	Height of Column(mm)	No. of layers	Ultimate Axial Strenth of Column (kN)	Avg. Ultimate Axial Strenth of Column (kN)
C1200M15W0	1200	0	500	500
			500	
C1200M15W1	1200	1	830	805
			780	
C1200M15W2	1200	2	960	930
			900	

M20 Grade Columns:

Table 4.5 represents the ultimate axial strength of C400M20W0 columns, C400M20W1 columns and C400M20W2 columns. Average ultimate axial strength of C400M20W0 column specimen increase from 620 kN to 705 kN with one layer of SSWM and further increase to 910kN with two layers of SSWM P.C.C.

Table 4.5: Ultimate Axial Strength of 400 mm Height M-20 Grade Column

Name of Column	Height of Column(mm)	No. of layers	Ultimate Axial Strenth of Column (kN)	Avg. Ultimate Axial Strenth of Column (kN)
C400M20W0	400	0	620	620
			620	
C400M20W1	400	1	710	705
			720	
C400M20W2	400	2	900	910
			920	

Table 4.6 represents the ultimate axial strength of C800M20W0 columns, C800M20W1 columns and C800M20W2 columns. Average ultimate axial strength of C800M20W0 column specimen increase from 660 kN to 970 kN with one layer of SSWM and further increase to 1105 kN with two layers of SSWM P.C.C.

Table 4.6: Ultimate Axial Strength of 800 mm Height M-20 Grade Column

Name of Column	Height of Column(mm)	No. of layers	Ultimate Axial Strenth of Column (kN)	Avg. Ultimate Axial Strenth of Column (kN)
C800M20W0	800	0	640	660
			680	
C800M20W1	800	1	960	970
			980	
C800M20W2	800	2	1100	1105
			1110	

Table 4.7 represents the ultimate axial strength of C1200M20W0 columns, C1200M20W1 columns and C1200M20W2 columns. Average ultimate axial strength of C1200M20W0 column specimen increase from 610 kN to 940 kN with one layer of SSWM and further increase to 1040 kN with two layers of SSWM P.C.C.

Table 4.7: Ultimate Axial Strength of 1200 mm Height M-20 Grade Column

Name of Column	Height of Column(mm)	No. of layers	Ultimate Axial Strenth of Column (kN)	Avg. Ultimate Axial Strenth of Column (kN)
C1200M20W0	1200	0	600	610
			620	
C1200M20W1	1200	1	980	940
			900	
C1200M20W2	1200	2	1060	1040
			1020	

M25 Grade Columns:

Table 4.8 represents the ultimate axial strength of C400M25W0 columns, C400M25W1 columns and C400M25W2 columns. Average ultimate axial strength of C400M25W0 column specimen increase from 800 kN to 920 kN with one layer of SSWM and further increase to 1110 kN with two layers of SSWM P.C.C.

Table 4.8: Ultimate Axial Strength of 400 mm Height M-25 Grade Column

Name of Column	Height of Column(mm)	No. of layers	Ultimate Axial Strenth of Column (kN)	Avg. Ultimate Axial Strenth of Column (kN)
C400M25W0	400	0	820	800
			780	
C400M25W1	400	1	900	920
			940	
C400M25W2	400	2	1100	1110
			1120	

Table 4.9 represents the ultimate axial strength of C800M25W0 columns, C800M25W1 columns and C800M25W2 columns. Average ultimate axial strength of C800M25W0 column specimen increase from 810 kN to 1050 kN with one layer of SSWM and further increase to 1230 kN with two layers of SSWM P.C.C.

Table 4.9: Ultimate Axial Strength of 800 mm Height M-25 Grade Column

Name of Column	Height of Column(mm)	No. of layers	Ultimate Axial Strenth of Column (kN)	Avg. Ultimate Axial Strenth of Column (kN)
C800M25W0	800	0	820	810
			800	
C800M25W1	800	1	1100	1050
			1000	
C800M25W2	800	2	1260	1230
			1200	

Table 4.10 represents the ultimate axial strength of C1200M25W0 columns, C1200M25W1 columns and C1200M25W2 columns. Average ultimate axial strength of C1200M25W0 column specimen increase from 790 kN to 1060 kN with one layer of SSWM and further increase to 1240 kN with two layers of SSWM P.C.C.

Table 4.10: Ultimate Axial Strength of 1200 mm Height M-25 Grade Column

Name of Column	Height of Column(mm)	No. of layers	Ultimate Axial Strenth of Column (kN)	Avg. Ultimate Axial Strenth of Column (kN)
C1200M25W0	1200	0	780	790
			800	
C1200M25W1	1200	1	1020	1060
			1100	
C1200M25W2	1200	2	1240	1240
			-	

Average ultimate axial strength has been considered for finding the percentage(%) increase strength with respect to control column specimens. Higher load carrying capacity of column is observed in circular SSwM wrapped columns with respect to the control P.C.C. columns. Comparison of experimental results are shown in tables 4.11 to 4.13. This represents comparison of experimental ultimate axial strength of circular P.C.C. columns and SSWM wrapped columns. In this table last column presents percentage strength increase with respect to control column. For each grade of concrete and for the same height of column the percentage increment were shown in following tables which were respectively without wrapping, 1 layer wrapping and 2 layer wrapping.

M15 Grade Concrete:

- C400M15W0, the load carrying capacity increase with one layer of SFRP up to 19% and further increase with two layers of SFRP up to 49%.
- C800M15W0, the load carrying capacity increase with one layer of SFRP up to 61% and further increase with two layers of SFRP up to 71%.
- C1200M15W0, the load carrying capacity increase with one layer of SFRP up to 61% and further increase with two layers of SFRP up to 86%.

Table 4.11: Comparison of Axial Strength(M-15 Grade) with respect to Layer of SFRP

Circular M-15 P.C.C Column				
Height of Column(mm)	No of SSWM layer	Experimental Value (kN)	Strength Increase (%)	Relative Strength
400	0	530		
	1	630	19	
	2	790	49	25.39
800	0	485		
	1	780	61	
	2	830	71	6.41
1200	0	500		
	1	805	61	
	2	930	86	15.52

M20 Grade Concrete:

- C400M20W0, the load carrying capacity increase with one layer of SFRP up to 15% and further increase with two layers of SFRP up to 47%.
- C800M20W0, the load carrying capacity increase with one layer of SFRP up to 47% and further increase with two layers of SFRP up to 67%.
- C1200M20W0, the load carrying capacity increase with one layer of SFRP up to 54% and further increase with two layers of SFRP up to 70%.

Table 4.12: Comparison of Axial Strength(M-20 Grade) with respect to Layer of SFRP

Circular M-20 P.C.C Column				
Height of Column(mm)	No of SSWM layer	Experimental Value (kN)	Strength Increase (%)	Relative Strength
400	0	620		
	1	715	15	
	2	910	47	27.27
800	0	660		
	1	970	47	
	2	1105	67	14
1200	0	610		
	1	940	54	
	2	1040	70	10.63

M25 Grade Concrete:

- C400M25W0, the load carrying capacity increase with one layer of SFRP up to 15% and further increase with two layers of SFRP up to 39%.
- C800M25W0, the load carrying capacity increase with one layer of SFRP up to 30% and further increase with two layers of SFRP up to 52%.
- C1200M25W0, the load carrying capacity increase with one layer of SFRP up to 34% and further increase with two layers of SFRP up to 57%.

Table 4.13: Comparison of Axial Strength(M-25 Grade) with respect to Layer of SFRP

Circular M-25 P.C.C Column				
Height of Column(mm)	No of SSWM layer	Experimental Value (kN)	Strength Increase (%)	Relative Strength
400	0	800		
	1	920	15	
	2	1110	39	20.65
800	0	810		
	1	1050	30	
	2	1230	52	17.14
1200	0	790		
	1	1060	34	
	2	1240	57	17

According to the experimental work the higher load carrying capacity of columns is observed in circular SSWM wrapped columns with respect to the control P.C.C. columns. In experimental work three heights of column were taken for knowing the effect of load carrying capacity of columns according to its height. Following tables 4.14 to 4.16 shown the results in percentage increment in axial strength of columns according to the slenderness aspect.

M-15 Grade of Concrete: In case of control column with increase in height of column, from 400 mm to 800 mm the strength decrease by 8% , with increase in height from 400 mm to 1200 mm , the decrement in strength is 6%. In case of wrapped column with one layer, increase in height of column, from 400 mm to 800 mm the strength increase by 24% , with increase in height from 400 mm to 1200 mm , the decrement in strength is 28%. In case of wrapped column with two layer, increase in height of column, from 400 mm to 800 mm the strength decrease by 5% , with increase in height from 400 mm to 1200 mm , the decrement in strength is 18%.

Table 4.14: Comparison of axial strength of M15 Grade Column

Circular M-15 P.C.C Column				
Name of Column	Height of Column(mm)	No of SSWM layer	Experimental Value (kN)	Strength Increase (%)
C400M15W0	400	0	530	
C800M15W0	800		485	-8
C1200M15W0	1200		500	-6
C400M15W1	400	1	630	
C800M15W1	800		780	24
C1200M15W1	1200		805	28
C400M15W2	400	2	790	
C800M15W2	800		830	5
C1200M15W2	1200		930	18

M-20 Grade of Concrete: In case of control column with increase in height of column, from 400 mm to 800 mm the strength increse by 6% , with increase in height from 400 mm to 1200 mm , the decrement in strength is 2%. In case of wrapped column with one layer, increase in height of column, from 400 mm to 800 mm the strength increase by 36% , with increase in height from 400 mm to 1200 mm , the decrement in strength is 31%. In case of wrapped column with two layer, increase in height of column, from 400 mm to 800 mm the strength decrease by 21% , with increase in height from 400 mm to 1200 mm , the decrement in strength is 14%.

Table 4.15: Comparison of axial strength of M20 Grade Column

Circular M-20 P.C.C Column				
Name of Column	Height of Column(mm)	No of SSWM layer	Experimental Value (kN)	Strength Increase (%)
C400M20W0	400	0	620	
C800M20W0	800		660	6
C1200M20W0	1200		610	-2
C400M20W1	400	1	715	
C800M20W1	800		970	36
C1200M20W1	1200		940	31
C400M20W2	400	2	910	
C800M20W2	800		1105	21
C1200M20W2	1200		1040	14

M-25 Grade of Concrete: In case of control column with increase in height of column, from 400 mm to 800 mm the strength increse by 1% , with increase in height from 400 mm to 1200 mm , the decrement in strength is 1%. In case of wrapped column with one layer, increase in height of column, from 400 mm to 800 mm the strength increase by 14% , with increase in height from 400 mm to 1200 mm , the decrement in strength is 15%. In case of wrapped column with two layer, increase in height of column, from 400 mm to 800 mm the strength decrease by 11% , with increase in height from 400 mm to 1200 mm , the decrement in strength is 12%.

Table 4.16: Comparison of axial strength of M25 Grade Column

Circular M-25 P.C.C Column				
Name of Column	Height of Column(mm)	No of SSWM layer	Experimental Value (kN)	Strength Increase (%)
C400M25W0	400	0	800	
C800M25W0	800		810	1
C1200M25W0	1200		790	-1
C400M25W1	400	1	920	
C800M25W1	800		1050	14
C1200M25W1	1200		1060	15
C400M25W2	400	2	1110	
C800M25W2	800		1230	11
C1200M25W2	1200		1240	12

Graphical representation of comparison of Axial load carrying capacity of column with respect to the number of layer wrapping done on column is shown in Fig. 4.1 to 4.3.

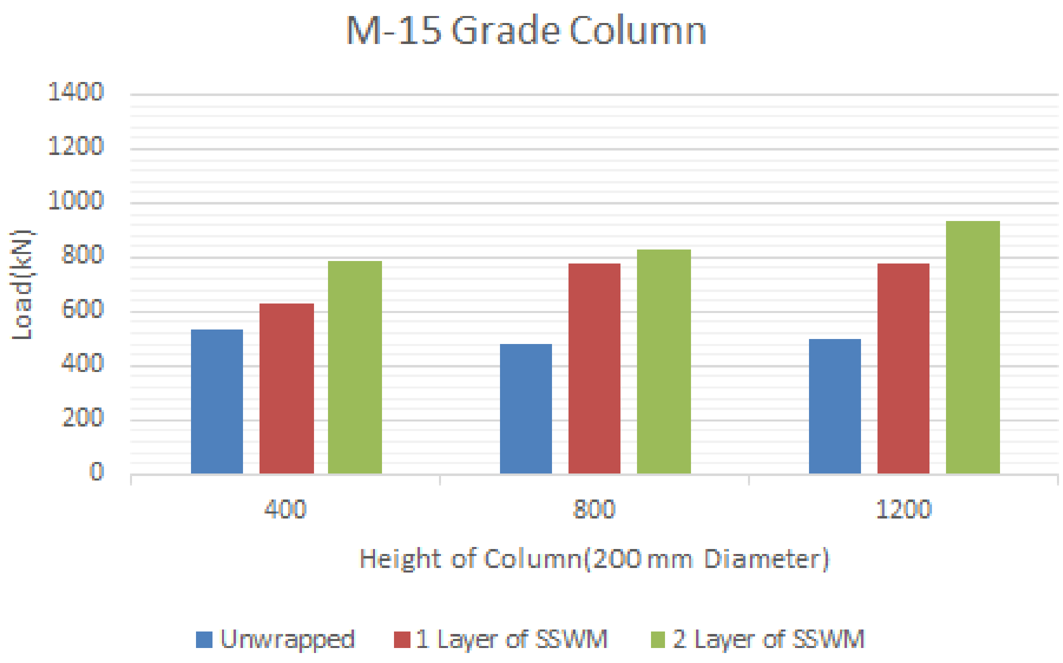


Figure 4.1: Comparison of Axial strength in Column (M-15)

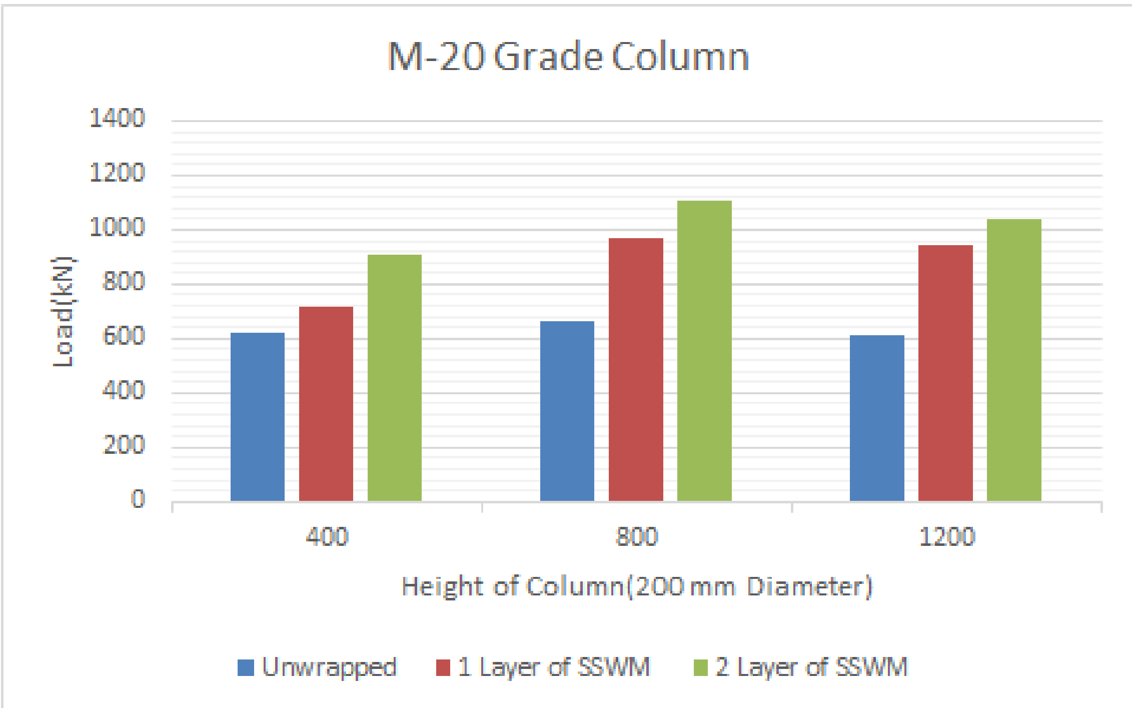


Figure 4.2: Comparison of Axial strength in Column (M-20)

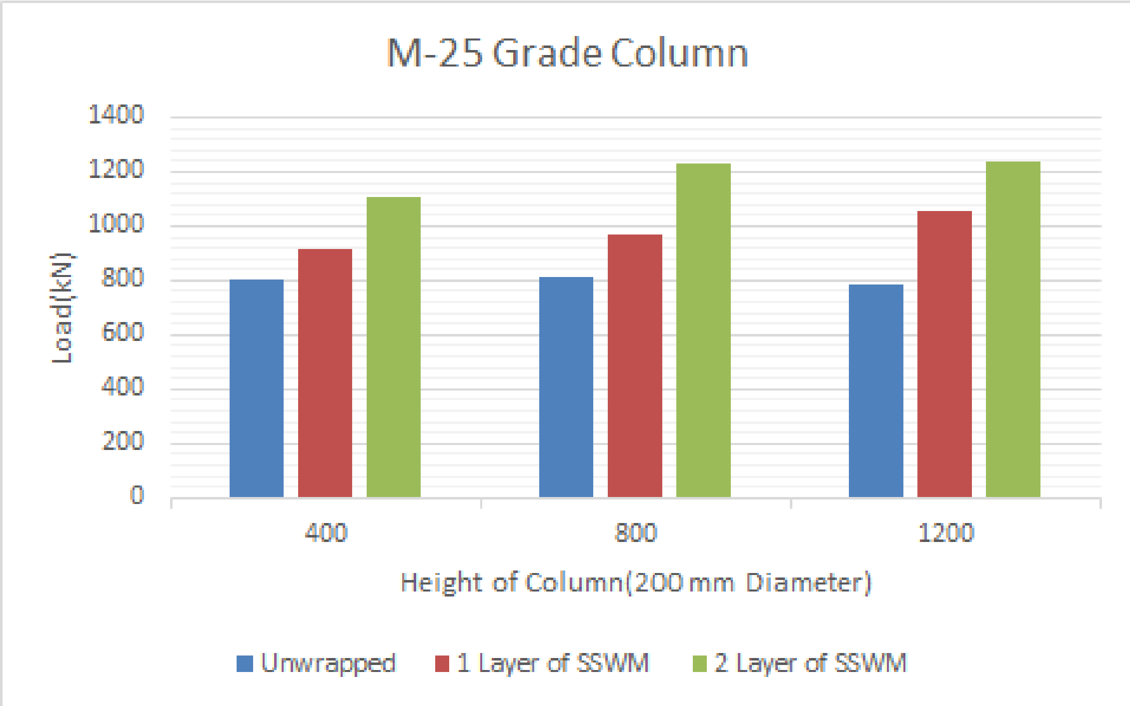


Figure 4.3: Comparison of Axial strength in Column (M-25)

Graphical representation of comparison of Axial load carrying capacity of column with respect to the height and number of layer wrapping done on column is shown in Fig. 4.4 to 4.6.

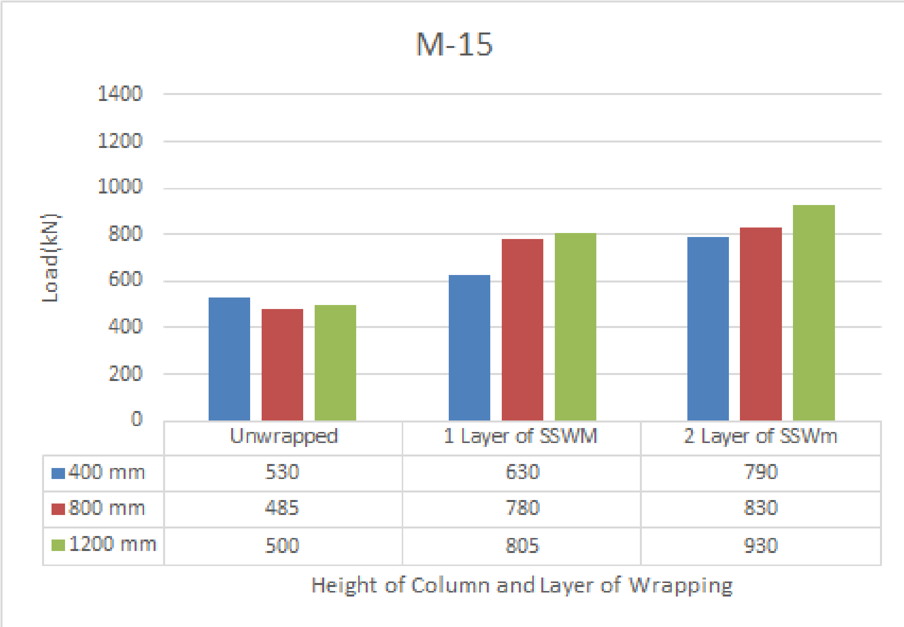


Figure 4.4: Comparison of Axial strength with respect to Height of Column(M-15)

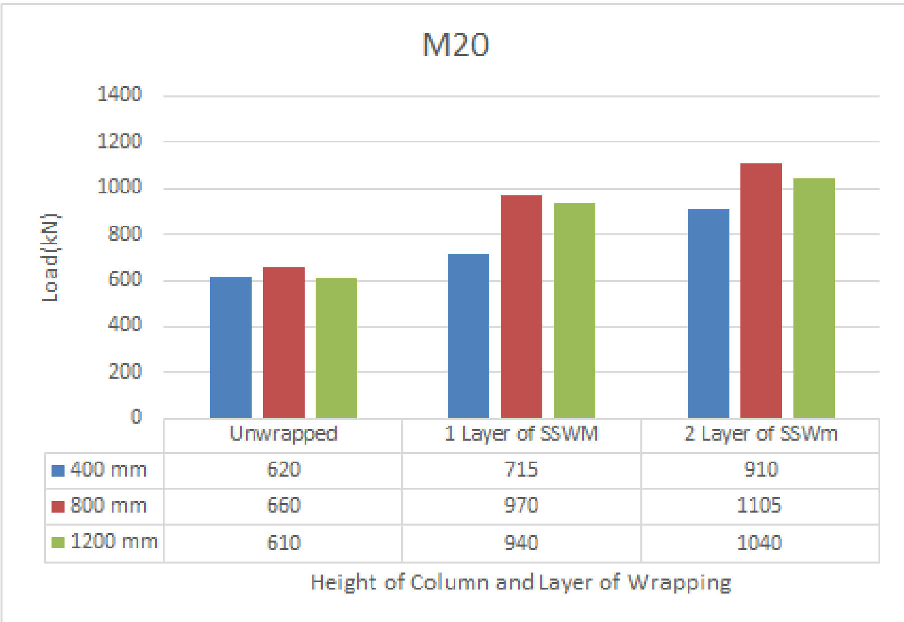


Figure 4.5: Comparison of Axial strength with respect to Height of Column(M-20)

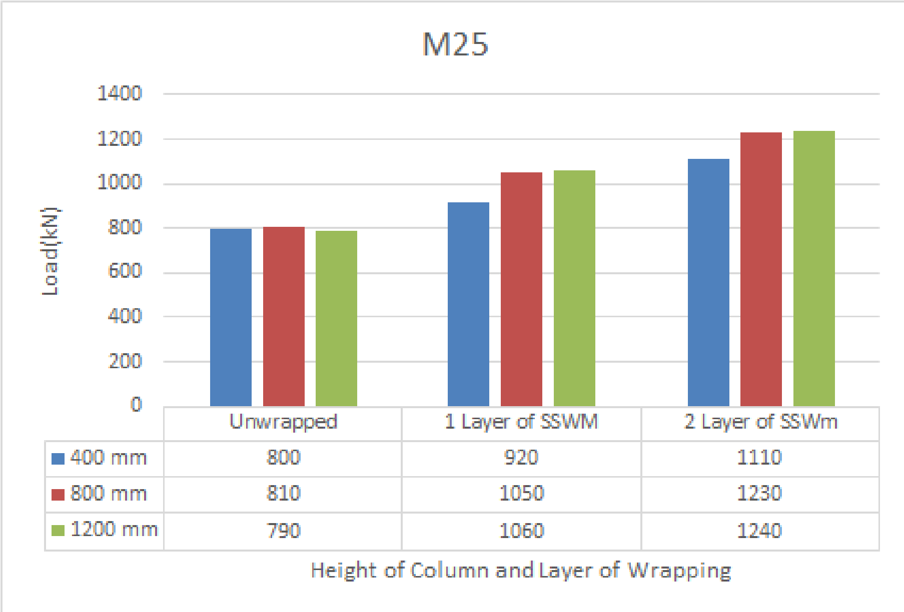
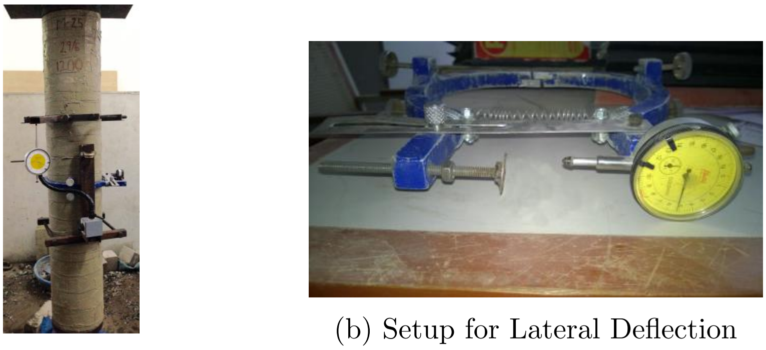


Figure 4.6: Comparison of Axial strength with respect to Height of Column(M-25)

4.4 Load Vs Linear deflection and Lateral Deflection

Linear Deflection was measured along the height of the columns. The gauge length of the columns for measuring the linear displacement was kept 400 mm. To set the Dial gauge for measuring the displacement of column, Steel frame setup was developed as shown in Figure 4.7. For Finding the Lateral Deflection, extensometer with dial gauge 0.002 least count was used as shown in Fig. 4.7. Displacements of all the columns were measured at intervals of every 20 kN load till the application of ultimate load. Axial deformation and lateral deformation of all columns were presented in the appendix A.



(a) Setup for Linear Deflection

(b) Setup for Lateral Deflection

Figure 4.7: Setup for Measurement of Deflection

Graphical representation of **load vs linear deflection** and **load vs lateral deflection** for all specimens:

Fig. 4.8 shows C400M15W0 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 560 kN and 500 kN.

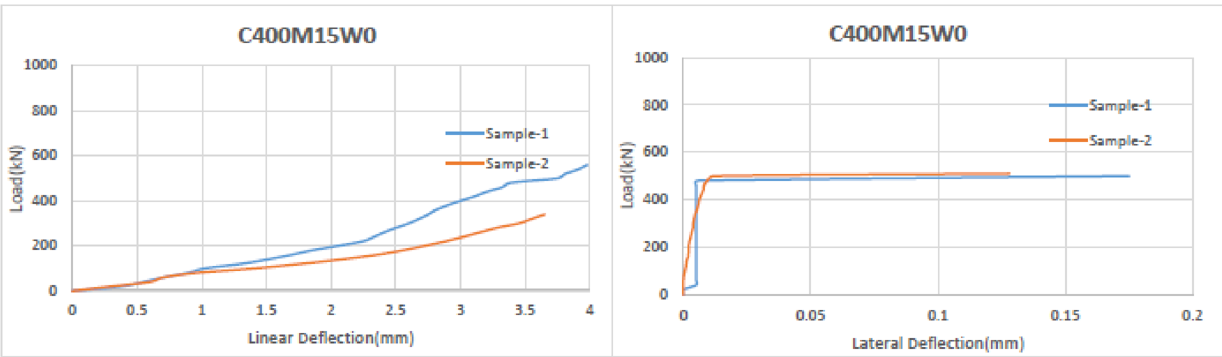


Figure 4.8: Linear and Lateral Deflection of column C400M15W0

Fig. 4.9 shows C800M15W0 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 490 kN and 480 kN.

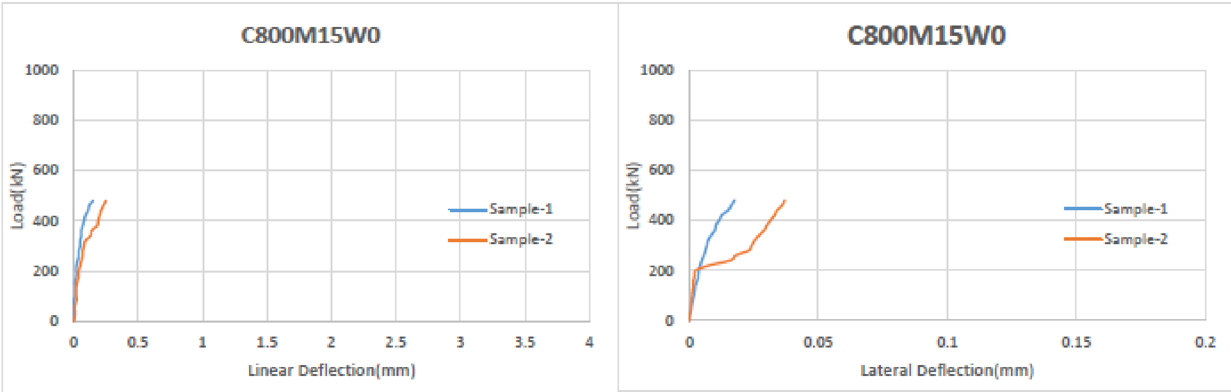


Figure 4.9: Linear and Lateral Deflection of column C800M15W0

Fig. 4.10 shows C1200M15W0 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 500 kN and 500 kN.

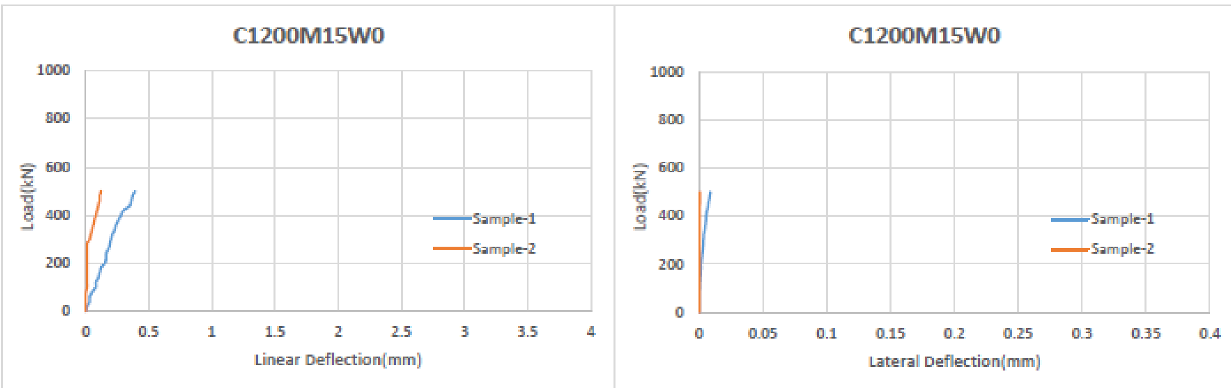


Figure 4.10: Linear and Lateral Deflection of column C1200M15W0

Fig. 4.11 shows C400M15W1 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 620 kN and 640 kN.

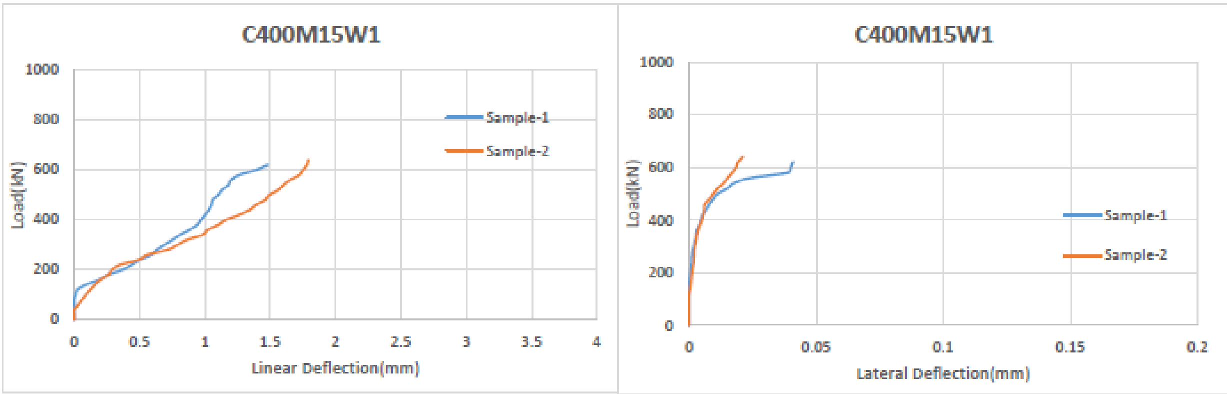


Figure 4.11: Linear and Lateral Deflection of column C400M15W1

Fig. 4.12 shows C800M15W1 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 800 kN and 760 kN.

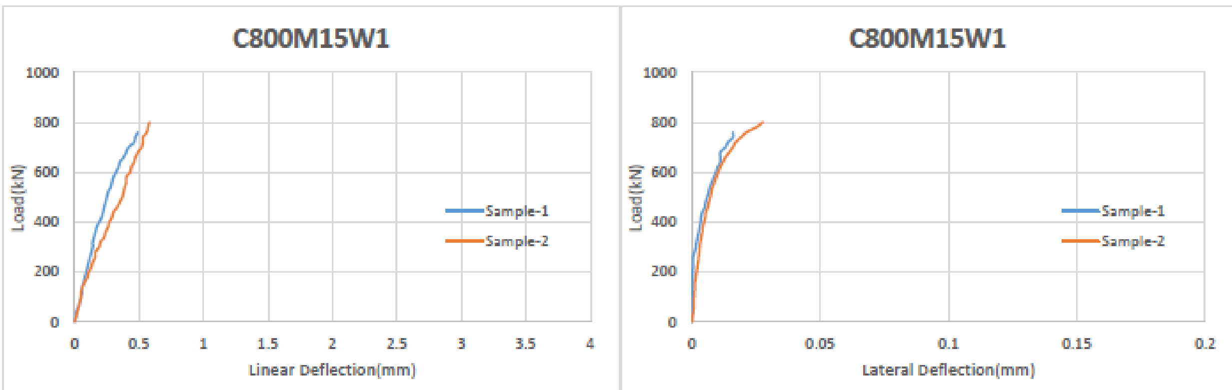


Figure 4.12: Linear and Lateral Deflection of column C800M15W1

Fig. 4.13 shows C1200M15W1 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 830 kN and 780 kN.

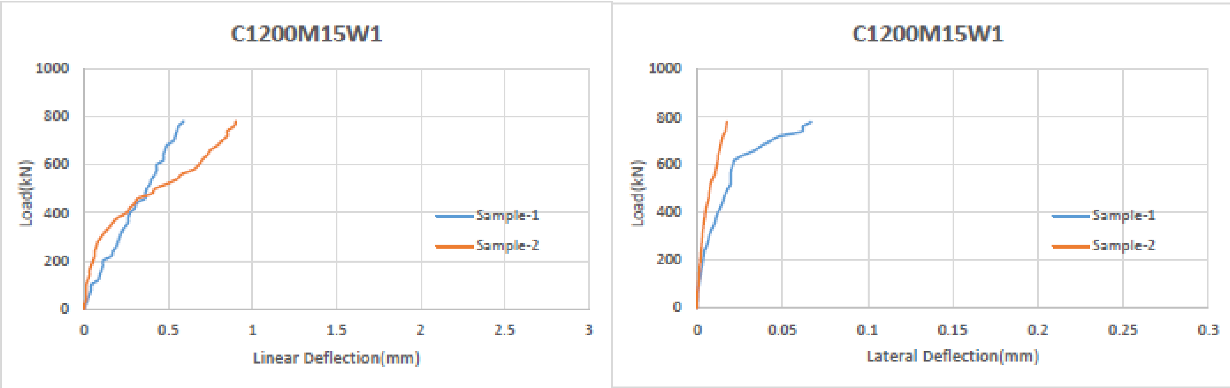


Figure 4.13: Linear and Lateral Deflection of column C1200M15W1

Fig. 4.14 shows C400M15W2 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 780 kN and 800 kN.

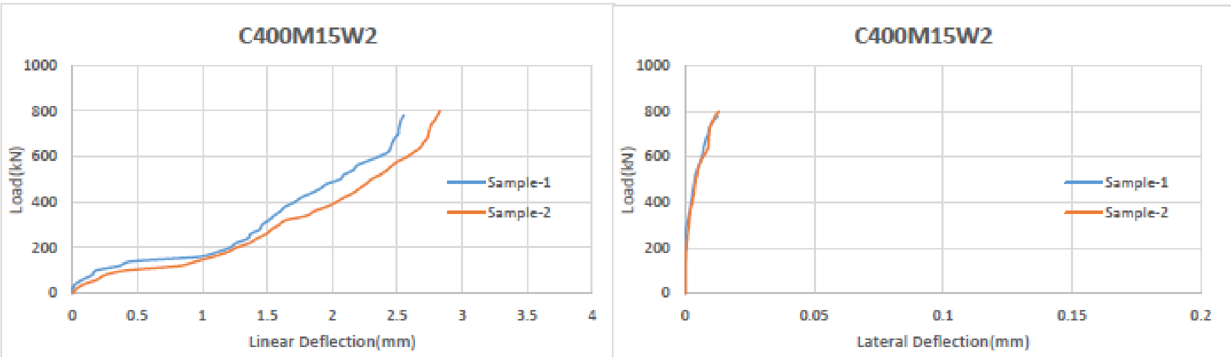


Figure 4.14: Linear and Lateral Deflection of column C400M15W2

Fig. 4.15 shows C800M15W2 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 820 kN and 840 kN.

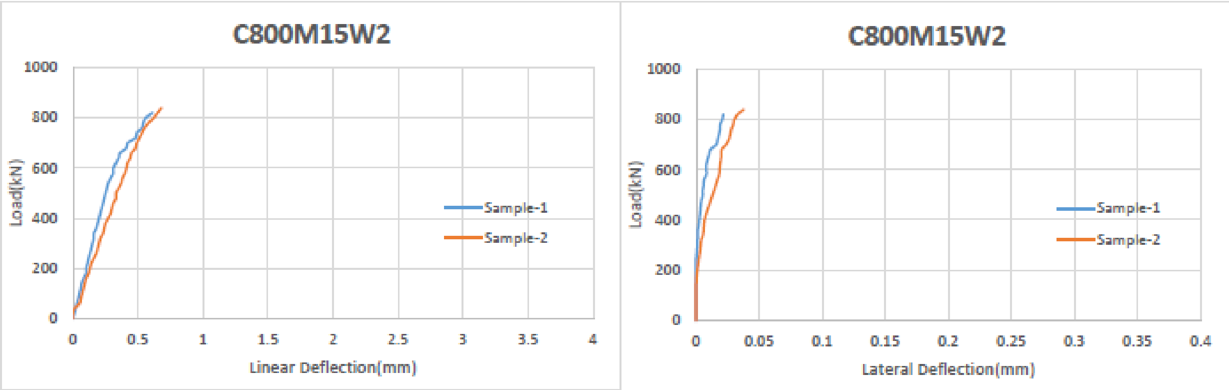


Figure 4.15: Linear and Lateral Deflection of column C800M15W2

Fig. 4.16 shows C1200M15W2 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 900 kN and 960 kN.

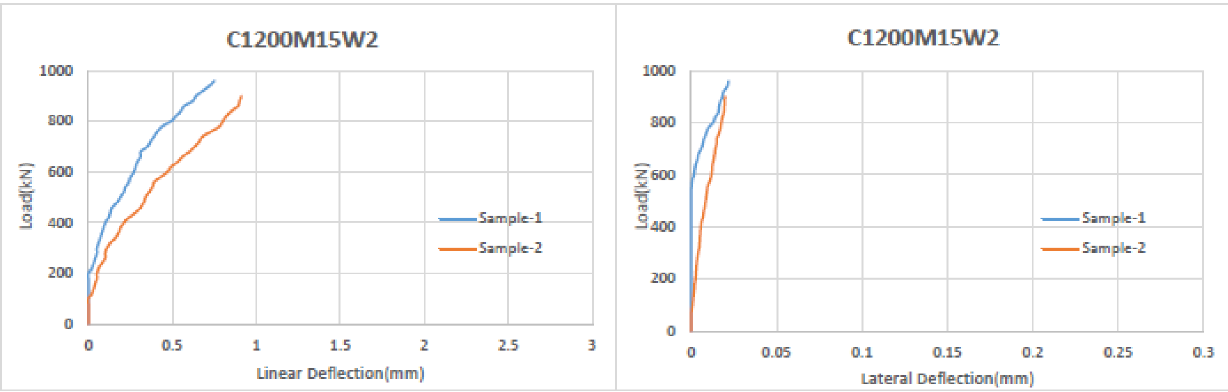


Figure 4.16: Linear and Lateral Deflection of column C1200M15W2

Comparision of average of two specimens linear deflection vs load for column with M15 grade concrete having different height for control and strengthened specimens with one layer of SSWm and two layer of SSWM is shown in Fig. 4.17. Comparision of average of two specimens lateral deflection vs load for column with M15 grade concrete having different height for control and strengthened specimens with one layer of SSWm and two layer of SSWM is shown in Fig. 4.18.

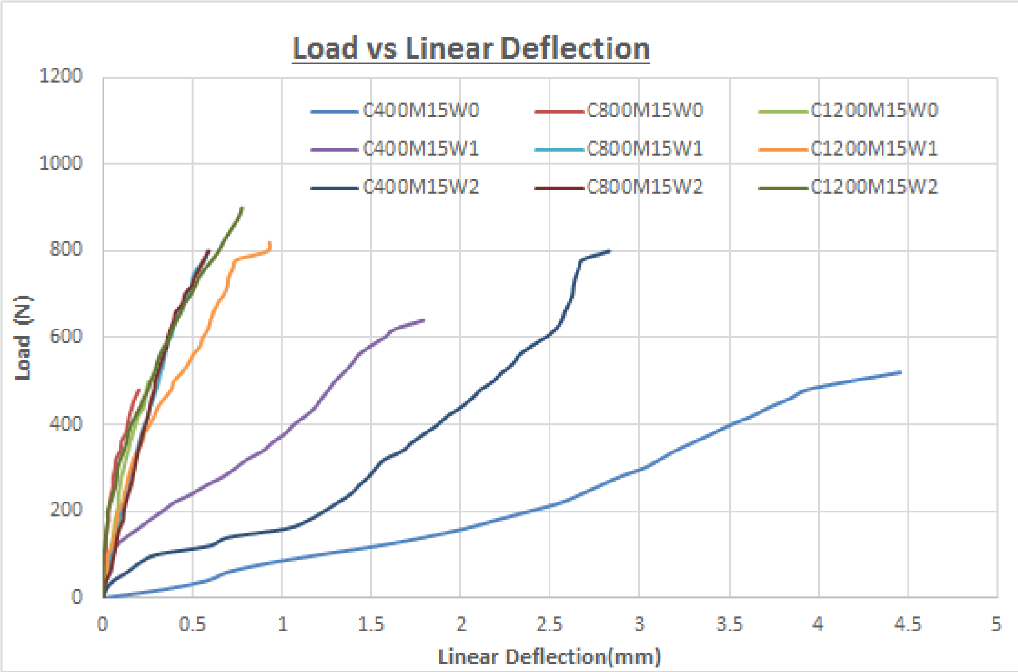


Figure 4.17: Load vs Linear Deflection (M15)

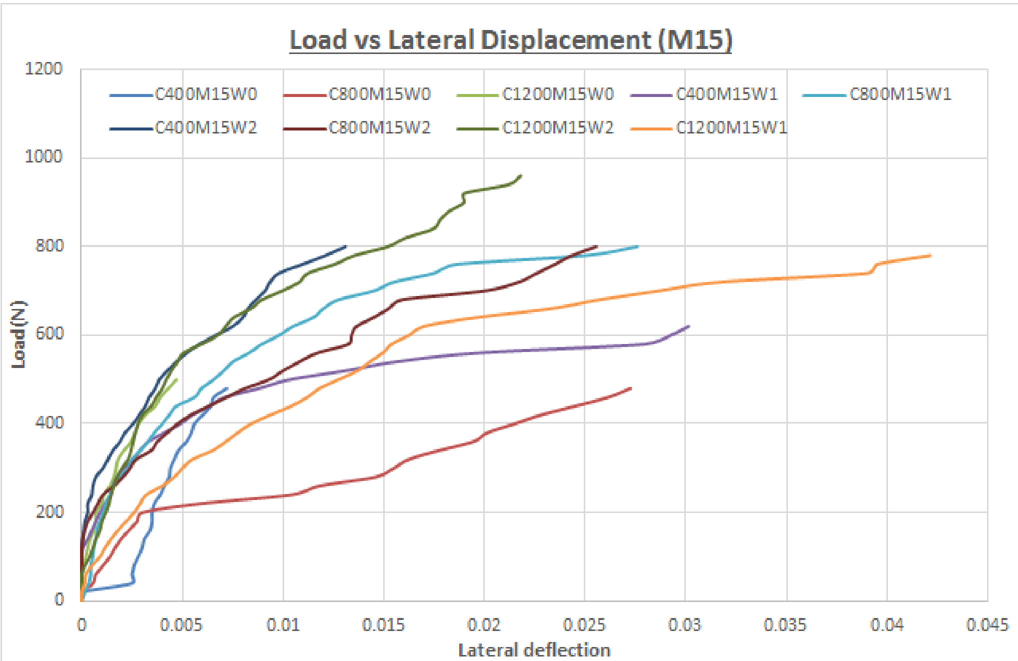


Figure 4.18: Load vs Lateral Deflection (M15)

Fig. 4.19 shows C400M20W0 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 620 kN and 620 kN.

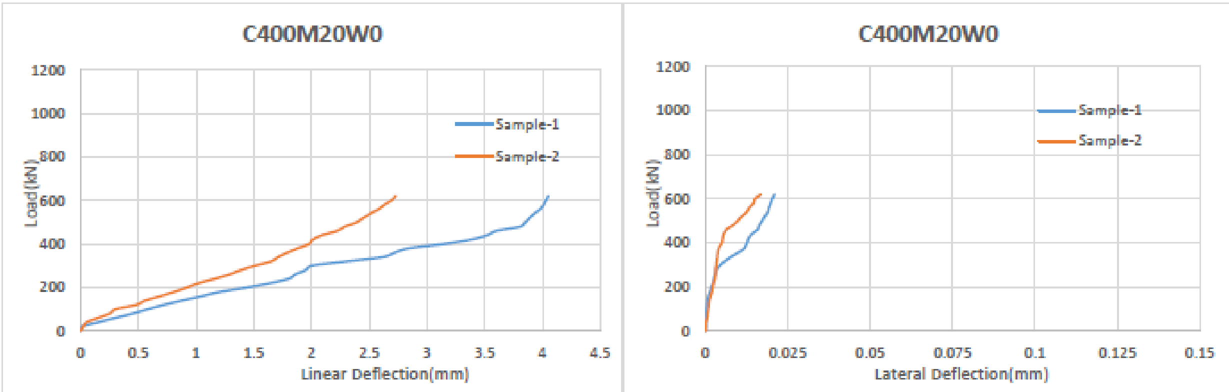


Figure 4.19: Linear and Lateral Deflection of column C400M20W0

Fig. 4.20 shows C800M20W0 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 640 kN and 680 kN.

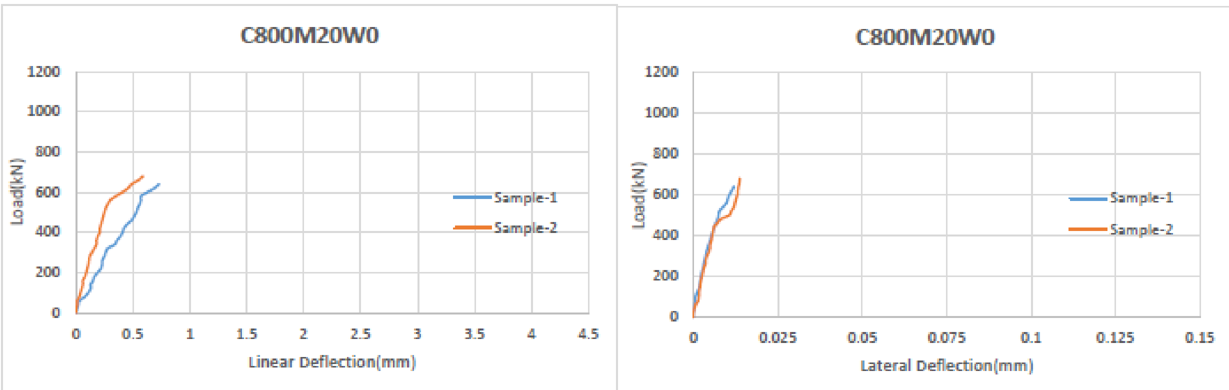


Figure 4.20: Linear and Lateral Deflection of column C800M20W0

Fig. 4.21 shows C1200M20W0 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 600 kN and 620 kN.

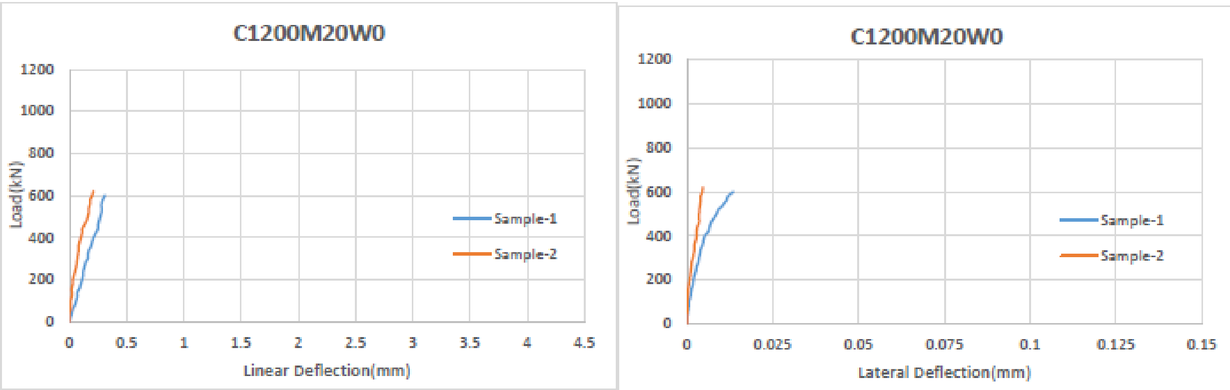


Figure 4.21: Linear and Lateral Deflection of column C1200M20W0

Fig. 4.22 shows C400M20W1 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 710 kN and 720 kN.

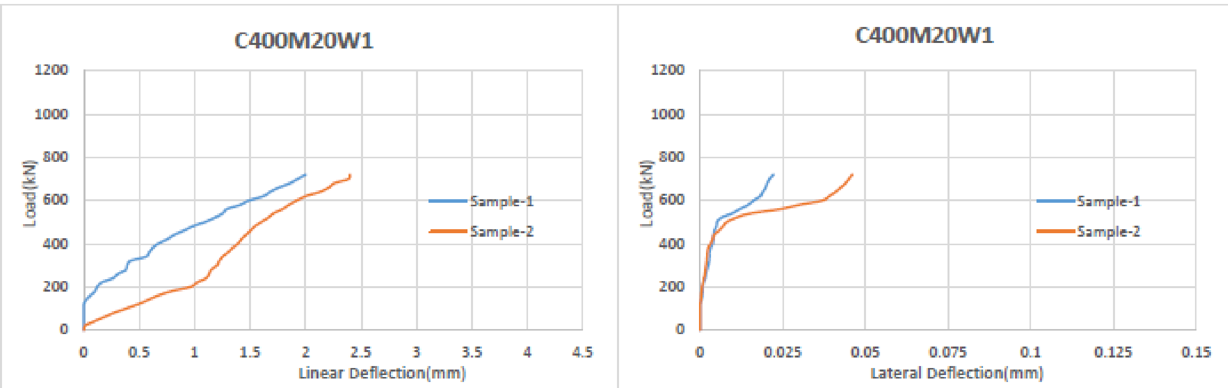


Figure 4.22: Linear and Lateral Deflection of column C400M20W1

Fig. 4.23 shows C800M20W1 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 980 kN and 960 kN.

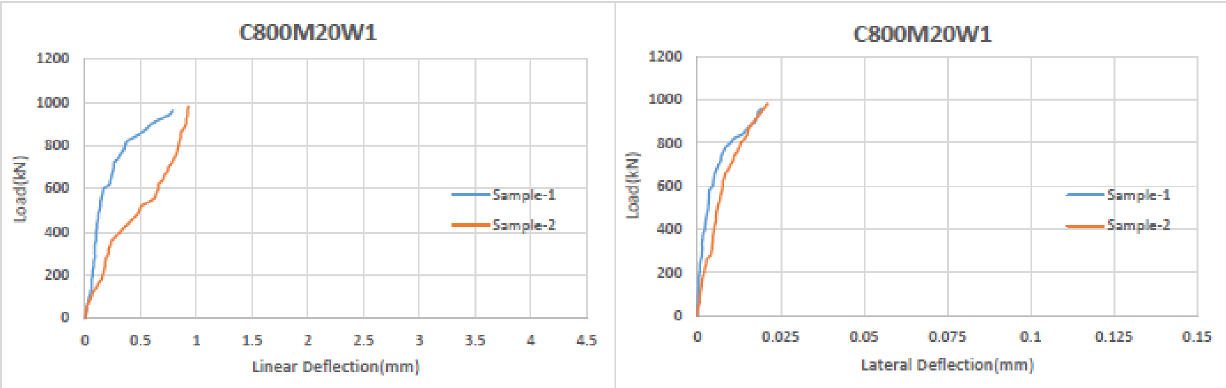


Figure 4.23: Linear and Lateral Deflection of column C800M20W1

Fig. 4.24 shows C1200M20W1 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 900 kN and 980 kN.

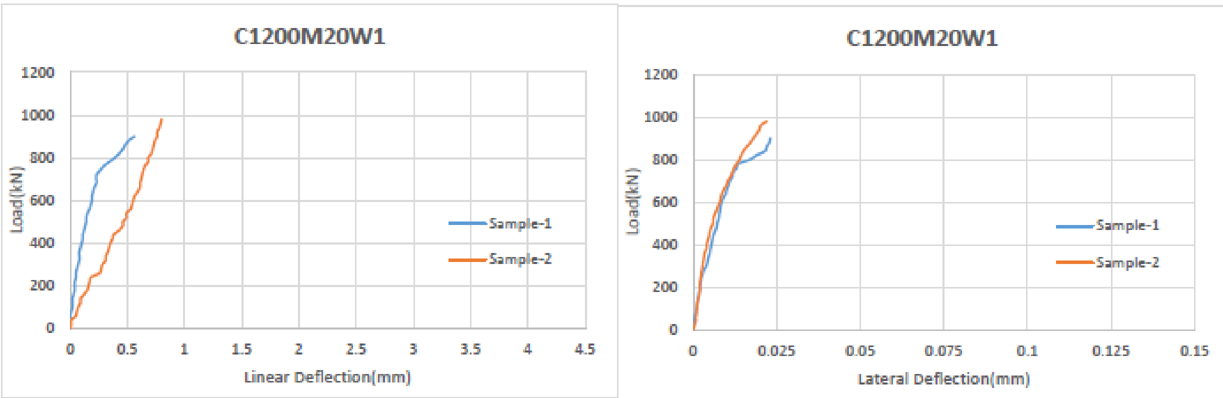


Figure 4.24: Linear and Lateral Deflection of column C1200M20W1

Fig. 4.25 shows C400M20W2 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 900 kN and 920 kN.

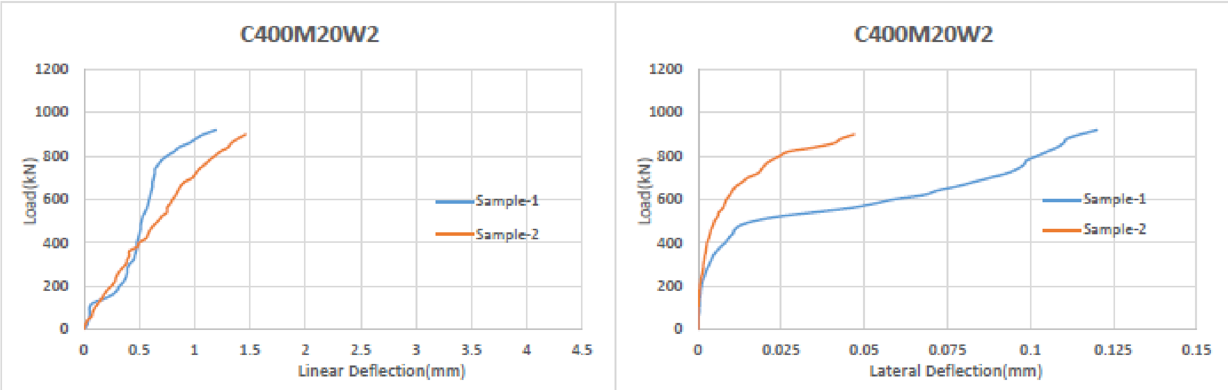


Figure 4.25: Linear and Lateral Deflection of column C400M20W2

Fig. 4.26 shows C800M20W2 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 1100 kN and 1110 kN.

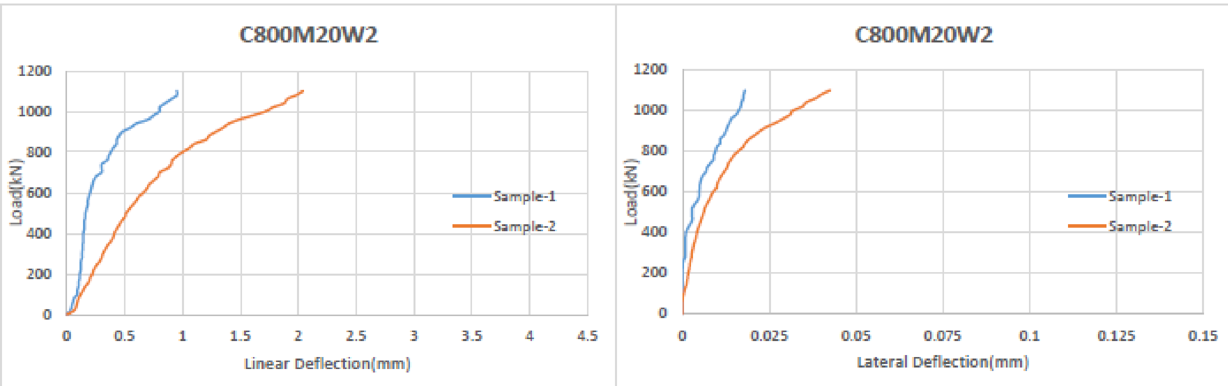


Figure 4.26: Linear and Lateral Deflection of column C800M20W2

Fig. 4.27 shows C1200M20W2 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 1060 kN and 1020 kN.

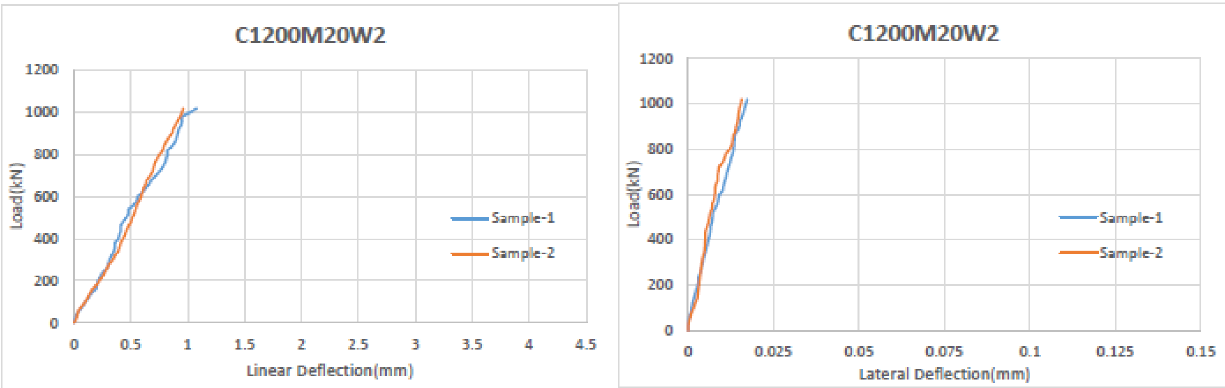


Figure 4.27: Linear and Lateral Deflection of column C1200M20W2

Comparision of average of two specimens linear deflection vs load for column with M20 grade concrete having different height for control and strengthened specimens with one layer of SSWm and two layer of SSWM is shown in Fig. 4.28. Comparision of average of two specimens lateral deflection vs load for column with M20 grade concrete having different height for control and strengthened specimens with one layer of SSWm and two layer of SSWM is shown in Fig. 4.29.

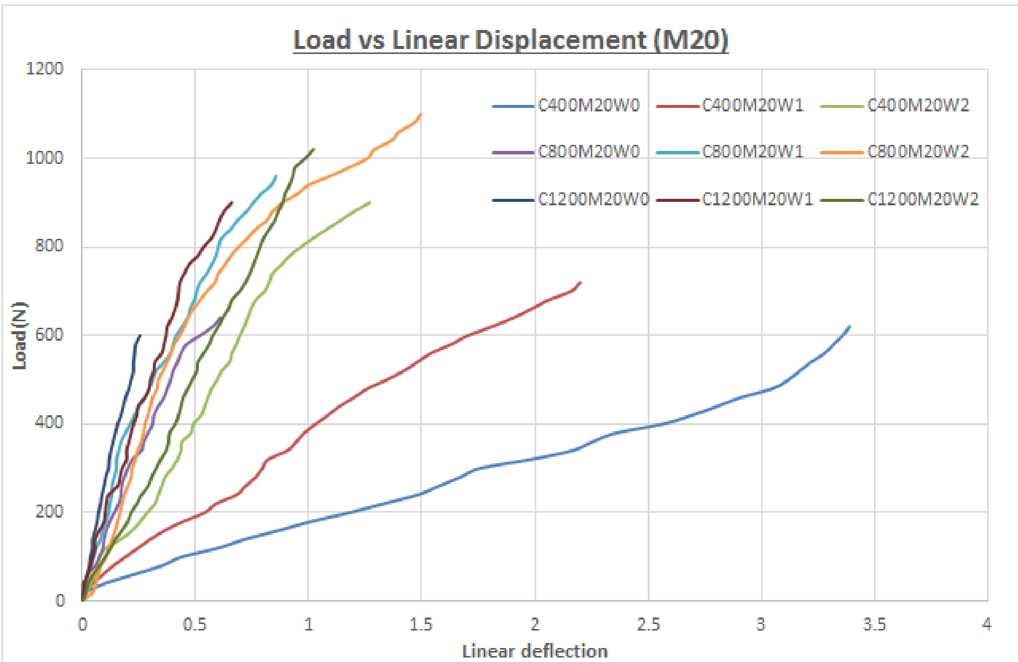


Figure 4.28: Load vs Linear deflection (M20)

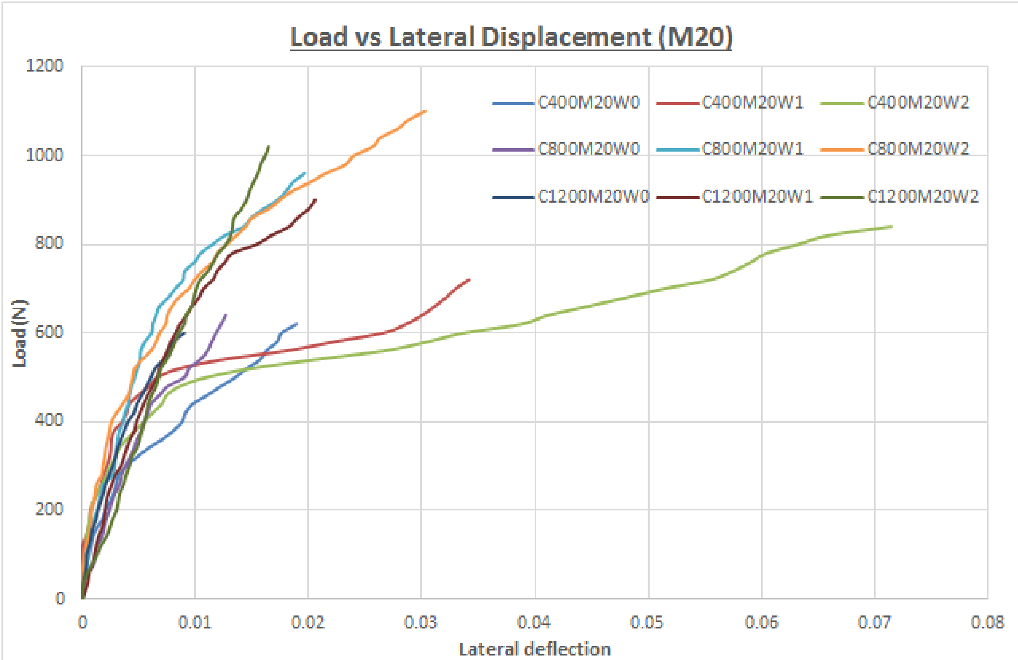


Figure 4.29: Load vs Lateral deflection (M20)

Fig. 4.30 shows C400M25W0 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 780 kN and 820 kN.

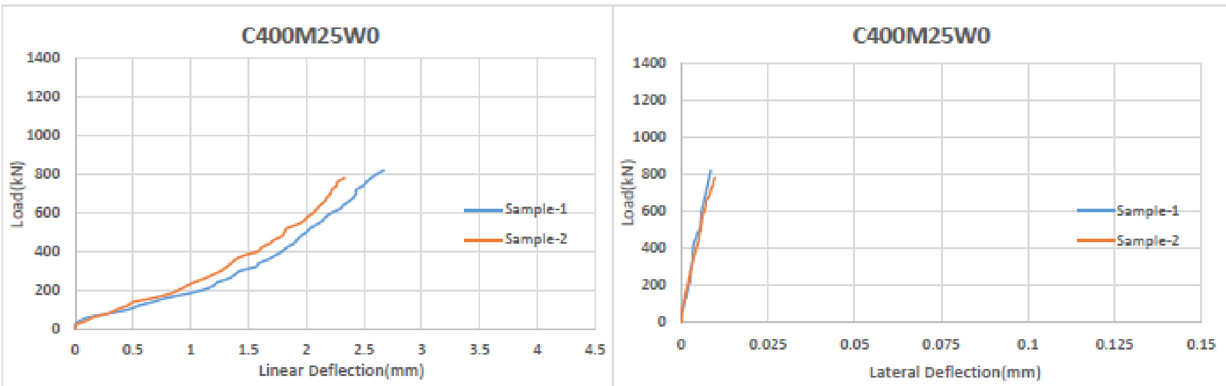


Figure 4.30: Linear and Lateral Deflection of column C400M25W0

Fig. 4.31 shows C800M25W0 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 800 kN and 820 kN.

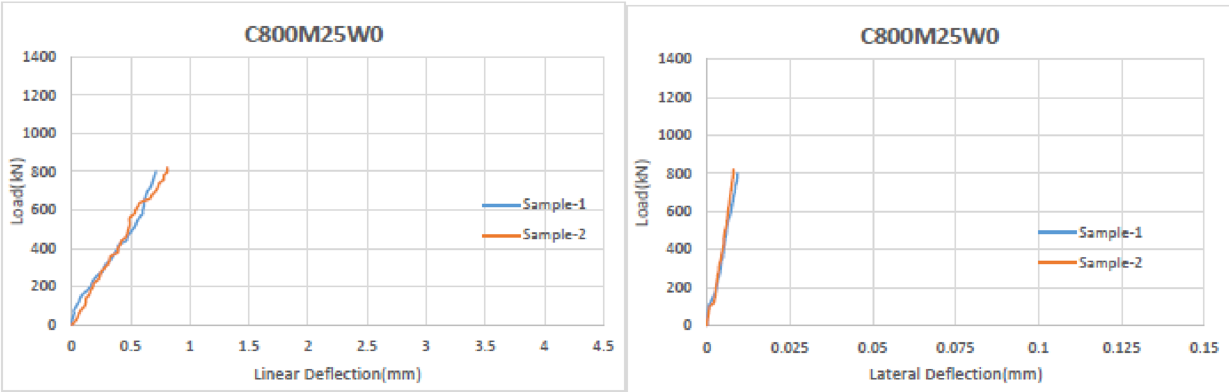


Figure 4.31: Linear and Lateral Deflection of column C800M25W0

Fig. 4.32 shows C1200M25W0 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 780 kN and 800 kN.

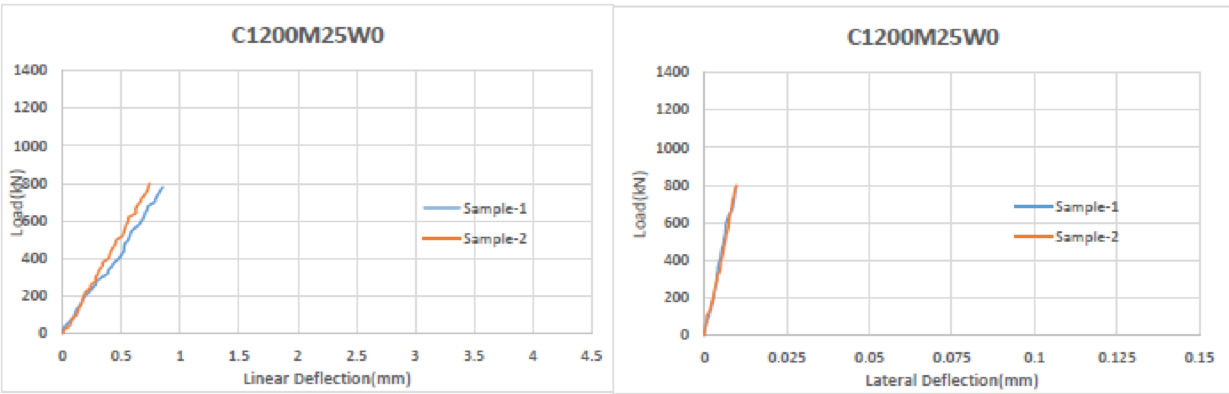


Figure 4.32: Linear and Lateral Deflection of column C1200M25W0

Fig. 4.33 shows C400M25W1 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 900 kN and 940 kN.

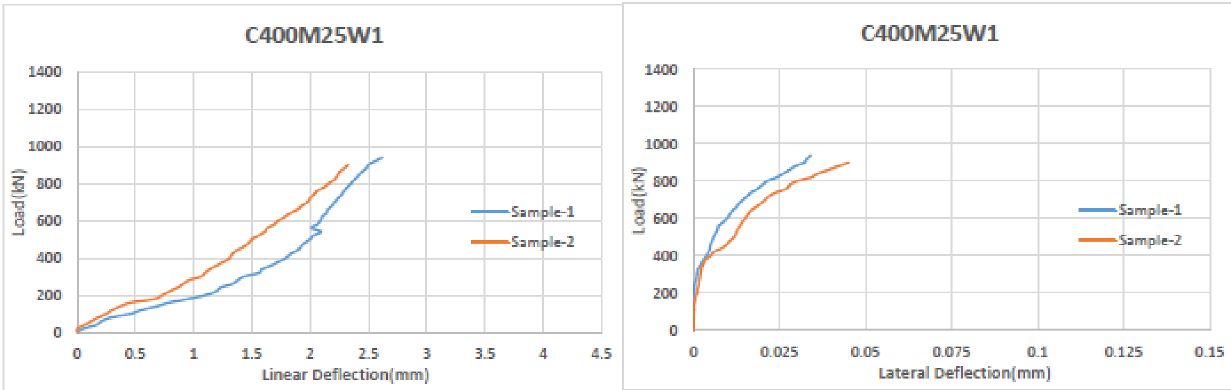


Figure 4.33: Linear and Lateral Deflection of column C400M25W1

Fig. 4.34 shows C800M25W1 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 1100 kN and 110 kN.

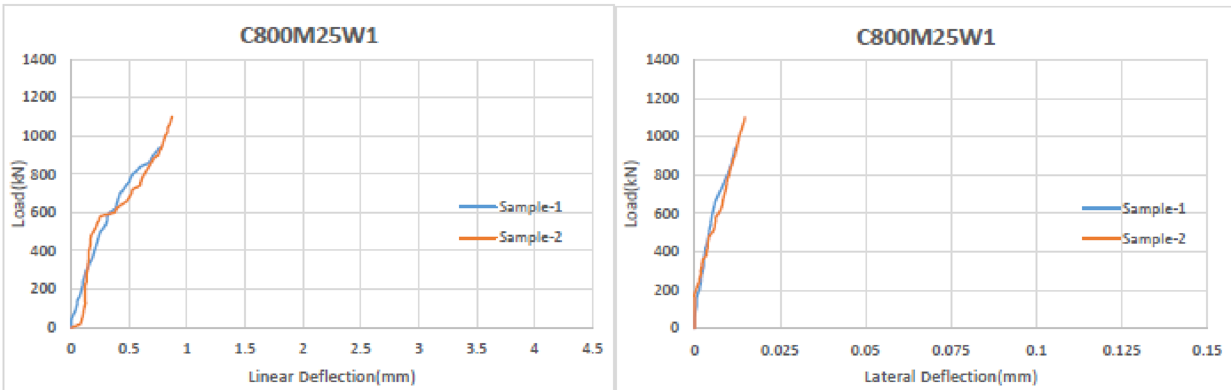


Figure 4.34: Linear and Lateral Deflection of column C800M25W1

Fig. 4.35 shows C1200M25W1 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 1020 kN and 1100 kN.

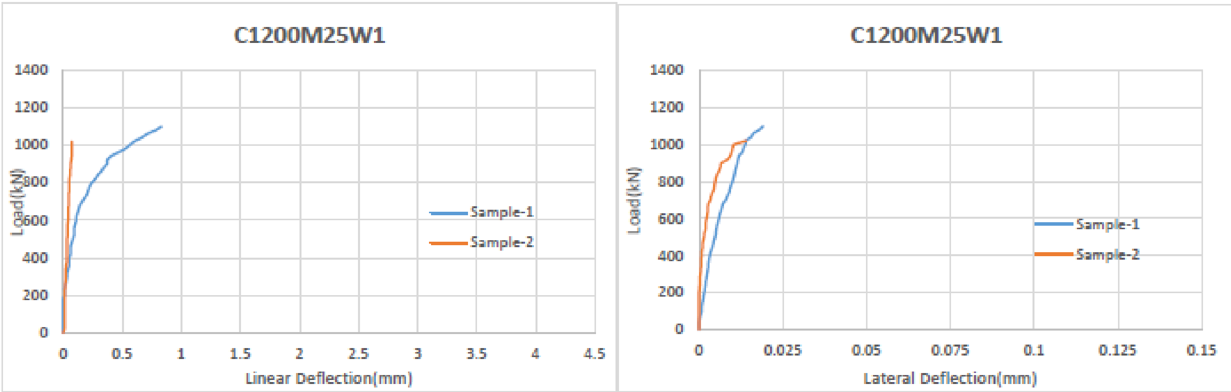


Figure 4.35: Linear and Lateral Deflection of column C1200M25W1

Fig. 4.36 shows C400M25W2 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 1100 kN and 1100 kN.

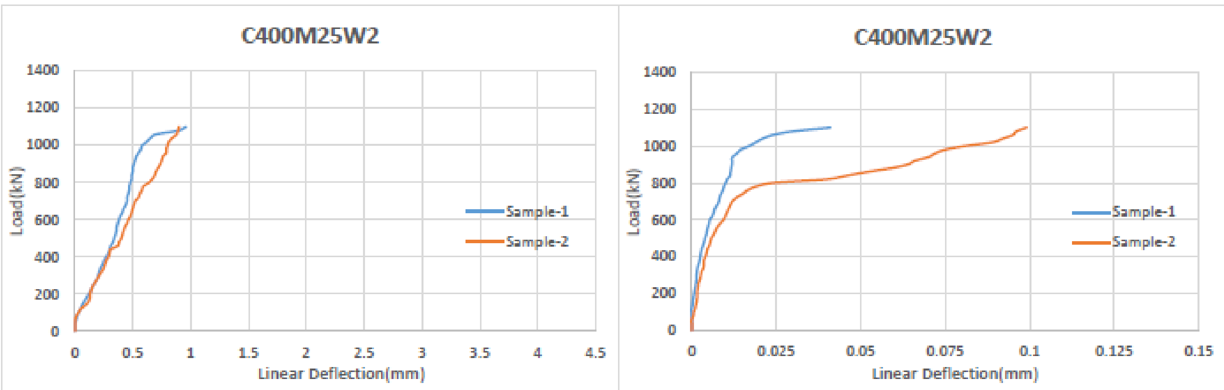


Figure 4.36: Linear and Lateral Deflection of column C400M25W2

Fig. 4.37 shows C800M25W2 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 1200 kN and 12600 kN.

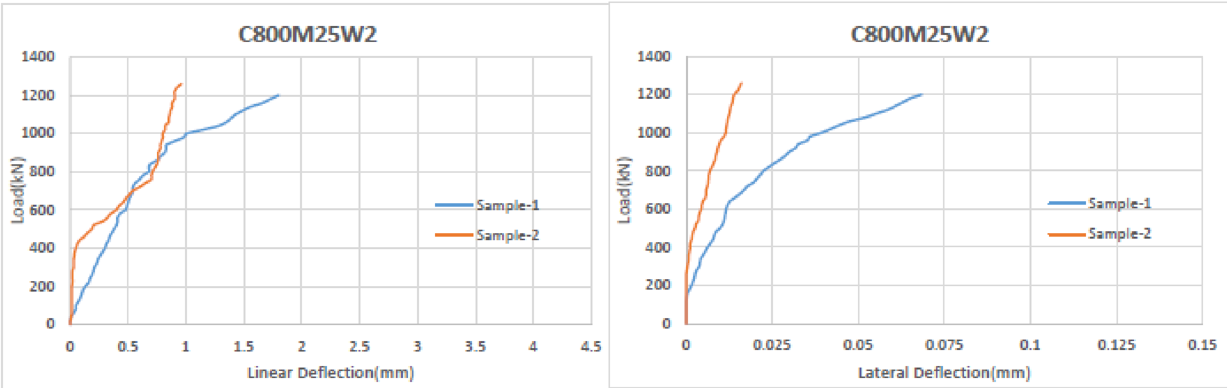


Figure 4.37: Linear and Lateral Deflection of column C800M25W2

Fig. 4.38 shows C1200M25W2 column load vs deflection and load vs lateral deflection relation. The Ultimate load carrying capacity was found 1200 kN.

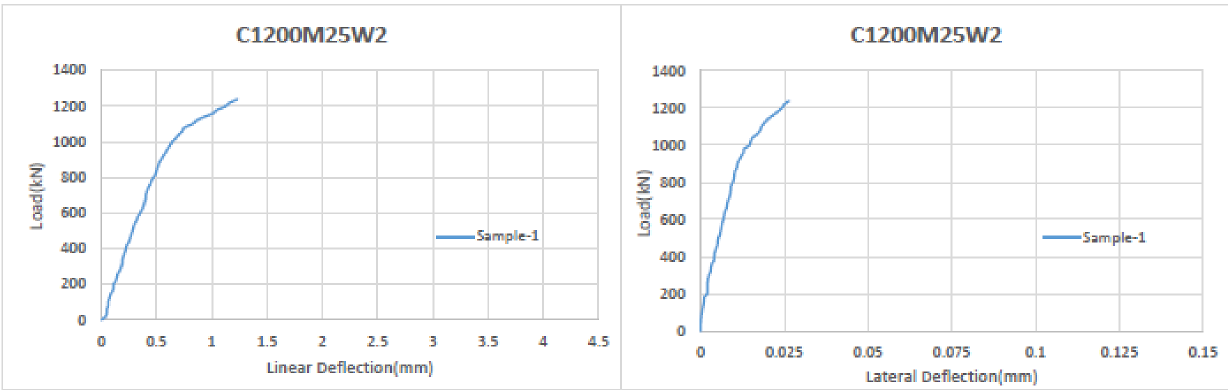


Figure 4.38: Linear and Lateral Deflection of column C1200M25W2

Comparision of average of two specimens linear deflection vs load for column with M25 grade concrete having different height for control and strengthened specimens with one layer of SSWm and two layer of SSWM is shown in Fig. 4.39. Comparision of average of two specimens lateral deflection vs load for column with M25 grade concrete having different height for control and strengthened specimens with one layer of SSWm and two layer of SSWM is shown in Fig. 4.40.

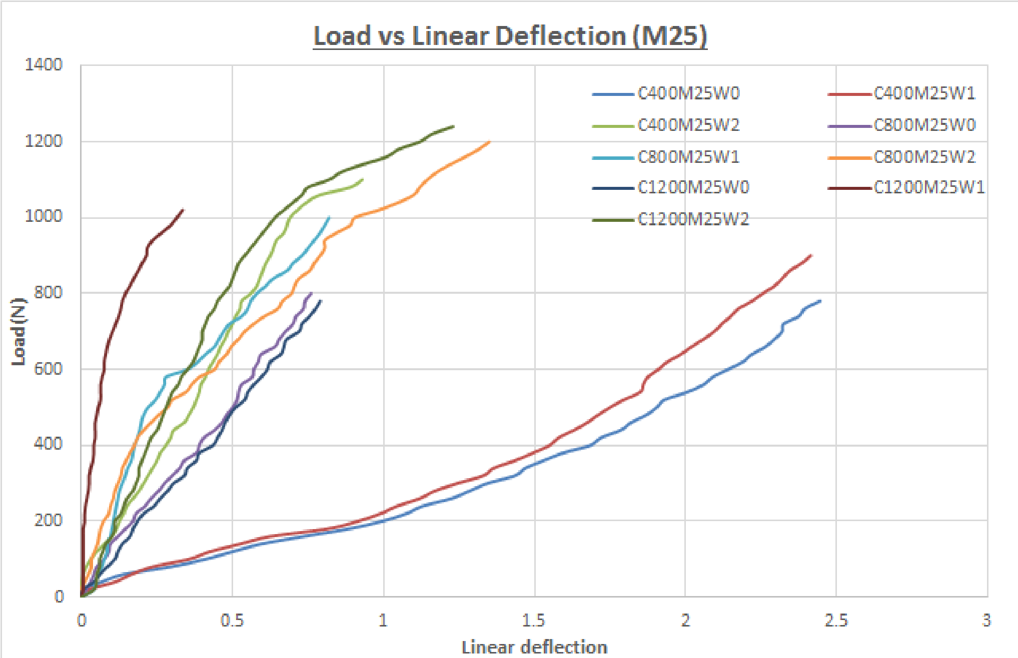


Figure 4.39: Load vs Linear deflection (M25)

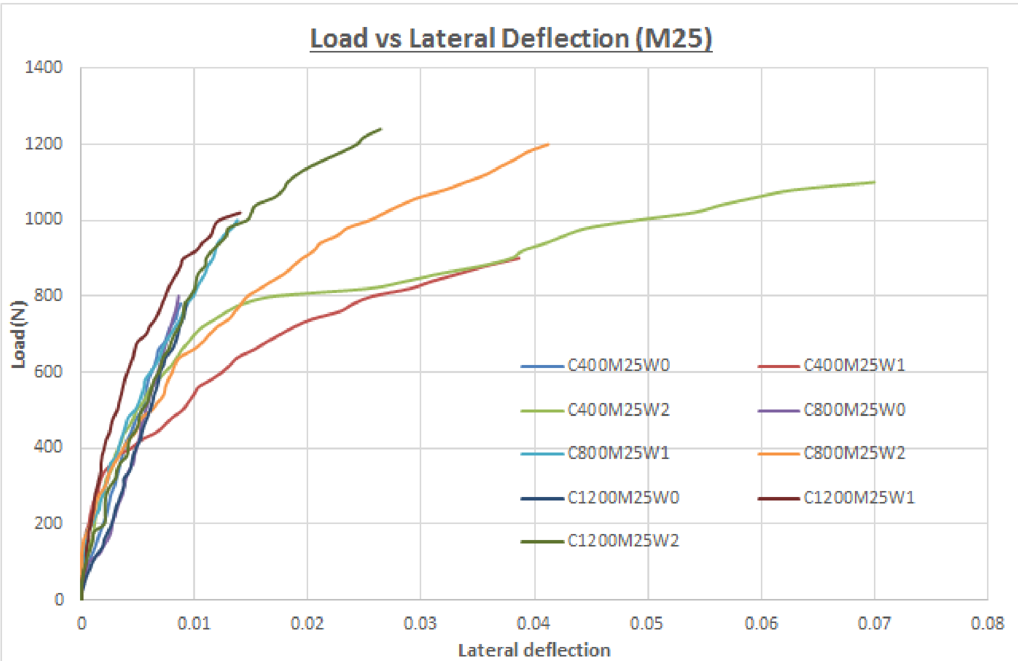


Figure 4.40: Load vs Lateral deflection (M25)

From the curves following observations are made:

- The linear deflection starts as soon as the axial load is applied and continues to increase with load proportionally till failure of specimen.
- Specimen 1 and 2 of all types of cylinders with different grades of concrete and height showing similar trend for linear displacement.
- It is observed that the lateral deflection increase at very slow rate with increaseing load. But start increasing with increase of load proportionally and at ultimate load the lateral deflection of both wrapped and unwrapped columns increases at high rate till failure of column specimen.

4.5 Failure Mode and Crack Patterns:

Control P.C.C column and Wrapped P.C.C Column specimens are tested under axial load with both ends partially fixed. Column Specimens are failed when the ultimate compressive strength is increased, which indicated by cracks in concrete in control columns and breaking of wire mesh in wrapped column. Most of the control specimens should brittle failure with Blasting sound. Failure mode of control specimens has been discussed below.

Control Circular P.C.C. : Control circular P.C.C. columns fail at top. Due to cracking, the columns failed in diagonal shear and crushing of concrete at top. In Fig. 4.35 and 4.36, the failure of column C400M15W0,C800M15W0 and C1200M20W0 are shown.

Figure 4.41: Spalling of Concrete and Crushing of Concrete Column C400M15W0

Figure 4.42: Shear Failure Pattern of Column C1200M20W0 and Shear Cracks from Top of Column C800M15W0

1-Layer Wrapped column: In this column, concrete crushed at top and column failed like a blast. Layer of SFRP was broken from top of the column due to hoop tension. No debonding occurred in SFRP. The wires of SFRP were in uniform tension hence the vertical crack developed. In Fig. 4.37 and 4.38, the failure of column C800M20W1,C800M15W1 and C400M25W1 are shown.

Figure 4.43: Shear Failure Pattern in Column C800M20W1

Figure 4.44: Crack generation in Column C800M15W1 and C400M25W1

2-Layer Wrapped column: In 2-layer wrapping concrete, confinement is more, so crack is developed slowly at top or bottom portion where concentration of stress is more. The crack propagated in vertical direction of column as seen following Figures. There is no debonding occure in any specimens. In Fig. 4.39,4.40 and 4.41, the failure of column C1200M25W2,C1200M15W2 and C1200M20W2 are shown.

Figure 4.45: Crack Initiate in Column C1200M25W2

Figure 4.46: Failure Pattern of Column C1200M15W2

Figure 4.47: Crack Propagate in Vertical Direction in Column C1200M20W2

4.6 Comparison of Axial Strength

The comparison have done between the expaerimental results and the analytical results(ACI 440.23 2008 and CNR-DT 200/2004). In the following Table 4.35 the comparison of axial increment of strength shown. [15]

Table 4.17: Comparision of Experimental result and Codes result

Grade of Concrete	No. of SSWM Layer	Axial Load carrying capacity of Column			Percentage increase in Load carrying capacity(%)		
		Experi-mental Result	ACI 440. 2R 2008	CNR-DT 200/2004	Experi-mental Result	ACI 440. 2R 2008	CNR-DT 200/2004
M15	0	505	471	471	-	-	-
	1	738.33	652	670	46.20	38.52	42.22
	2	850	1096	812	68.31	132.96	72.39
M20	0	630	628	628	-	-	-
	1	875	722	837	38.88	10.12	33.28
	2	1018.33	1166	993	61.64	85.56	58.12
M25	0	800	785	785	-	-	-
	1	1010	852	1000	26.25	8.53	27.38
	2	1180	1253	1168	47.5	57.32	48.78

Chapter 5

Summary and Conclusion

5.1 Summary

Present investigation includes determination of tensile strength of SSWM, evaluation of bond strength of SSWM with concrete using epoxy and uses of SSWM in axial strengthening of plain concrete columns. In tension test of SSWM two different sample of SSWM are tested, one is simple SSWM and second is Composite SSWM. And for bond test two types of bonding materials are used for preparation of bond specimens i.e. MasterBrace and Sikadur 30LP.
All columns samples are categorized in three different grade of concrete M15, M20 and M25 and also categorized according to their height as 400mm, 800mm and 1200mm. In all category of columns three types of specimens are considered i.e. without strengthening (control specimens) and with one and two layers of SSWM for strengthening.

5.2 Conclusion

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

a. **Tensile Test of SSWM:** In tension test, the average ultimate tensile strength of the steel fiber was found to be 785.91 MPa for the selected wire mesh 40×32 which is 13% higher than steel plates. The average ultimate tensile strength of the mesh of thickness 0.25mm was found to be 235.4 MPa. The ultimate average rupture strain is 0.048 mm/mm and the modulus of elasticity of mesh is 1.51×10^5 N/mm^2.

b. **Bond Test of SSWM:** In bond test, no debonding occurred with bonding material Sikadur 30 LP. However, Sikadur 30 LP yield higher tensile strength of 837.75 MPa compared to 695.49 MPa with MasterBrace and also debonding was observed in case of MasterBrace. Sikadur 30LP being of higher viscosity, the bonding of SFRP with concrete cylinder was found better during the wrapping process.
During testing of cylinders of all grades concrete and all height of columns, no debonding was observed indicating that Sikadur 30LP is most suitable for SSWM wrapping.

c. **M15 Grade Circular Column:**

- There are 19% and 49% increase in axial strength respectively with single wrap and double wrapp of SSWM as compared to control specimen of P.C.C circular column of 400 mm height.
- There are 61% and 71% increase in axial strength respectively with single wrap and double wrapp of SSWM as compared to control specimen of P.C.C circular column of 800 mm height.
- There are 61% and 86% increase in axial strength respectively with single wrap and double wrapp of SSWM as compared to control specimen of P.C.C circular column of 1200 mm height.

d. **M20 Grade Circular Column:**

- There are 15% and 47% increase in axial strength respectively with single wrap and double wrapp of SSWM as compared to control specimen of P.C.C circular column of 400 mm height.

- There are 47% and 67% increase in axial strength respectively with single wrap and double wrapp of SSWM as compared to control specimen of P.C.C circular column of 800 mm height.
- There are 54% and 70% increase in axial strength respectively with single wrap and double wrapp of SSWM as compared to control specimen of P.C.C circular column of 1200 mm height.

e. **M25 Grade Circular Column:**

- There are 15% and 39% increase in axial strength respectively with single wrap and double wrapp of SSWM as compared to control specimen of P.C.C circular column of 400 mm height.
- There are 30% and 52% increase in axial strength respectively with single wrap and double wrapp of SSWM as compared to control specimen of P.C.C circular column of 800 mm height.
- There are 34% and 57% increase in axial strength respectively with single wrap and double wrapp of SSWM as compared to control specimen of P.C.C circular column of 1200 mm height.

f. **Failure of Specimens:** In case of P.C.C column of all grades concrete, the failure was in the form of shear cracks and total collapse with blasting effect under continuous axial loading.
In case of wrapped column, the failure was due to tearing of the wire mesh mostly at the top portion under high stress concentration at the top. With further increase in load the columns fractured into number of pieces with a blasting effect.

g. **Overall Conclusion:**

- The percentage increase in strength is found to be higher in case of 800 mm and 1200 mm columns with one and two wraps as compared to 400 mm columns in all concrete grades.

- The percentage increase in strength with SSWM wrapping decreases with increase in concrete grade from M15 to M25.
- The SFRP mesh 40×32 which is locally available can be used for the structural strengthening of concrete columns successfully for higher axial loads even up to 86%.
- Most of the buildings constructed 10-20 years back with M15 grade concrete can be effectively strengthened with SSWM type 40×32 for higher axial loads.
- In the existing R.C.C buildings the columns with the reinforcement corrosion having reduced load bearing capacity can be strengthened with this SSWM without increasing the size of the column.
- With increase in number of wraps, the axial strength of column can be further increased but at a lesser rate as observed in case of single and double wraps.
- The SSWM is locally available cost Rs. 592 per squre meter which is much cheaper than CFRP(Rs. 3500 per square meter) and GFRP(Rs. 1800 per square meter) meshes, hence can be used for structural strengthening at much lesser cost.
- The experimental results obtain for ultimate strength are found to match with CNR-DT 200/2004 code better than the values obtained using the ACI 440.2R 2008.

5.3 Future Scope of Work

Present work can be extended further to include following aspects:

- Lateral loading conditions for seismic strengthening.
- Square and rectangular columns of different sizes with different corner radius.
- The study can be extended for flexural and shear strengthening of R.C.C beams and slabs.

- The further study can be carried out with other locally available stainless steel wire meshes for the better results.
- Development of the confinement model for SFRP wrapped concrete column subjected to axial load for preparation of design codes for structural retrofitting with SSWM.

Appendix A

Load Vs Linear & Lateral Deflection

Displacement were measured along the height of the columns. Displacements of all the columns were measured at intervals of every 20 kN load. The results of every two column specimens of each parameters, load vs linear deflection and load vs lateral deflection were shown as in following tables.

M15 Grade Columns:

Table A.1: C400M15W0 and C400M15W1 Column

C400M15W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0.38	0	0.3	0
40	0.55	0.005	0.6	0
60	0.7	0.005	0.7	0
80	0.89	0.005	0.95	0.0002
100	1.02	0.005	1.4	0.0006
120	1.3	0.005	1.76	0.001
140	1.51	0.005	2.08	0.0012
160	1.69	0.005	2.35	0.0018
180	1.85	0.005	2.55	0.002
200	2.05	0.005	2.72	0.002
220	2.24	0.005	2.88	0.0022
240	2.33	0.005	3.02	0.0028
260	2.41	0.005	3.15	0.0032
280	2.5	0.005	3.28	0.0037
300	2.6	0.005	3.45	0.0038
320	2.68	0.005	3.55	0.0042
340	2.75	0.005	3.65	0.0046
360	2.81	0.005	3.8	0.0054
380	2.9	0.005	3.92	0.0059
400	3	0.005	4.02	0.0062
420	3.11	0.005	4.15	0.007
440	3.2	0.005	4.25	0.0078
460	3.32	0.005	4.36	0.0081
480	3.39	0.005	4.48	0.0094
500	3.75	0.275	4.6	0.012
520	3.81	0.3	5.1	0.128
540	3.91	0.33		
560	3.98	0.33		

C400M15W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0	0	0	0
40	0	0	0	0
60	0	0	0.03	0
80	0	0	0.06	0
100	0.01	0	0.09	0
120	0.02	0	0.12	0.0001
140	0.09	0.0001	0.16	0.0005
160	0.19	0.0002	0.2	0.0008
180	0.26	0.0004	0.26	0.001
200	0.37	0.0006	0.29	0.0012
220	0.44	0.0008	0.35	0.0015
240	0.5	0.001	0.49	0.0019
260	0.59	0.0011	0.56	0.002
280	0.63	0.0014	0.71	0.0021
300	0.69	0.0019	0.79	0.0023
320	0.75	0.0023	0.86	0.0028
340	0.81	0.0028	0.98	0.003
360	0.88	0.003	1.02	0.0036
380	0.94	0.004	1.1	0.0042
400	0.97	0.0047	1.16	0.0051
420	1	0.0054	1.26	0.0056
440	1.03	0.0068	1.34	0.0059
460	1.05	0.008	1.39	0.0062
480	1.06	0.0095	1.46	0.0081
500	1.1	0.0112	1.49	0.0095
520	1.13	0.015	1.56	0.0112
540	1.18	0.0176	1.6	0.0136
560	1.2	0.0242	1.65	0.0152
580	1.26	0.039	1.72	0.017
600	1.39	0.04	1.75	0.0185
620	1.48	0.041	1.78	0.0193
640			1.79	0.0213

Table A.2: C400M15W2 Column

C400M15W2				
Load (kN)	Sample-1		Sample-2	
	Linear Deflection(mm)	Lateral Deflection(mm)	Linear Deflection(mm)	Lateral Deflection(mm)
0	0	0	0	0
20	0	0	0.03	0
40	0.02	0	0.09	0
60	0.08	0	0.19	0
80	0.15	0	0.25	0
100	0.18	0	0.41	0
120	0.36	0	0.82	0
140	0.45	0	0.95	0.0001
160	0.97	0	1.08	0.0002
180	1.11	0	1.19	0.0003
200	1.21	0	1.26	0.0006
220	1.26	0	1.36	0.0006
240	1.35	0.0001	1.42	0.0009
260	1.37	0.0001	1.49	0.001
280	1.44	0.0002	1.53	0.0012
300	1.46	0.0006	1.59	0.0015
320	1.51	0.001	1.64	0.0016
340	1.55	0.0013	1.8	0.0018
360	1.6	0.0018	1.86	0.002
380	1.64	0.002	1.96	0.0023
400	1.71	0.0023	2.03	0.0028
420	1.76	0.0026	2.09	0.0031
440	1.84	0.0028	2.16	0.0035
460	1.91	0.0031	2.21	0.0036
480	1.96	0.0034	2.26	0.0039
500	2.06	0.0037	2.3	0.004
520	2.09	0.0039	2.37	0.0046
540	2.16	0.0046	2.42	0.0048
560	2.19	0.0051	2.46	0.0053
580	2.27	0.0058	2.51	0.0059
600	2.36	0.0064	2.58	0.0069
620	2.43	0.0069	2.63	0.0081
640	2.45	0.0071	2.68	0.0089
660	2.46	0.0075	2.7	0.009
680	2.48	0.0081	2.73	0.0092
700	2.51	0.0089	2.74	0.0093
720	2.51	0.0092	2.75	0.0095
740	2.52	0.0098	2.76	0.0098
760	2.53	0.0111	2.79	0.0108
780	2.55	0.0126	2.81	0.0116
800			2.83	0.0131

Table A.3: C800M15W0 and C800M15W1 Column

C800M15W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0	0.0001	0.01	0
40	0	0.0005	0.01	0.0006
60	0	0.0008	0.01	0.0006
80	0	0.0013	0.02	0.0008
100	0.01	0.0018	0.02	0.001
120	0.01	0.0021	0.02	0.0012
140	0.01	0.0023	0.02	0.0016
160	0.01	0.0031	0.03	0.0016
180	0.02	0.0035	0.04	0.002
200	0.02	0.0036	0.04	0.0024
220	0.02	0.0042	0.05	0.0076
240	0.03	0.0048	0.06	0.016
260	0.04	0.0056	0.07	0.018
280	0.04	0.0062	0.07	0.023
300	0.05	0.0068	0.08	0.0242
320	0.05	0.0072	0.09	0.0253
340	0.06	0.0085	0.13	0.027
360	0.06	0.0099	0.14	0.029
380	0.07	0.0103	0.18	0.03
400	0.08	0.0115	0.19	0.0315
420	0.09	0.0126	0.2	0.033
440	0.11	0.0150	0.21	0.034
460	0.12	0.0163	0.23	0.036
480	0.15	0.0175	0.25	0.037

C800M15W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0.01	0.0001	0.01	0.0002
40	0.01	0.0001	0.02	0.0006
60	0.03	0.0001	0.03	0.0008
80	0.04	0.0001	0.04	0.0008
100	0.05	0.0002	0.05	0.0009
120	0.06	0.0002	0.05	0.001
140	0.06	0.0002	0.06	0.0012
160	0.07	0.0003	0.08	0.0012
180	0.08	0.0003	0.1	0.0015
200	0.09	0.0003	0.11	0.0018
220	0.1	0.0004	0.13	0.002
240	0.11	0.0004	0.14	0.0024
260	0.12	0.0005	0.16	0.0026
280	0.13	0.001	0.16	0.0028
300	0.14	0.0016	0.19	0.003
320	0.14	0.0018	0.2	0.0032
340	0.15	0.0022	0.23	0.0036
360	0.16	0.0026	0.24	0.004
380	0.17	0.003	0.26	0.0042
400	0.19	0.0033	0.27	0.0047
420	0.21	0.0035	0.29	0.0052
440	0.22	0.004	0.3	0.0054
460	0.23	0.005	0.33	0.0062
480	0.24	0.0053	0.35	0.0066
500	0.25	0.0059	0.37	0.0072
520	0.26	0.0065	0.38	0.0076
540	0.28	0.007	0.39	0.008
560	0.29	0.0078	0.4	0.0088
580	0.3	0.0085	0.4	0.0094
600	0.32	0.0094	0.43	0.0102
620	0.34	0.01	0.44	0.011
640	0.35	0.011	0.46	0.012
660	0.38	0.011	0.47	0.013
680	0.4	0.011	0.49	0.0145
700	0.42	0.133	0.52	0.016
720	0.46	0.014	0.53	0.017
740	0.47	0.016	0.53	0.019
760	0.49	0.016	0.56	0.0212
780			0.57	0.025
800			0.58	0.0276

Table A.4: C800M15W2 Column

C800M15W2				
Load(kN)	Sample-1		Sample-2	
	Linear Def.(mm)	Lateral Def.(mm)	Linear Def.(mm)	Lateral Def.(mm)
0	0	0	0	0
20	0.01	0	0	0
40	0.02	0	0.01	0
60	0.03	0	0.05	0
80	0.04	0	0.06	0
100	0.05	0	0.07	0
120	0.06	0	0.08	0
140	0.065	0	0.09	0.0001
160	0.08	0	0.1	0.0003
180	0.1	0	0.12	0.0006
200	0.1	0	0.13	0.0011
220	0.11	0	0.14	0.0016
240	0.12	0	0.16	0.0021
260	0.13	0.0004	0.18	0.0028
280	0.14	0.0008	0.19	0.0033
300	0.15	0.001	0.2	0.0038
320	0.16	0.0012	0.21	0.0042
340	0.16	0.0014	0.23	0.0055
360	0.18	0.0015	0.24	0.006
380	0.19	0.0022	0.25	0.0063
400	0.2	0.0026	0.27	0.0069
420	0.21	0.003	0.29	0.0078
440	0.22	0.0035	0.3	0.0091
460	0.23	0.0038	0.31	0.0106
480	0.24	0.0044	0.33	0.0118
500	0.25	0.0054	0.33	0.0132
520	0.26	0.0054	0.35	0.0146
540	0.27	0.006	0.37	0.0156
560	0.29	0.0064	0.38	0.017
580	0.31	0.0082	0.4	0.0183
600	0.31	0.0082	0.41	0.0186
620	0.33	0.0082	0.42	0.0191
640	0.35	0.0092	0.44	0.0198
660	0.36	0.0104	0.45	0.0201
680	0.41	0.0115	0.48	0.0203
700	0.42	0.016	0.49	0.0240
720	0.48	0.0172	0.51	0.0263
740	0.49	0.0181	0.53	0.0271
760	0.53	0.019	0.55	0.0280
780	0.54	0.0192	0.58	0.0295
800	0.56	0.0208	0.62	0.0303
820	0.61	0.0216	0.65	0.0330
840			0.68	0.0338

Table A.5: C1200M15W0 and C1200M15W1 Column

C1200M15W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0.01	0	0	0
40	0.03	0	0	0
60	0.03	0	0	0
80	0.05	0.0002	0	0
100	0.08	0.0004	0.01	0
120	0.08	0.0006	0.01	0
140	0.1	0.0008	0.01	0
160	0.11	0.0012	0.01	0
180	0.12	0.0014	0.01	0
200	0.15	0.0014	0.01	0
220	0.16	0.002	0.01	0
240	0.16	0.0022	0.01	0
260	0.18	0.0028	0.01	0
280	0.19	0.0032	0.01	0
300	0.2	0.0034	0.03	0
320	0.21	0.0036	0.04	0
340	0.23	0.0042	0.05	0
360	0.24	0.0048	0.06	0.0001
380	0.26	0.0052	0.07	0.0001
400	0.28	0.0054	0.08	0.0002
420	0.3	0.006	0.09	0.0003
440	0.35	0.007	0.1	0.0003
460	0.36	0.0074	0.11	0.0004
480	0.37	0.0082	0.11	0.0004
500	0.39	0.0088	0.12	0.0006

C1200M15W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0.01	0	0	0
40	0.02	0.0002	0.01	0.0001
60	0.03	0.0002	0.01	0.0002
80	0.04	0.0006	0.01	0.0004
100	0.04	0.001	0.01	0.0008
120	0.08	0.0014	0.02	0.0009
140	0.09	0.0019	0.03	0.001
160	0.1	0.0024	0.03	0.0012
180	0.11	0.003	0.04	0.0014
200	0.11	0.0034	0.05	0.0018
220	0.16	0.0038	0.06	0.002
240	0.17	0.0042	0.06	0.0049
260	0.19	0.0055	0.06	0.0022
280	0.2	0.0064	0.08	0.0028
300	0.21	0.007	0.1	0.003
320	0.22	0.0078	0.15	0.0036
340	0.24	0.0094	0.17	0.0039
360	0.26	0.0104	0.2	0.0045
380	0.26	0.011	0.25	0.0048
400	0.27	0.012	0.27	0.0052
420	0.3	0.0135	0.30	0.006
440	0.31	0.0148	0.31	0.0062
460	0.36	0.0156	0.32	0.0068
480	0.36	0.0166	0.4	0.007
500	0.37	0.018	0.42	0.0075
520	0.39	0.0196	0.49	0.0078
540	0.4	0.0196	0.55	0.009
560	0.42	0.0196	0.58	0.0103
580	0.43	0.02	0.65	0.0108
600	0.43	0.021	0.68	0.0115
620	0.47	0.022	0.70	0.0120
640	0.47	0.027	0.73	0.0130
660	0.48	0.0336	0.75	0.0136
680	0.49	0.0378	0.79	0.0143
700	0.53	0.043	0.82	0.0150
720	0.54	0.0484	0.85	0.0165
740	0.55	0.0616	0.89	0.0170
760	0.56	0.062	0.90	0.0173
780	0.59	0.067	0.92	0.0180
800			0.93	0.0184

Table A.6: C1200M15W2 Column

C1200M15W2				
Load	Sample-1		Sample-2	
(kN)	Linear Def.(mm)	Lateral Def.(mm)	Linear Def.(mm)	Lateral Def.(mm)
0	0	0	0	0
20	0	0	0	0
40	0	0	0	0
60	0	0	0	0
80	0	0	0	0.0003
100	0	0	0	0.0008
120	0	0	0.02	0.0011
140	0	0	0.03	0.0014
160	0	0	0.04	0.0018
180	0	0	0.05	0.002
200	0	0	0.05	0.0024
220	0.02	0	0.06	0.0027
240	0.03	0	0.08	0.0029
260	0.04	0	0.1	0.0032
280	0.05	0	0.1	0.0035
300	0.05	0	0.11	0.004
320	0.06	0	0.13	0.0046
340	0.07	0	0.16	0.0049
360	0.08	0	0.18	0.0051
380	0.09	0	0.19	0.0053
400	0.1	0	0.21	0.0056
420	0.12	0	0.24	0.006
440	0.13	0	0.28	0.0069
460	0.14	0	0.31	0.0074
480	0.17	0	0.33	0.008
500	0.19	0	0.34	0.0084
520	0.21	0	0.36	0.0089
540	0.22	0.0002	0.38	0.0093
560	0.24	0.0003	0.39	0.0098
580	0.25	0.0007	0.43	0.0112
600	0.27	0.0016	0.47	0.0119
620	0.28	0.002	0.49	0.0123
640	0.29	0.0026	0.53	0.0125
660	0.31	0.0036	0.56	0.0132
680	0.31	0.0042	0.6	0.0137
700	0.35	0.0058	0.63	0.0141
720	0.37	0.0068	0.66	0.0148
740	0.39	0.0076	0.68	0.0149
760	0.41	0.0088	0.73	0.0163
780	0.44	0.01	0.78	0.0171
800	0.49	0.0128	0.8	0.0176

C1200M15W2				
Load	Sample-1		Sample-2	
(kN)	Linear Def.(mm)	Lateral Def.(mm)	Linear Def.(mm)	Lateral Def.(mm)
820	0.52	0.014	0.82	0.0182
840	0.55	0.0158	0.85	0.0191
860	0.57	0.0162	0.89	0.0194
880	0.62	0.017	0.9	0.0195
900	0.64	0.0182	0.91	0.0198
920	0.68	0.019		
940	0.72	0.0212		
960	0.75	0.0218		

M-20 Grade Column

Table A.7: C400M20W0 and C400M20W1 Column

C400M20W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0.01	0.0002	0.02	0.0001
40	0.15	0.0002	0.05	0.0001
60	0.3	0.0002	0.15	0.0005
80	0.45	0.0002	0.25	0.0006
100	0.58	0.0003	0.3	0.0009
120	0.72	0.0005	0.48	0.001
140	0.88	0.0006	0.56	0.0012
160	1.05	0.0009	0.69	0.0016
180	1.21	0.0014	0.81	0.0021
200	1.44	0.0018	0.92	0.0022
220	1.64	0.0024	1.02	0.0025
240	1.8	0.0026	1.16	0.0029
260	1.86	0.003	1.29	0.003
280	1.95	0.0034	1.39	0.003
300	2	0.0045	1.51	0.0033
320	2.31	0.0062	1.65	0.0034
340	2.62	0.008	1.71	0.0036
360	2.72	0.0104	1.79	0.0037
380	2.84	0.012	1.88	0.0041
400	3.15	0.0126	1.98	0.005
420	3.38	0.013	2.01	0.0052
440	3.52	0.014	2.09	0.0055
460	3.6	0.0158	2.22	0.0063
480	3.81	0.0163	2.29	0.0082
500	3.85	0.0172	2.39	0.0098
520	3.89	0.0192	2.58	0.011
540	3.93	0.0189	2.51	0.0125
560	3.98	0.0192	2.58	0.0133
580	4.01	0.0198	2.63	0.0146
600	4.03	0.0202	2.69	0.015
620	4.05	0.021	2.73	0.0168

C400M20W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0	0	0.01	0
40	0	0	0.09	0
60	0	0	0.18	0
80	0	0	0.27	0
100	0	0	0.38	0
120	0	0	0.49	0
140	0.02	0.0004	0.58	0.0002
160	0.06	0.0007	0.67	0.0003
180	0.1	0.0008	0.79	0.0005
200	0.12	0.0008	0.96	0.0006
220	0.16	0.001	1.02	0.0009
240	0.26	0.0016	1.1	0.0011
260	0.31	0.0018	1.13	0.0015
280	0.38	0.0021	1.15	0.0016
300	0.39	0.0025	1.2	0.0018
320	0.42	0.0028	1.22	0.002
340	0.56	0.0029	1.25	0.0021
360	0.59	0.0029	1.3	0.0022
380	0.62	0.0032	1.34	0.0024
400	0.67	0.0038	1.39	0.0032
420	0.75	0.004	1.42	0.0038
440	0.81	0.0041	1.46	0.0042
460	0.9	0.0043	1.5	0.0056
480	0.98	0.0049	1.54	0.0069
500	1.09	0.0051	1.6	0.0081
520	1.18	0.0064	1.66	0.0108
540	1.25	0.0096	1.71	0.0152
560	1.29	0.012	1.79	0.0242
580	1.41	0.0145	1.85	0.03
600	1.49	0.0162	1.92	0.037
620	1.62	0.0182	2	0.039
640	1.68	0.019	2.13	0.041
660	1.76	0.0198	2.21	0.0425
680	1.86	0.0203	2.26	0.044
700	1.93	0.021	2.39	0.045
720	2	0.0223	2.4	0.046

Table A.8: C400M20W2 Column

C400M20W2				
Load	Sample-1		Sample-2	
(kN)	Linear Def.(mm)	Lateral Def.(mm)	Linear Def.(mm)	Lateral Def.(mm)
0	0	0	0	0
20	0.03	0	0.01	0
40	0.04	0	0.03	0
60	0.05	0.0001	0.07	0
80	0.05	0.0004	0.08	0
100	0.05	0.0004	0.1	0
120	0.08	0.0005	0.13	0.0001
140	0.18	0.0005	0.16	0.0002
160	0.26	0.0007	0.18	0.0003
180	0.3	0.0008	0.21	0.0004
200	0.32	0.001	0.25	0.0005
220	0.36	0.0012	0.28	0.0007
240	0.38	0.0018	0.29	0.0009
260	0.39	0.0022	0.31	0.0013
280	0.39	0.0027	0.34	0.0015
300	0.41	0.0034	0.38	0.0016
320	0.45	0.004	0.39	0.0018
340	0.46	0.0045	0.41	0.002
360	0.47	0.0055	0.41	0.0023
380	0.48	0.0068	0.48	0.0025
400	0.48	0.0082	0.5	0.0027
420	0.49	0.0092	0.56	0.0032
440	0.5	0.0104	0.58	0.0036
460	0.51	0.011	0.6	0.0039
480	0.51	0.0128	0.63	0.0045
500	0.52	0.017	0.67	0.0049
520	0.53	0.024	0.7	0.0058
540	0.55	0.035	0.75	0.0062
560	0.57	0.046	0.75	0.0075
580	0.58	0.053	0.78	0.008
600	0.59	0.059	0.8	0.0085
620	0.6	0.068	0.83	0.0096
640	0.61	0.072	0.85	0.0103
660	0.62	0.078	0.87	0.0114
680	0.62	0.083	0.91	0.0133
700	0.63	0.088	0.98	0.015
720	0.64	0.093	1.01	0.018
740	0.64	0.096	1.04	0.0191
760	0.67	0.098	1.09	0.0202
780	0.7	0.099	1.13	0.022

C400M20W2				
Load (kN)	Sample-1		Sample-2	
	Linear Def.(mm)	Lateral Def.(mm)	Linear Def.(mm)	Lateral Def.(mm)
800	0.75	0.102	1.18	0.0246
820	0.81	0.105	1.23	0.027
840	0.86	0.108	1.3	0.035
860	0.95	0.11	1.33	0.041
880	1.01	0.111	1.39	0.043
900	1.08	0.115	1.46	0.047
920	1.19	0.12		

Table A.9: C800M20W0 and C800M20W1 Column

C800M20W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0.01	0	0	0
40	0.02	0.0002	0.01	0.0002
60	0.03	0.0004	0.01	0.0006
80	0.08	0.0006	0.03	0.0014
100	0.11	0.0006	0.04	0.0016
120	0.13	0.001	0.05	0.0016
140	0.13	0.0016	0.06	0.0018
160	0.15	0.0018	0.06	0.002
180	0.16	0.002	0.08	0.0022
200	0.19	0.0022	0.09	0.0025
220	0.22	0.0024	0.1	0.0028
240	0.23	0.0028	0.11	0.003
260	0.23	0.003	0.115	0.0036
280	0.25	0.0033	0.12	0.0036
300	0.26	0.0036	0.14	0.004
320	0.28	0.0038	0.16	0.0046
340	0.34	0.0042	0.18	0.0049
360	0.36	0.0046	0.18	0.005
380	0.39	0.005	0.19	0.0054
400	0.41	0.0053	0.21	0.0056

C800M20W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def.(mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0.01	0	0.01	0
40	0.02	0	0.01	0.0002
60	0.02	0.0001	0.02	0.0006
80	0.03	0.0002	0.04	0.0006
100	0.04	0.0002	0.06	0.0008
120	0.05	0.0003	0.07	0.001
140	0.06	0.0004	0.1	0.0012
160	0.06	0.0004	0.12	0.0014
180	0.06	0.0004	0.15	0.0016
200	0.07	0.0006	0.16	0.002
220	0.07	0.0007	0.17	0.0022
240	0.08	0.0007	0.18	0.0026
260	0.08	0.001	0.18	0.0028
280	0.09	0.0013	0.19	0.004
300	0.09	0.0014	0.21	0.0043
320	0.09	0.0014	0.21	0.0044
340	0.09	0.0014	0.23	0.0046
360	0.1	0.0016	0.24	0.0046
380	0.1	0.0017	0.28	0.0048
400	0.1	0.0022	0.32	0.005

C800M20W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
420	0.42	0.0058	0.21	0.0058
440	0.45	0.0061	0.22	0.006
460	0.49	0.0066	0.23	0.007
480	0.51	0.0071	0.24	0.008
500	0.53	0.0074	0.25	0.0106
520	0.54	0.0076	0.26	0.0112
540	0.56	0.0088	0.28	0.012
560	0.57	0.0098	0.3	0.0123
580	0.57	0.0102	0.35	0.0126
600	0.63	0.0106	0.41	0.013
620	0.69	0.0114	0.46	0.0131
640	0.73	0.012	0.49	0.0133
660			0.55	0.0136
680			0.59	0.0137

C800M20W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def.(mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
420	0.11	0.0023	0.35	0.0052
440	0.11	0.0025	0.39	0.0056
460	0.12	0.0027	0.43	0.0056
480	0.12	0.003	0.47	0.0057
500	0.13	0.0032	0.49	0.006
520	0.14	0.0033	0.51	0.0064
540	0.14	0.0034	0.58	0.0068
560	0.15	0.0034	0.63	0.0069
580	0.16	0.0036	0.64	0.0074
600	0.17	0.0046	0.66	0.0076
620	0.22	0.0048	0.66	0.0076
640	0.23	0.005	0.7	0.008
660	0.24	0.0052	0.71	0.0084
680	0.25	0.0058	0.74	0.0094
700	0.26	0.0064	0.75	0.01
720	0.26	0.007	0.78	0.0108
740	0.3	0.0071	0.8	0.011
760	0.32	0.0078	0.82	0.012
780	0.35	0.0084	0.83	0.0125
800	0.36	0.01	0.84	0.013
820	0.38	0.011	0.85	0.0142
840	0.45	0.0135	0.86	0.015
860	0.51	0.0146	0.86	0.0152
880	0.56	0.016	0.89	0.016
900	0.6	0.0175	0.91	0.017
920	0.67	0.018	0.91	0.018
940	0.75	0.0182	0.92	0.019
960	0.79	0.0193	0.92	0.02
980			0.93	0.021

Table A.10: C800M20W2 Column

C800M20W2				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0.03	0	0.06	0
40	0.04	0	0.08	0
60	0.05	0	0.09	0
80	0.06	0	0.1	0.0001
100	0.09	0	0.12	0.0004
120	0.09	0	0.14	0.0006
140	0.1	0	0.16	0.0011
160	0.1	0	0.19	0.0013
180	0.11	0	0.2	0.0015
200	0.11	0	0.22	0.0016
220	0.12	0	0.23	0.002
240	0.12	0.0001	0.25	0.0021
260	0.12	0.0002	0.28	0.0023
280	0.13	0.0008	0.3	0.0026
300	0.13	0.0009	0.31	0.0027
320	0.135	0.0009	0.33	0.003
340	0.135	0.0009	0.35	0.0032
360	0.14	0.0009	0.38	0.0036
380	0.14	0.0009	0.4	0.0039
400	0.14	0.001	0.41	0.0041
420	0.15	0.0015	0.43	0.0045
440	0.15	0.0022	0.45	0.0049
460	0.15	0.0028	0.47	0.0053
480	0.16	0.0028	0.5	0.0057
500	0.16	0.0028	0.51	0.0061
520	0.17	0.0028	0.54	0.0064
540	0.18	0.0035	0.57	0.007
560	0.18	0.0044	0.6	0.0077
580	0.19	0.0048	0.62	0.0082
600	0.2	0.0048	0.66	0.0088
620	0.21	0.0049	0.69	0.0098
640	0.22	0.005	0.71	0.01
660	0.23	0.0053	0.75	0.0105
680	0.25	0.0058	0.79	0.0112
700	0.3	0.0068	0.8	0.012
720	0.3	0.007	0.87	0.0128
740	0.3	0.008	0.9	0.0132
760	0.35	0.009	0.91	0.014
780	0.36	0.009	0.95	0.0148
800	0.38	0.0095	1	0.016
820	0.4	0.0098	1.06	0.0174
840	0.43	0.0108	1.1	0.018
860	0.43	0.0108	1.2	0.0192
880	0.45	0.012	1.23	0.0209
900	0.48	0.0125	1.29	0.0224
920	0.55	0.0129	1.35	0.0242
940	0.6	0.0135	1.4	0.0268
960	0.7	0.014	1.49	0.029
980	0.75	0.0155	1.61	0.031
1000	0.8	0.0162	1.72	0.0318
1020	0.8	0.0168	1.78	0.0345
1040	0.85	0.017	1.88	0.0356
1060	0.9	0.0175	1.9	0.0382
1080	0.95	0.0176	1.98	0.04
1100	0.95	0.018	2.04	0.0425
1120			2.33	0.044

Table A.11: C1200M20W0 and C1200M20W1 Column

C1200M20W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def, (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0.01	0	0	0
40	0.02	0.0002	0	0
60	0.03	0.0004	0.01	0.0001
80	0.05	0.0006	0.01	0.0001
100	0.06	0.0006	0.01	0.0001
120	0.07	0.001	0.02	0.0002
140	0.07	0.0012	0.02	0.0003
160	0.09	0.0014	0.02	0.0004
180	0.1	0.0018	0.03	0.0006
200	0.11	0.0019	0.03	0.0008
220	0.12	0.0022	0.04	0.001
240	0.12	0.0026	0.05	0.0011
260	0.13	0.0028	0.06	0.0013
280	0.14	0.0033	0.065	0.0014
300	0.16	0.0035	0.07	0.0018
320	0.16	0.0038	0.075	0.002
340	0.17	0.004	0.08	0.0022
360	0.19	0.0046	0.08	0.0022
380	0.2	0.0048	0.09	0.0026
400	0.21	0.0052	0.1	0.0028
420	0.23	0.0063	0.11	0.0028
440	0.25	0.0066	0.11	0.003
460	0.25	0.007	0.13	0.0035
480	0.26	0.0078	0.15	0.0035
500	0.27	0.0086	0.16	0.0035
520	0.28	0.0092	0.17	0.0036
540	0.28	0.0105	0.17	0.0038
560	0.28	0.0115	0.18	0.004
580	0.29	0.012	0.18	0.004
600	0.31	0.0135	0.2	0.0045
620			0.21	0.0046

C1200M20W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0	0.0001	0.01	0.0004
40	0	0.0002	0.01	0.0008
60	0	0.0004	0.05	0.0008
80	0.01	0.0008	0.06	0.001
100	0.02	0.001	0.07	0.0011
120	0.02	0.0012	0.09	0.0012
140	0.02	0.0014	0.09	0.0014
160	0.03	0.0016	0.12	0.0018
180	0.04	0.0018	0.15	0.002
200	0.04	0.002	0.16	0.002
220	0.04	0.0022	0.17	0.002
240	0.05	0.0024	0.18	0.0022
260	0.05	0.0028	0.26	0.0024
280	0.06	0.0032	0.27	0.0026
300	0.07	0.004	0.28	0.0028
320	0.08	0.0043	0.31	0.003
340	0.08	0.0046	0.31	0.0032
360	0.08	0.005	0.33	0.0034
380	0.09	0.0052	0.34	0.004
400	0.1	0.0055	0.35	0.004
420	0.11	0.0058	0.37	0.0044
440	0.11	0.006	0.38	0.0048
460	0.12	0.0065	0.43	0.005
480	0.13	0.007	0.46	0.0054
500	0.14	0.0072	0.46	0.006
520	0.14	0.0076	0.49	0.006
540	0.15	0.0078	0.49	0.0064
560	0.17	0.008	0.53	0.007
580	0.18	0.0082	0.54	0.0074
600	0.19	0.0085	0.55	0.008
620	0.19	0.009	0.56	0.0082
640	0.2	0.0098	0.59	0.0086
660	0.21	0.0101	0.61	0.0092
680	0.23	0.0106	0.61	0.01
700	0.23	0.011	0.62	0.0104
720	0.23	0.0118	0.63	0.0112
740	0.26	0.012	0.64	0.0118
760	0.29	0.013	0.65	0.0122
780	0.34	0.0135	0.68	0.013
800	0.39	0.017	0.68	0.0138

C1200M20W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
820	0.43	0.019	0.71	0.0144
840	0.46	0.0215	0.72	0.015
860	0.48	0.022	0.73	0.016
880	0.51	0.0228	0.74	0.0172
900	0.56	0.0231	0.76	0.018
920			0.76	0.019
940			0.78	0.0198
960			0.79	0.0202
980			0.8	0.022

Table A.12: C1200M20W2 Column

C1200M20W2									
Load	Sample-1		Sample-2		Load	Sample-1		Sample-2	
(kN)	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)	(kN)	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0	560	0.52	0.0086	0.55	0.0071
20	0.01	0	0.02	0	580	0.55	0.0088	0.57	0.0076
40	0.02	0.0001	0.03	0.0002	600	0.56	0.0092	0.59	0.0078
60	0.05	0.0003	0.04	0.0006	620	0.6	0.0101	0.6	0.0079
80	0.08	0.0008	0.07	0.001	640	0.63	0.0103	0.61	0.008
100	0.1	0.001	0.1	0.0016	660	0.66	0.0107	0.63	0.0086
120	0.13	0.0012	0.12	0.002	680	0.68	0.0111	0.64	0.0086
140	0.15	0.0016	0.14	0.0026	700	0.72	0.0113	0.67	0.0088
160	0.19	0.002	0.16	0.0028	720	0.75	0.0118	0.69	0.009
180	0.2	0.0023	0.2	0.003	740	0.78	0.0122	0.7	0.01
200	0.21	0.0028	0.22	0.0032	760	0.8	0.0125	0.71	0.0106
220	0.23	0.003	0.25	0.0033	780	0.81	0.013	0.73	0.011
240	0.25	0.0031	0.27	0.0035	800	0.82	0.0133	0.75	0.0121
260	0.29	0.0037	0.29	0.0036	820	0.82	0.0134	0.78	0.0128
280	0.3	0.0039	0.31	0.0038	840	0.86	0.0135	0.79	0.013
300	0.31	0.0043	0.34	0.004	860	0.89	0.0136	0.81	0.0132
320	0.33	0.0045	0.36	0.0042	880	0.9	0.0143	0.83	0.0138
340	0.35	0.005	0.39	0.0046	900	0.91	0.015	0.86	0.014
360	0.36	0.0053	0.4	0.0048	920	0.92	0.0151	0.87	0.0144
380	0.36	0.0056	0.41	0.0049	940	0.94	0.0156	0.89	0.0146
400	0.39	0.0059	0.43	0.005	960	0.95	0.0162	0.91	0.0148
420	0.4	0.0063	0.45	0.005	980	0.95	0.0165	0.93	0.015
440	0.41	0.0065	0.46	0.0051	1000	1.02	0.0169	0.95	0.0154
460	0.41	0.0066	0.48	0.0056	1020	1.08	0.0173	0.96	0.0156
480	0.43	0.007	0.5	0.006	1040			0.98	0.0158
500	0.46	0.0072	0.51	0.0062	1060			0.98	0.016
520	0.48	0.0073	0.53	0.0065					
540	0.48	0.0079	0.54	0.007					

Table A.13: C400M25W0 and C400M25W1 Column

C400M25W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def, (mm)
0	0	0	0	0
20	0	0	0.01	0
40	0.04	0.0001	0.09	0
60	0.12	0.0002	0.16	0.0001
80	0.3	0.0006	0.29	0.0003
100	0.46	0.0008	0.36	0.0005
120	0.55	0.0009	0.45	0.0009
140	0.68	0.0014	0.51	0.001
160	0.79	0.0016	0.68	0.0012
180	0.96	0.0018	0.81	0.0015
200	1.1	0.002	0.89	0.0018
220	1.19	0.0024	0.96	0.0019
240	1.23	0.0025	1.03	0.0021
260	1.33	0.0025	1.12	0.0024
280	1.38	0.0026	1.19	0.0026
300	1.43	0.0029	1.26	0.0029
320	1.56	0.003	1.31	0.0031
340	1.59	0.0032	1.35	0.0033
360	1.67	0.0032	1.39	0.0036
380	1.73	0.0032	1.46	0.004
400	1.79	0.0033	1.58	0.0042
420	1.83	0.0034	1.61	0.0046
440	1.89	0.0038	1.68	0.0049
460	1.92	0.0042	1.72	0.005
480	1.95	0.0045	1.79	0.0052
500	2	0.0052	1.81	0.0055
520	2.03	0.0054	1.83	0.0056
540	2.09	0.0055	1.92	0.0058
560	2.14	0.0056	1.98	0.0059
580	2.17	0.0057	2.01	0.0061
600	2.22	0.0058	2.06	0.0065
620	2.29	0.006	2.09	0.0069
640	2.32	0.0063	2.12	0.007
660	2.37	0.0065	2.16	0.0071
680	2.41	0.0068	2.18	0.0079
700	2.43	0.007	2.21	0.0082
720	2.43	0.0072	2.22	0.0085
740	2.49	0.0075	2.26	0.0091
760	2.52	0.0077	2.27	0.0092
780	2.56	0.008	2.33	0.0095

C400M25W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0.05	0	0	0
40	0.16	0	0.06	0
60	0.21	0	0.12	0
80	0.29	0	0.18	0
100	0.46	0.0002	0.25	0
120	0.55	0.0002	0.3	0.0001
140	0.68	0.0002	0.37	0.0002
160	0.79	0.0002	0.46	0.0005
180	0.96	0.0002	0.67	0.0006
200	1.1	0.0002	0.73	0.0011
220	1.19	0.0003	0.79	0.0012
240	1.23	0.0003	0.86	0.0015
260	1.33	0.0005	0.91	0.0016
280	1.38	0.0009	0.96	0.0019
300	1.43	0.001	1.06	0.002
320	1.56	0.0012	1.1	0.0022
340	1.59	0.0017	1.14	0.0024
360	1.67	0.0024	1.2	0.003
380	1.73	0.0029	1.26	0.0034
400	1.79	0.0038	1.31	0.005
420	1.83	0.0044	1.33	0.0059
440	1.89	0.0048	1.37	0.0082
460	1.92	0.005	1.43	0.0096
480	1.95	0.0054	1.47	0.0106
500	2	0.0059	1.5	0.0119
520	2.03	0.0064	1.56	0.0124
540	2.09	0.007	1.61	0.0128
560	2.01	0.0072	1.63	0.0134
580	2.06	0.0086	1.69	0.0142
600	2.09	0.0098	1.73	0.015
620	2.1	0.0105	1.78	0.0158
640	2.14	0.0112	1.83	0.0165
660	2.15	0.0125	1.89	0.018
680	2.19	0.0131	1.93	0.0196
700	2.21	0.0144	1.98	0.0208
720	2.24	0.0156	2	0.022
740	2.27	0.0168	2.03	0.024
760	2.29	0.0186	2.06	0.027
780	2.32	0.02	2.12	0.028

C400M25W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def, (mm)
800	2.61	0.0081		
820	2.67	0.0084		

C400M25W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
800	2.35	0.0214	2.16	0.03
820	2.38	0.024	2.21	0.034
840	2.41	0.026	2.23	0.036
860	2.44	0.0278	2.25	0.039
880	2.48	0.0295	2.29	0.042
900	2.5	0.0322	2.33	0.045
920	2.56	0.033		
940	2.62	0.034		

Table A.14: C400M25W2 Column

C400M25W2									
Load	Sample-1		Sample-2		Load	Sample-1		Sample-2	
(kN)	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)	(kN)	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0	560	0.36	0.0048	0.43	0.0075
20	0	0	0	0	580	0.37	0.0051	0.45	0.0084
40	0	0	0	0	600	0.38	0.0053	0.46	0.0094
60	0.01	0	0	0	620	0.39	0.0061	0.48	0.0099
80	0.02	0	0.01	0.0005	640	0.41	0.0065	0.49	0.0104
100	0.03	0	0.03	0.0006	660	0.42	0.0068	0.5	0.0109
120	0.05	0	0.05	0.001	680	0.44	0.0075	0.51	0.0114
140	0.06	0.0002	0.09	0.0012	700	0.45	0.008	0.52	0.012
160	0.08	0.0003	0.12	0.0015	720	0.45	0.0082	0.55	0.0132
180	0.1	0.0005	0.13	0.0016	740	0.46	0.0086	0.56	0.015
200	0.12	0.0007	0.13	0.0016	760	0.47	0.0092	0.58	0.0165
220	0.14	0.0008	0.14	0.0017	780	0.47	0.0095	0.59	0.019
240	0.15	0.0011	0.15	0.0019	800	0.48	0.01	0.64	0.024
260	0.17	0.0012	0.17	0.002	820	0.49	0.0105	0.67	0.04
280	0.19	0.0014	0.19	0.0025	840	0.49	0.0114	0.69	0.046
300	0.2	0.0014	0.21	0.0027	860	0.5	0.0115	0.7	0.052
320	0.21	0.0015	0.23	0.0029	880	0.5	0.0117	0.72	0.059
340	0.22	0.0017	0.25	0.0035	900	0.51	0.0119	0.74	0.064
360	0.24	0.002	0.26	0.0036	920	0.52	0.0119	0.75	0.066
380	0.25	0.0023	0.27	0.0036	940	0.53	0.012	0.76	0.07
400	0.27	0.0025	0.29	0.004	960	0.55	0.0134	0.79	0.072
420	0.29	0.0027	0.3	0.0044	980	0.57	0.0145	0.79	0.075
440	0.3	0.0029	0.31	0.0046	1000	0.58	0.017	0.8	0.081
460	0.31	0.0033	0.37	0.0052	1020	0.62	0.019	0.81	0.089
480	0.33	0.0037	0.38	0.0055	1040	0.65	0.021	0.84	0.092
500	0.34	0.0039	0.4	0.0058	1060	0.7	0.004	0.88	0.095
520	0.35	0.0043	0.41	0.0065	1080	0.89	0.03	0.89	0.096
540	0.36	0.0045	0.42	0.007	1100	0.96	0.041	0.9	0.099

Table A.15: C800M25W0 and C800M25W1 Column

C800M25W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0	0	0.03	0
40	0.01	0	0.05	0.0002
60	0.02	0.0001	0.06	0.0004
80	0.02	0.0003	0.08	0.0006
100	0.04	0.0004	0.11	0.0008
120	0.06	0.001	0.12	0.002
140	0.07	0.0015	0.12	0.0023
160	0.09	0.0021	0.15	0.0025
180	0.13	0.0026	0.16	0.0026
200	0.16	0.0028	0.18	0.0026
220	0.17	0.003	0.19	0.0028
240	0.19	0.0032	0.23	0.003
260	0.22	0.0036	0.24	0.0031
280	0.26	0.0039	0.25	0.0034
300	0.27	0.004	0.28	0.0035
320	0.29	0.0042	0.31	0.0036
340	0.33	0.0043	0.32	0.004
360	0.35	0.0048	0.33	0.0043
380	0.37	0.0049	0.39	0.0044
400	0.39	0.005	0.39	0.0047
420	0.4	0.0052	0.41	0.0049
440	0.46	0.0054	0.42	0.005
460	0.47	0.0055	0.46	0.005
480	0.49	0.0058	0.47	0.0052
500	0.52	0.0059	0.48	0.0054
520	0.54	0.006	0.49	0.0058
540	0.55	0.0062	0.49	0.0059
560	0.57	0.0065	0.49	0.006
580	0.6	0.007	0.53	0.0062
600	0.6	0.0072	0.54	0.0063

C800M25W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0	0	0.08	0
40	0	0	0.09	0
60	0.01	0.0001	0.1	0
80	0.03	0.0002	0.105	0
100	0.04	0.0004	0.11	0
120	0.05	0.0006	0.12	0
140	0.05	0.0006	0.12	0
160	0.07	0.0006	0.12	0
180	0.08	0.0009	0.12	0
200	0.09	0.0014	0.12	0.0004
220	0.1	0.0016	0.12	0.0008
240	0.1	0.0018	0.13	0.0013
260	0.11	0.0019	0.13	0.0014
280	0.12	0.002	0.13	0.0018
300	0.13	0.0023	0.14	0.0018
320	0.15	0.0026	0.14	0.0021
340	0.16	0.0026	0.145	0.0022
360	0.18	0.0027	0.15	0.0024
380	0.19	0.0028	0.15	0.0034
400	0.2	0.003	0.15	0.0035
420	0.21	0.0031	0.16	0.0038
440	0.22	0.0036	0.165	0.0038
460	0.23	0.0038	0.165	0.004
480	0.24	0.004	0.17	0.0042
500	0.25	0.0042	0.19	0.0052
520	0.28	0.0043	0.21	0.0058
540	0.3	0.0047	0.22	0.0059
560	0.31	0.0048	0.24	0.0062
580	0.31	0.005	0.25	0.0062
600	0.33	0.0052	0.37	0.007

C800M25W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
620	0.61	0.0074	0.56	0.0065
640	0.61	0.0076	0.58	0.0067
660	0.62	0.0078	0.66	0.0068
680	0.63	0.008	0.68	0.007
700	0.64	0.0083	0.71	0.0071
720	0.67	0.0084	0.73	0.0073
740	0.68	0.0086	0.74	0.0075
760	0.69	0.009	0.78	0.0076
780	0.7	0.0091	0.78	0.0078
800	0.71	0.0092	0.81	0.0079
820			0.81	0.0079

C800M25W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
620	0.38	0.0055	0.39	0.0076
640	0.39	0.0058	0.43	0.008
660	0.4	0.006	0.48	0.0082
680	0.41	0.0065	0.5	0.0084
700	0.42	0.007	0.52	0.0087
720	0.45	0.0076	0.53	0.009
740	0.47	0.0081	0.59	0.0093
760	0.5	0.0086	0.6	0.0094
780	0.51	0.009	0.61	0.0096
800	0.53	0.0096	0.63	0.0101
820	0.57	0.01	0.65	0.0103
840	0.6	0.0104	0.67	0.0106
860	0.67	0.0108	0.69	0.011
880	0.69	0.011	0.71	0.0113
900	0.71	0.0114	0.75	0.0118
920	0.74	0.0116	0.76	0.012
940	0.76	0.0118	0.78	0.0123
960	0.79	0.0126	0.79	0.0125
980	0.81	0.0138	0.8	0.0128
1000	0.83	0.0145	0.81	0.013
1020			0.83	0.0133
1040			0.83	0.0138
1060			0.85	0.0141
1080			0.86	0.0145
1100			0.87	0.0146

Table A.16: C800M25W2 Column

C800M25W2				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0
20	0	0	0	0
40	0.01	0	0.01	0
60	0.03	0	0.015	0
80	0.05	0	0.015	0
100	0.05	0	0.015	0
120	0.07	0	0.015	0
140	0.09	0.0001	0.015	0
160	0.1	0.0002	0.015	0
180	0.11	0.0005	0.015	0
200	0.13	0.0008	0.015	0
220	0.16	0.001	0.02	0
240	0.17	0.0012	0.02	0
260	0.19	0.0013	0.02	0
280	0.2	0.0015	0.02	0.0002
300	0.21	0.0019	0.03	0.0004
320	0.23	0.0020	0.03	0.0006
340	0.24	0.0021	0.03	0.0008
360	0.26	0.0025	0.035	0.0008
380	0.28	0.0028	0.04	0.001
400	0.3	0.0031	0.05	0.0012
420	0.31	0.0035	0.06	0.0012
440	0.33	0.0039	0.08	0.0016
460	0.34	0.0041	0.12	0.0018
480	0.36	0.0043	0.15	0.002
500	0.38	0.0049	0.19	0.0026
520	0.4	0.0053	0.2	0.0028
540	0.41	0.0055	0.28	0.0035
560	0.41	0.0056	0.32	0.0036
580	0.43	0.0057	0.35	0.0039
600	0.48	0.0058	0.4	0.0044
620	0.49	0.006	0.42	0.0045
640	0.5	0.0063	0.46	0.0048
660	0.51	0.0071	0.48	0.0056
660	0.51	0.0071	0.48	0.0056
680	0.53	0.0078	0.51	0.0058
700	0.54	0.0084	0.54	0.0058
720	0.54	0.0089	0.6	0.0062
740	0.56	0.0098	0.65	0.0064
760	0.6	0.0103	0.7	0.0065
780	0.63	0.0108	0.7	0.0066
800	0.68	0.0112	0.71	0.0069
820	0.68	0.012	0.73	0.0075
840	0.69	0.0128	0.75	0.008
860	0.75	0.0137	0.76	0.0085
880	0.78	0.0144	0.76	0.0086
900	0.82	0.015	0.76	0.009
920	0.83	0.0159	0.78	0.0092
940	0.83	0.0163	0.78	0.0096
960	0.9	0.0176	0.79	0.01
980	0.98	0.018	0.8	0.011
1000	1.01	0.0197	0.8	0.0115
1020	1.15	0.021	0.82	0.0116
1040	1.28	0.0223	0.82	0.0118
1060	1.35	0.0238	0.85	0.012
1080	1.39	0.026	0.85	0.0122
1100	1.43	0.0276	0.86	0.0126
1120	1.49	0.0293	0.865	0.0128
1140	1.56	0.0304	0.88	0.013
1160	1.66	0.0315	0.88	0.0135
1180	1.73	0.0326	0.9	0.0136
1200	1.8	0.0342	0.9	0.014
1220			0.9	0.015
1240			0.92	0.0155
1260			0.96	0.016

Table A.17: C1200M25W0 and C1200M25W1 Column

C1200M25W0					C1200M25W1				
Load (kN)	Sample-1		Sample-2		Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)		Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
0	0	0	0	0	0	0	0	0	0
20	0	0	0.01	0	20	0	0	0.01	0
40	0.02	0.0002	0.06	0.0002	40	0	0	0.01	0
60	0.05	0.0004	0.07	0.0004	60	0	0.0002	0.01	0
80	0.09	0.0008	0.08	0.0006	80	0	0.0005	0.01	0
100	0.1	0.0013	0.12	0.0006	100	0	0.0008	0.01	0
120	0.11	0.0015	0.13	0.0012	120	0	0.0008	0.01	0
140	0.13	0.0019	0.14	0.0018	140	0	0.0009	0.01	0
160	0.16	0.002	0.16	0.002	160	0	0.0012	0.01	0
180	0.17	0.0023	0.17	0.0024	180	0	0.0013	0.01	0
200	0.19	0.0027	0.18	0.0026	200	0.01	0.0016	0.01	0
220	0.22	0.0028	0.19	0.0029	220	0.01	0.0017	0.01	0.0001
240	0.25	0.003	0.23	0.003	240	0.01	0.0019	0.015	0.0002
260	0.28	0.0033	0.24	0.0032	260	0.02	0.002	0.015	0.0002
280	0.29	0.0034	0.28	0.0036	280	0.025	0.0022	0.02	0.0002
300	0.33	0.0037	0.28	0.0038	300	0.03	0.0024	0.02	0.0004
320	0.38	0.0037	0.3	0.0038	320	0.03	0.0026	0.02	0.0005
340	0.39	0.0039	0.31	0.0046	340	0.04	0.0028	0.02	0.0006
360	0.42	0.004	0.34	0.0048	360	0.05	0.0028	0.025	0.0006
380	0.44	0.0042	0.34	0.0049	380	0.05	0.003	0.03	0.0006
400	0.48	0.0046	0.39	0.005	400	0.05	0.0032	0.03	0.0008
420	0.5	0.0049	0.4	0.0054	420	0.06	0.0035	0.03	0.0008
440	0.52	0.005	0.41	0.0056	440	0.06	0.0039	0.03	0.001
460	0.52	0.0052	0.43	0.0058	460	0.06	0.0042	0.03	0.001
480	0.53	0.0056	0.45	0.006	480	0.07	0.0044	0.03	0.0012
500	0.56	0.0058	0.46	0.0063	500	0.08	0.0048	0.03	0.0015
520	0.57	0.006	0.51	0.0065	520	0.09	0.005	0.035	0.0016
540	0.58	0.0062	0.52	0.0066	540	0.09	0.0051	0.035	0.0019
560	0.61	0.0063	0.53	0.007	560	0.09	0.0053	0.035	0.002
580	0.65	0.0064	0.54	0.0072	580	0.1	0.0056	0.035	0.002
600	0.67	0.0065	0.56	0.0073	600	0.11	0.0059	0.04	0.0022

C1200M25W0				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
620	0.69	0.007	0.56	0.0075
640	0.7	0.0073	0.62	0.0076
660	0.72	0.008	0.62	0.008
680	0.73	0.0085	0.63	0.0081
700	0.78	0.0087	0.66	0.0083
720	0.79	0.0089	0.67	0.0084
740	0.81	0.0091	0.7	0.0088
760	0.83	0.0092	0.72	0.009
780	0.85	0.0093	0.73	0.0092
800			0.74	0.0098

C1200M25W1				
Load (kN)	Sample-1		Sample-2	
	Linear Def. (mm)	Lateral Def. (mm)	Linear Def. (mm)	Lateral Def. (mm)
620	0.11	0.0061	0.04	0.0025
640	0.12	0.0065	0.04	0.0026
660	0.13	0.0068	0.04	0.0026
680	0.14	0.0071	0.045	0.0028
700	0.16	0.008	0.045	0.0034
720	0.18	0.0084	0.045	0.0036
740	0.2	0.009	0.045	0.004
760	0.21	0.0092	0.05	0.0045
780	0.22	0.0096	0.05	0.0046
800	0.24	0.01	0.05	0.0048
820	0.27	0.0103	0.05	0.005
840	0.29	0.0106	0.055	0.0054
860	0.32	0.0108	0.055	0.006
880	0.34	0.0111	0.06	0.0064
900	0.37	0.0114	0.06	0.0066
920	0.37	0.0116	0.065	0.0086
940	0.4	0.0119	0.07	0.0094
960	0.46	0.013	0.07	0.0098
980	0.52	0.0133	0.07	0.01
1000	0.56	0.0138	0.07	0.0105
1020	0.6	0.014	0.07	0.014
1040	0.66	0.0155		
1060	0.71	0.0162		
1080	0.78	0.018		
1100	0.83	0.0191		

Table A.18: C1200M25W2 Column

C1200M25W2					
Sample-1					
Load (kN)	Linear Def.(mm)	Lateral Def.(mm)	Load (kN)	Linear Def.(mm)	Lateral Def.(mm)
0	0	0	640	0.38	0.0072
20	0.04	0	660	0.39	0.0077
40	0.05	0	680	0.4	0.0079
60	0.05	0.0001	700	0.4	0.0082
80	0.06	0.0002	720	0.41	0.0086
100	0.06	0.0004	740	0.42	0.0089
120	0.07	0.0006	760	0.44	0.009
140	0.08	0.0008	780	0.45	0.0091
160	0.1	0.001	800	0.47	0.0096
180	0.11	0.0011	820	0.49	0.01
200	0.11	0.002	840	0.5	0.0101
220	0.13	0.0021	860	0.51	0.0103
240	0.14	0.0021	880	0.52	0.0109
260	0.15	0.0021	900	0.54	0.011
280	0.17	0.0022	920	0.56	0.0115
300	0.18	0.0025	940	0.58	0.0122
320	0.19	0.003	960	0.6	0.0128
340	0.19	0.0031	980	0.62	0.013
360	0.2	0.0034	1000	0.64	0.0146
380	0.21	0.004	1020	0.67	0.015
400	0.22	0.0041	1040	0.7	0.0154
420	0.23	0.0042	1060	0.73	0.017
440	0.25	0.0046	1080	0.75	0.0178
460	0.26	0.005	1100	0.82	0.0182
480	0.27	0.0051	1120	0.86	0.019
500	0.28	0.0053	1140	0.93	0.0201
520	0.29	0.0058	1160	1.01	0.0215
540	0.3	0.006	1180	1.05	0.023
560	0.32	0.0062	1200	1.12	0.0243
580	0.33	0.0064	1220	1.16	0.025
600	0.35	0.0068	1240	1.23	0.0264

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