Strengthening of Reinforced Concrete Cylinders by using Aluminum Alloy Sheet

By

Asad Bashir

(Registration No: 00000328737)

Department of Structural Engineering

NUST Institute of Civil Engineering

School of Civil and Environmental Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2024)

Strengthening of Reinforced Concrete Cylinders

by using Aluminum Alloy Sheet

By

Asad Bashir

(Registration No: 00000328737)

A thesis submitted to the National University of Sciences and Technology, Islamabad,

in partial fulfillment of the requirements for the degree of

Masters of Science

in

Structural Engineering

Thesis Supervisor: Dr. Muhammad Usman

NUST Institute of Civil Engineering

School of Civil and Environmental Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

THESIS ACCEPTANCE CERTIFICATE

It is certified that Mr. Asad Bashir, Registration No. 00000328737of MS Structural Engineering of batch 2020 has completed his thesis work and submitted final copy which was evaluated and found to be complete in all aspects as per policy of NUST/Regulations, is free of plagiarism, errors and mistakes and is accepted as partial fulfillment for award of MS degree. It is further certified that necessary amendments as pointed by GEC members of the scholar have been incorporated in the said thesis.

Signature: ______________________

Supervisor: Dr. Muhammad Usman

Date: 13-9-24

Signature: ______________________

Head of Department: Dr. Muhammad Usman

HoD Structural Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

Date: 13-9-24

Signature: ______________________

Associate Dean: Dr. S. Muhammad Jamil

Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

Date: 13/09/2024

Signature: ______________________

Principal & Dean (SCEE-NICE): Dr. Muhammad Irfan

Date: 13 SEP 2024

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

Form TH-4

National University of Sciences and Technology

MASTER'S THESIS WORK

We hereby recommend that the dissertation prepared under our Supervision by Student Name: **Asad Bashir** & Regn No. **00000328737** Titled: "**Strengthening of Reinforced Concrete Cylinders by using Aluminum Alloy Sheet**" be accepted in partial fulfillment of the requirements for the award of degree with (B+ Grade).

Examination Committee Members

1. Name: **DR. AZAM KHAN** Signature: ________

2. Name: **DR. JUNAID AHMAD** Signature: ________

Supervisor's name: **DR. MUHAMMAD USMAN** Signature: ________

HoD Structural Engineering
Head of Department
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

(Associate Dean)
Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

COUNTERSIGNED

Date: 13 SEP 2024

Dean/Principal SCEE
PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

Certificate of Approval

This is to certify that the research work presented in this thesis, entitled **"Strengthening of Reinforced Concrete Cylinders by using Aluminum Alloy Sheet"** was conducted by Mr. Asad Bashir under the supervision of Dr. Muhammad Usman.

No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the National University of Sciences and Technology (NUST) in partial fulfillment of the requirements for the degree of Master of Science in field of Urban & Regional Planning from NUST institute of Civil Engineering (NICE), School of Civil and Environmental Engineering (SCEE), NUST

Student Name: Asad Bashir — Signature: ____________

Examination Committee:

a) GEC Member 1: Dr. Azam Khan
Associate Professor (SCEE, NUST) — Signature ____________

b) GEC Member 2: Dr. Junaid Ahmed
Assistant Professor (SCEE, NUST) — Signature ____________

Supervisor Name: Dr. Muhammad Usman — Signature: ____________

Name of HOD: Dr. Muhammad Usman — Signature: ____________

HoD Structural Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

Name of Associate Dean: Dr. S. Muhammad Jamil — Signature: ____________

Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

Name of Principal & Dean: Prof. Dr. Muhammad Irfan — Signature: ____________

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

Author's Declaration

I Mr. Asad Bashir hereby state that my MS thesis titled "Strengthening of Reinforced Concrete Cylinders by using Aluminum Alloy Sheet" is my own work and has not been submitted previously by me for taking any degree from this University

National University of Sciences & Technology (NUST) Islamabad, Pakistan.

or anywhere else in the country/ world.

At any time if my statement is found to be incorrect even after I graduate, the university has the right to withdraw my MS degree.

Name of Student: Asad Bashir

Date: 13-09-2024

Plagiarism Undertaking

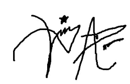
I solemnly declare that research work presented in the thesis titled "Strengthening of Reinforced Concrete Cylinders by using Aluminum Alloy Sheet"

is solely my research work with no significant contribution from any other person. Small contribution/ help wherever taken has been duly acknowledged and that complete thesis has been written by me.

I understand the zero tolerance policy of the HEC and University

National University of Sciences & Technology (NUST) Islamabad, Pakistan
towards plagiarism. Therefore, I as an author of the above titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS degree, the University reserves the rights to withdraw/revoke my MS degree and that HEC and the University has the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized thesis.

Student/Author Signature: 

Name: Asad Bashir

ACKNOWLEDGEMENTS

"In the name of Allah, the most beneficent the most merciful"

First and foremost, I would like to express my gratitude to my research supervisors, Dr. Muhammad Usman, and Dr. Ather Ali for their dedication, curiosity, and vast expertise. Their advice was helpful to me throughout the entire research and thesis-writing process. Their kind and hospitable demeanor allowed me to thoroughly share my viewpoint on the subject and had all of my questions answered.

It is important to note that my devoted and supportive colleagues made it feasible for this study to be completed on time. Along with my GEC committee members and supervisor, I would also like to express my gratitude to my friends, in particular Manzoor Rehman and Arbaz Khan, for their unwavering support during my studies.

In the end, I would like to express my sincere gratitude to my family members, for everything they have meant to me during this crucial period of completion of my studies.

ABSTRACT

The aim of this research study is to develop an efficient and cost effective confining technique for compression elements in Pakistan using indigenous materials and local skills. The most common technique for concrete confinement is jacketing by either reinforced concrete, special concrete, steel, composite material and FRP. The issues related to current techniques are brittleness, expensive, corrosion, de-bonding and requirement of experienced labor. In the current study Aluminum Alloy sheets along with bolted connection are used for confinement of concrete. Aluminum alloys are becoming increasingly prevalent in the construction industry due to their high strength and lightweight, simplicity of fabrication, high ductility, resistance to corrosion, and distinctive appearance. Concrete cylinders of 200 mm diameter are casted and divided into seven categories based on the variables including height, number of layers of Aluminum Alloy Sheet and number of bolts. All the samples are tested under uniaxial compression. Results have shown considerable increase in ultimate strength of modified members. It is also observed that external confinement has reduced the ductility of members slightly. Modified samples has also shown greater initial stiffness and delayed initial cracking. Experimental results are compared with different analytical models. Analytical models presented by Mander (1988), Canadian Standard Association (CSA) S806-02, Kaushik & Singh (1999), and Samaan et al. (1998) have shown close correlation with experimental data.

Keywords: Concrete, Confinement, Compression, Aluminum Alloy, Strength, Ductility

TABLE OF CONTENTS

Page No.

LIST OF TABLES

Page No.

LIST OF FIGURES

Page No.

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

AA	Aluminum Alloy
FRP	Fiber Reinforced Polymer
SSWM	Stainless Steel Wire Mesh
UHPC	Ultra High Performance Concrete
HPC	High Performance Concrete

CHAPTER 1: INTRODUCTION

1.1 General

Reinforced Concrete structures are the backbone of modern infrastructure. Due to essential strength and durability, RC structures are widely used for construction of buildings, dams, roads and bridges etc. However, with time, even concrete structures are susceptible to degradation and damage from a variety of sources, including exposure to adverse weather conditions, significant stresses, inadequate construction, and environmental variables. Besides deterioration, there are certain other phenomenon which demands for increase in performance of structure such as: increase in load demand, decrease in load capacity, safety and durability assurance, code compliance, risk reduction etc.

Following are different methods to improve the performance of structure:

- Re-construction
- Retrofitting
- Strengthening
- Repairing
- Providing Supports (like under pinning)

Strengthening of a structure refers to the process of enhancing the structural integrity, load-carrying capacity, durability, and overall performance of buildings.

To improve a concrete member's ability to support heavier loads, structural strengthening implies either expanding the cross-sectional area or adding more reinforcement. This method is usually applied when an excessive load is placed on a concrete member or when the structure's overall strength needs to be increased. Adding extra reinforcement, post-tensioning, external confinement with fiber-reinforced polymers (FRPs) especially carbon fiber reinforced polymers (CFRPs) or glass fiber reinforced polymers (GFRPs) are a few structural strengthening approaches.

Retrofitting is the act of reinforcing pre-existing structures—such as residential and historical buildings and bridges—after they have sustained damage. By employing this method, they can be strengthened against earthquakes, volcanic eruptions, and other natural calamities like storms, floods, and slope failures. In order to restore strength, broken concrete components are retrofitted. It also helps to keep additional damage to concrete components from occurring. Errors in the design or poor workmanship may be the cause of a concrete element's insufficient strength. The reduction could also be caused by the aggressiveness of dangerous compounds. The extent of the damage will determine how much of the original capacity of the structure may be restored once the appropriate retrofitting technology has been applied and specified.

There are several advantages of strengthening the existing structures such as:

- It enhances the load carrying capacity
- Ensure safety and durability of structure
- Crucial for upgrading structures to meet modern codes and standards, especially in seismic regions where improved resilience against earthquakes is essential
- Due to space constraints and over costs, demolishing and reconstruction is impractical especially in urban areas, so it has more value over there.

This research study is focused on strengthening of compression members. Different strengthening techniques used for the strengthening of compression members are adding additional layer of concrete, jacketing with steel, Wrapping composite materials or FRPs. In this research study Aluminum Alloy sheet is used to wrap the reinforced concrete cylinders with bolted connections.

1.2 Problem Statement

Most commonly used materials for concrete confinement in columns are special concrete, steel, and composite materials like FRPs. Adding external layer of concrete significantly increases the cross sectional area and dead load of the structure. This solution may be problematic is close spaces. Increase in dead load may also require strengthening of foundation and adjoining structural elements. Steel is prone to corrosion and has low fire resistance. FRPs bear drawbacks of installation challenges, de-bonding, premature failure, limited repair-ability, low fire resistance, high initial cost etc.

1.3 Research Objective

The objectives of this research study are:

- To study the effect of wrapping Aluminum Alloy (AA) sheet on concrete cylinder.
- To analyze the effect of increasing number of layers of Aluminum Alloy (AA) sheet.
- To analyze the effect of changing height of sample.
- To check the suitability of both bolted and epoxy connections.
- Comparison of Experimental results with different Analytical Models.

1.4 Organization of Thesis

The thesis of current research study is organized as following:

CHAPTER NO. 1 – Introduction: This chapter includes the problems related to current concrete confining techniques, requirement of a new technique and its impact on country demands, objectives and methodology.

CHAPTER NO. 2 – Literature Review: This chapter accomplish an overview of the different materials and techniques commonly utilized for strengthening of reinforced concrete columns.

CHAPTER NO. 3 – Methodology: This chapter includes the details of material used in this research study and individual ingredient tests performed to confirm the properties of materials.

CHAPTER NO. 4 – Experimental Program: This chapter includes detail of formwork, Preparation of testing samples, confining of samples, and organization of loading assembly.

CHAPTER NO. 5 – Result and Discussion: This chapter focuses on compiling and analyzing the experimental results. Different analytical models that were developed for ultimate strength of reinforced concrete strengthened column are also discussed.

CHAPTER NO. 6 –Conclusions: It illustrates how the goals of the research have been accomplished. It also summarizes the benefits of using aluminum alloy for strengthening applications.

CHAPTER 2: LITERATURE REVIEW

Even though structures constructed with reinforced concrete (RC) are projected to survive for a long time, environmental forces eventually lead them to deteriorate. Increased applied loads, alterations to the structure's functionality, seismic damage, or even amendments to the design specifications all lead RC structures and its components to progressively decrease durability and ductility. They must therefore be strengthened and made more rigid. The conventional technique of sustaining members made of reinforced concrete (RC) entailed reinforcing and expanding the structure. (Ashraf, 2010) Nevertheless, there are inherent drawbacks to this technique, including a higher dead load and the greater susceptibility of the extra reinforcement to corrosion. It demands that steel must be galvanized and coated. It decreases the capacity of area that is capable of being allocated to living space (headroom and area) and raises maintenance costs. As a consequence, numerous tactics to strengthen the members of RC have been put forth. Steel plates became the most widely used external coupled reinforcing technique for reinforced concrete structures in the 1960s. In this method, an adhesive was used to join the exterior of the RC component with the steel. The epoxy layer that separates the two components transfers the shear loads between the plate and the concrete. Contrarily, steel has shown throughout time to be unsuitable for use as an external bonded reinforcement material because of corrosion and other problems. As a result, it became imperative to create substitute materials for steel plates so that stronger and more long-lasting structures could be built. (Theodoros Chrysanidis, 2020)

One of the most often used methods for reinforcing structures is the Externally Bonded

Reinforcement (EBR) emergence of Fiber Reinforced Polymers (FRP). Enhancing the resilience to stress of deteriorated RC sections is the main objective of FRP. (Theodoros Chrysanidis, 2020)

2.1 Strengthening of Column

Column confinement is the crucial aspect in structural engineering to exaggerate the load-bearing capacity and overall ductility of reinforced concrete columns. This research study is focused on strengthening of compression members. Compression members are the most critical part of the building. Different strengthening techniques used for the strengthening of compression members are concrete jacketing, jacketing with steel, Wrapping composite materials or FRPs. (Theodoros Chrysanidis, 2020) In this research study Aluminum Alloy sheet is used to wrap the reinforced concrete cylinders with bolted connections. Following are some literature studies related to above-mentioned techniques.

2.1.1 Concrete Jacketing

The process of placing a second layer of concrete around an existing column is known as concrete jacketing. Increasing the column's cross-sectional area and load capacity with this technology is advantageous. To offer better mechanical qualities and durability, Ultra High Performance concrete (UHPC) and High Performance concrete (HPC) are developed (Meda A, 2008).

Because of its mechanical properties and compatibility with inorganic materials, textile-reinforced mortar (TRM) has become more popular for strengthening concrete structures. It provides advantages for structural reinforcement while getting around the drawbacks of organic materials (Park, 2021).

Al-Osta et al. evaluated columns constructed with reinforced concrete (RC) and confined with the help of Ultra High Performance Concrete (UHPC). Experimental findings endorsed the competency of UHPC confinement to strengthen reinforced concrete column loaded eccentrically. The rate of improvement in performance directly depends upon the thickness of UHPC layer and is inversely related to the degree of eccentricity.(Mohammed A. Al-Osta, 2021)

Vecchio et al. investigated deteriorated reinforced concrete columns externally confined with UHPC. The modified columns were then tested by applying concentric loading and results have declared considerable improvement in the capacity tested samples (C. Del Vecchio, 2018).

Xie et al. assessed the RC columns modified by adding extra layer of UHPC. The study includes both experimental and numerical analysis. The width of UHPC layer and cross sectional dimensions of the column were the main variables which are considered in this study. The finding of study proven that columns with circular cross section perform better as compared to rectangular cross section.(Xie Jian, 2019)

2.1.2 Steel Jacketing

One of the another commonly used material for strengthening of RC column is Steel jackets. These includes enclosing the column in a steel shell, which enhances the column's load-bearing capacity and confinement. Analysis of the bearing capacity and earthquake performance of columns made of RC upgraded employing externally encased steel plates has shown significant improvements in the columns' capacity for energy dissipation, plastic deformation, and earthquake performance after strengthening (C. Zhou, Li, X., Wang, D., & Xia, S, 2019).

V. Kumar et. al investigated axial strength of circular columns made up of plain cement concrete of different grades having strength of 15, 20, and 25 MPA. Columns are modified with ready accessible stainless steelswire mesh, SSWM from the nearby area. Column specimens were constructed with diameter of 200 mm and various heights of 400, 800 and 1200 mm. These samples are then wrapped with single and double layers of SSWM. The axial load performance of samples was compared to that of control specimens. To determine whether SSWM could be strengthened, researchers looked at the material's ultimate tensile strength and binding strength with concrete. According to a research study of 54 column specimens Axial compressive strength can be enhanced by up to 61% & 86%, respectively, when samples are externally wrapped with one or two layers of SSWM (Varinder Kumar 2016).

Chrysanidis et al. looked into novel approaches and strategies to improve the confinement and axial and transverse load-carrying capability of RC concrete columns with circular cross sectional shape. The process of strengthening columns involved building jackets made of metallic semi-circular pipe systems mixed with either spiral reinforcement and high strength mortar or high strength mortar alone. Nine test specimens that simulate circular shaped cross section RC concrete columns have been built and put through testing with both an axial load history and a transverse load history. They came to the conclusion that compared to other traditional procedures, this one can be adopted in the building industry more swiftly and easily. Additionally, they are less expensive than traditional methods, and they also preserve the same level of mechanical behavior improvement in the form of strength and durability (Theodoros Chrysanidis, 2020).

The use of steel bracing as a strengthening method by adding diagonal stiffeners to structural elements has been effective in improving the overall stability and performance of buildings (Ismail, 2021).

Regarding prestressing techniques, external prestressing methods have been utilized to strengthen concrete structures by applying tension to weak tensile areas, thereby increasing the usability and safety of the structure, especially in scenarios where deflection and deformation need to be controlled (Kim, 2021). Furthermore, distributed prestressed high-strength steel wire ropes have been explored for strengthening reinforced concrete beams, emphasizing the importance of innovative materials and techniques to enhance the flexural strength and durability of structural elements (G. Wu, Wu, Z., Wei, Y., Jiang, J., & Cui, Y., 2012).

2.1.3 Wrapping with Composite Materials

Beyond FRPs, other advanced composites like textile-reinforced concrete (TRC) and hybrid composite systems are being explored for their improved mechanical properties and adaptability. The application of Hybrid FRP composites in strengthening columns has been studied, showing significant improvements in performance under eccentric compression (Chellapandian, 2019). Studies have also explored the use of pre-tensioned steel jackets and Ferrocement jacketing combined with Aramid fiber sheet wrapping to strengthen short RC columns, indicating positive outcomes in terms of increased load taking capacity and durability (Kozman, 2023).

The axial compression behavior of compression elements additionally reinforced with externally applied cementitious grout jackets and rectangular steel tubes was assessed by F. Wang et al. The outcome showed that employing this strengthening technique could significantly increase the original RC column's strength, stiffness, and ductility. As aspect ratio and concrete cross sectional area ratio increase, stub column's axial compressive resistance falls. As the concrete cross-sectional area ratio decreases and the aspect ratio and concrete strength are varied in ascending order, the ductility index value decreases as well (Fengqin Wang, 2021).

2.1.4 Wrapping with Fiber Reinforced Polymers

Because of its excellent high strength, low weight and simplicity of use, FRP composites are frequently employed. To increase the load bearing capacity and durability of RC concrete columns, they are usually wrapped externally. the application of Fiber Reinforced Polymer (FRP) wrapping or jacketing, which has been demonstrated to be useful for strengthening concrete columns (Guo, 2018). Studies have demonstrated that columns strengthened with FRP materials exhibit improved stress-strain relationships, higher load carrying capacities, and increased ductility compared to conventional techniques (Janwaen, 2019).

Fiber reinforced polymer (FRP) composites, are known for their high strength, low weight and high resistance for corrosion, make them suitable for enhancing the load bearing capacity of steel structures without the need for welding. By avoiding welding, which can introduce fire risks and weaken the structure, bonding FRP laminates provides a viable alternative for strengthening steel structures (J. Teng, Yu, T., & Fernando, D, 2012). Similarly, in concrete structures, FRP materials are used for flexural and shear strengthening of beam, slab, and column, contributing to improved structural performance under static and seismic loads (J. Teng, Chen, J., Smith, S., & Lam, L., 2003).

Abadel et. al investigated the proficiency of different confining techniques by using carbon fiber reinforced polymer (CFRP) wraps and near surface mounted (NSM) steel reinforcement bars for the rehabilitation of circular shaped and square shaped RC concrete columns which are damaged because they were revealed to high rise temperature. For three hours, the heated columns were being revealed to the temperature of 600°C. Two construction plans were assessed. The initial strengthening plan used NSM steel bars with unidirectional CFRP strips. The second plan called for strengthening exclusively using unidirectional CFRP strips. Axial compression testing was performed on each column until it failed. According to the test results, exposed to high temperatures reduced the load taking ability of square shaped columns by 29% and circular shaped columns by 38%. In heat-damaged RC columns, both strengthening strategies successfully restored and exceeded (by around 16%) their initial load-carrying capacity. Achieving the pre-damaged stiffness value of the heated columns was more successful when CFRP strips were used in conjunction with NSM steel bars than when CFRP strips were used alone. In comparison to square columns, the early stiffness achievement was more noticeable in circular shaped columns. Before being exposed to heat, the stiffness of the circular shaped columns was 15% higher than that of the control specimen. Prior to heat exposure, the stiffness of square shaped columns was equal to the control RC column specimen (Aref A. Abadel, 2021).

Shorter RC concrete square column elements were being strengthened employing both Externally wrapped CFRP fabrics and Near Surface Mounted (NSM) CFRP laminates in an inventive hybrid confining technique investigated by M. Chellapandian et al. In order to examine the effectiveness of various strengthening technique combinations, ten number of square shaped column elements with a cross section of 230mm by 230mm and the height of samples 450 mm were cast, reinforced, and checked by applying concentric compression load. RC columns that were just NSM- or CFRP-confined showed lower increases in strength, stiffness, and ductility. In contrast, hybrid strengthening proved to be more effective (M. Chellapandian, 2017).

Short, rectangular reinforced concrete (RC) columns with rounded sides that were subjected to an axial load strengthening utilizing Glass Fiber Reinforced Polymer (GFRP) cloth bonded with epoxy were evaluated by Madupu et al. When GFRP fabric is wrapped around an RC rectangular column specimen and adhered with epoxy as adhesive, they report a considerably increase in the column's axial load bearing capacity. It is preferable to wrap the column entirely with strips rather than a single piece of continuous cloth. When it comes to strip width, wider strips produce finer results than narrower strips. Staggered strips are preferable to single-layer strips when they have two or more layers wrapped around them. Using two layers of GFRP strips increases the axial load capacity, while using three wraps of GFRP strips resulted in a drop in axial load taking capacity (L.N.K. Sai Madupu, 2020).

2.2 Limitations of Current Techniques

Every technique has certain drawbacks, limitations and challenges. This portion of research study is an attempt to address the drawbacks associated with different techniques and lead towards new material and technique.

Following are the drawbacks and limitations of above-mentioned techniques.

2.2.1 Concrete Jacketing

Adding external layer of concrete significantly increases the cross sectional area and dead load of the structure. This solution may be problematic is close spaces. Increase in dead load may also require strengthening of foundation and adjoining structural elements.

- The bonding of old and new concrete is also a question. Secondly difference in shrinkage rate of old and new concrete may also lead to development of cracks and failure of bond.
- This technique also requires greater amount of time.
- Use of cement concrete increases carbon footprint.

2.2.2 Steel Jacketing

Following are the issues related to steel jacketing:

- Steel is prone to corrosion which can compromise the integrity and durability of the structure. Therefore, it cannot be used in industrial and coastal areas.
- Steel is heavy and difficult to handle during strengthening. It also increases the cross sectional area and dead load of the structure. Increase in dead load may also require strengthening of foundation and adjoining structural elements.
- Installation of steel jacketing requires surface preparation, use of special tools and techniques. So it is labor-intensive and time consuming also.
- It also has low fire resistance.

2.2.3 Fiber Reinforced Polymers Wrapping

Most commonly used FRPs are carbon fiber reinforced polymers (CFRPs) or glass fiber reinforced polymers (GFRPs). FRPs are preferred because of their high strength to weight ratio. The issues related to the use of FRPs are:

- FRPs are expensive.

- Prone to de-bonding and pre-mature failure.
- Can degrade under high temperature and ultraviolet radiation.
- Requires surface preparation, skilled labor and greater installation time.
- CFRP has low fire resistance.
- Have limited repair-ability.
- Production of CFRP emits greenhouse gases.
- High strength FRPs are brittle.

2.3 Use of Aluminum Alloy

In recent years, the use of metal sheets, particularly aluminum alloy sheets, has emerged as a promising alternative for strengthening RC structures. Aluminum alloys offer a unique combination of properties that make them suitable for structural applications. Research has shown that aluminum alloys, such as 6082-T6 and 7A04-T6, have been used in the fabrication of columns, demonstrating improved mechanical properties (Bashir, 2024; Y. Wang, Lin, S., Fan, F., Zhai, X., & Qian, H. , 2016). These aluminum alloys have been combined with different materials like concrete, wooden, and carbon fiber reinforced plastic (CFRP) to create composite columns, showcasing enhanced performance (Fan, 2024). Additionally, aluminum has been employed as an outer tube in concrete-filled double-skin aluminum tubular columns to reduce weight while maintaining structural integrity (Yan, 2023).

Studies have indicated that the use of aluminum in column structures can lead to increased load-carrying capacity, with aluminum tube thicknesses playing a crucial role in enhancing the performance of the columns (Alshimmeri, 2016). Furthermore, filling columns with aluminum foam has been found to provide significant energy absorption, contributing to crashworthiness and structural safety (Lee, 2009). Optimization techniques have been employed to enhance the energy absorption capabilities of aluminum-filled columns, further improving their performance (Chahardoli, 2022). Aluminum has also been utilized in conjunction with concrete to create columns that offer high strength and stiffness, leveraging the benefits of both materials (F. a. Y. Zhou, B., 2009). The utilization of aluminum in the design of rolled aluminum channel section columns has been explored, providing insights into the structural design considerations for such columns (Pham, 2023). Moreover, the substitution of steel tubes with aluminum alloy tubes in concrete-filled columns has gained attention in the scientific community, highlighting the versatility and potential of aluminum in structural applications (Ding, 2021). The mechanical behaviors of concrete-filled aluminum tubular (CFAT) columns have been compared to those of concrete-filled steel tubular (CFST) columns, indicating comparable performance due to similar material properties (Rohilla, 2023). Parametric studies and design considerations have been conducted to optimize the performance of aluminum alloy tubular columns, emphasizing the importance of material selection and design methodologies (Zhu, 2006). Experimental investigations have been performed to analyze the behavior of aluminum columns under different loading circumstances, providing valuable data for structural design and analysis (Z. Wang, Wang, Y., Yun, X., Gardner, L., & Hu, X., 2020; Y. a. Z. Wu, Q, 2011).

Furthermore, Zhou & Young (2009) examined concrete-filled aluminum circular hollow section columns strengthened with fiber-reinforced plastic (FRP), illustrating the effectiveness of FRP in enhancing the column's performance (F. a. Y. Zhou, B., 2009). Rosalia et al. conducted an experimental analysis on the crashworthiness response of hybrid aluminum/glass fiber reinforced polymer (GFRP) crash-box structures, showing that adding external layer of composites to aluminum columns improved their energy absorption capacity (Rosalia, 2020).

Bolts play a crucial role in connecting steel beams to concrete columns in structural engineering applications. Various studies have been organized to examine the behavior and performance of bolted connections in concrete columns. For instance, Li et al. (2017) introduced a new type of joint using high-strength bolted end plates in steel beam-reinforced concrete column connections, demonstrating excellent seismic performance (Li, 2017). Through bolts have been studied as parameters affecting the moment-resistant behavior of connections between double steel tubular column filled with concrete and steel beam ("Parametric studies on the moment resistant beamcolumn connection behavior of concrete filled double steel tubular columns and i steel beams..", 2022). Tizani et al. (2022) aimed to understand the behavior of anchored blind bolt connections in concrete-filled columns to establish appropriate design rules for moment-resisting connections (Tizani, 2022). Additionally, Pascual et al. (2015) assessed blind bolted connections to tubular column filled with concrete for fire performance, highlighting the advantage of utilizing steel bolts with high fire resistance (Pascual, 2015).

CHAPTER 3: METHODOLOGY

Methodology used for this research work includes collection and testing of materials followed by preparation of samples and their testing. This chapter includes the detail of material employed in this research study. Different tests are conducted on individual ingredients to find their properties and suitability of materials for the research work.

3.1 Materials and Their Properties

Following are the different materials used in this research work:

3.1.1 Ordinary Portland Cement

Ordinary Portland Cement of Grade 43 (OPC 43), produced by Cherat Cement Industry, was used in the research project throughout. The cement was free from any Aggregates, hard lumps and uniform in color. The fineness of cement was tested as per procedure given in ASTM C 786, by sieving through sieve 200. The Normal Consistency Test of cement was performed as per procedure given in ASTM C 187-16.

<u>Percentage Fineness of Cement</u>

This test is performed according to (ASTM C 786). Fineness describes the size of the particles in the cement. The fineness of cement is important to determine because of following reasons:

- Cement fineness influences the rate of hydration and, thus, the strength. Elevating the fineness results in higher heat generation, greater strength, and a faster rate of hydration.

- Increasing fineness might decrease bleeding. But higher fineness can also mean that more water is needed to make the material workable, which raises the risk of dry shrinkage.
- More surface area will be accessible for the interaction of water and cement per unit volume by virtue of the higher surface area to volume ratio.

Figure 3-1 Cement Sample for Fineness Test

The fineness of cement used in this experimental work is 93%.

Normal Consistency of Cement

A certain amount of water is required to react with cement to make a past with appropriate plasticity; less water would not complete the chemical reaction and result in a reduction in strength; more water would increase the water-cement ratio and so reduce strength; consistency is resistance to shear deformation and is therefore important to determine when determining the compressive strength of concrete or workability test for concrete. The Normal Consistency Test of cement was carried out using a Vicat Apparatus.

Figure 3-2 Consistency Test with Vicat Apparatus

Normal consistency of cement used in this research work is 27%.

3.1.2 Fine Aggregate

The most popular use for natural sand, also known as river sand, is as a fine aggregate.

As a naturally occurring granular material made up of finely divided rock and mineral particles, river sand can replenish itself. The composition of sand varies greatly depending on the local rock sources and conditions, but silica (silicon dioxide), usually in the form of quartz, is the most common component resistant to weathering. There are many applications for sand found in floodplains and river channels in the building industry, making it a crucial raw material. The fine aggregate utilized was medium sand with a fineness modulus of 2.84 from Nizampur.

Physical properties of the sand i.e. gradation, fineness modulus, and specific gravity are evaluated according to the procedures given by the American Society of Testing and Materials (ASTM).

Gradation of Fine Aggregate

The process of determining the aggregate's particle-size distribution is known as grading. Because these characteristics have an impact on the quantity of aggregate used, as well as the amount of cement and water needed, as well as the strength, workability, and durability of concrete, grading restrictions and maximum aggregate size are defined. In accordance with ASTM C 136 protocol, a series of sieves was used to filter the sand, and the results were compared to ASTM C 33 specifications. Then using the result of sieve analysis, the fineness modulus of sand was calculated.

Figure 3-3 Set of Sieves For Gradation of Sand

Table 3-1 Result of Sieve Analysis

Sieve no	Weight Retained (gm)	%age weight retained	%age Cumulative Passing	%age Cumulative retained
#4	8.5	1.7	98.3	1.7
#8	52.5	10.5	87.8	12.2
#16	77.5	15.5	72.3	27.7
#30	146	29.2	43.1	56.9
#50	145	29	14.1	85.9
#100	67	13.4	0.7	99.3

#200	0.5	0.1	0.6	-
Pan	1.5	0.3	0.3	-
Fineness Modulus = 2.84				

Specific Gravity of Fine Aggregate (ASTM D-854)

The weight of a specific volume of aggregate divided by the weight of an equivalent volume of water is known as specific gravity. Specific gravity matters for a number of reasons. Certain harmful particles have a lower weight than the "good" aggregates. Monitoring specific gravity can occasionally reveal an alteration in composition or potential contamination. Specific Gravity of sand was tested as per procedure given in ASTM D 854. Specific Gravity was calculated by the Pycnometer method.

Specific Gravity of fine aggregate is 2.68.

3.1.3 Coarse Aggregate

The coarse aggregate of 12mm size from the Margalla crush Plant are used in this research work.

3.1.4 Steel Reinforcement

Two type of steel reinforcement is used. No.#4 bar as main reinforcement and No.#3 as circular ties.

Table 3-2 Properties of Steel Reinforcement

S. No:	**Bar No**	**Density (kg/m)**	**Nominal diameter (mm)**	**Cross-section Area (mm^2)**
1	#03	0.561	9.5	71
2	#04	0.996	12.7	129

Tensile Strength of Steel Reinforcement

Three steel bars were tested at in the lab under tensile loading in Universal Testing Machine (UTM) to determine the mechanical properties of the steel bars employed in current research work. The rate of loading was kept 2 mm/min. Test is performed in accordance with ASTM A370-18.

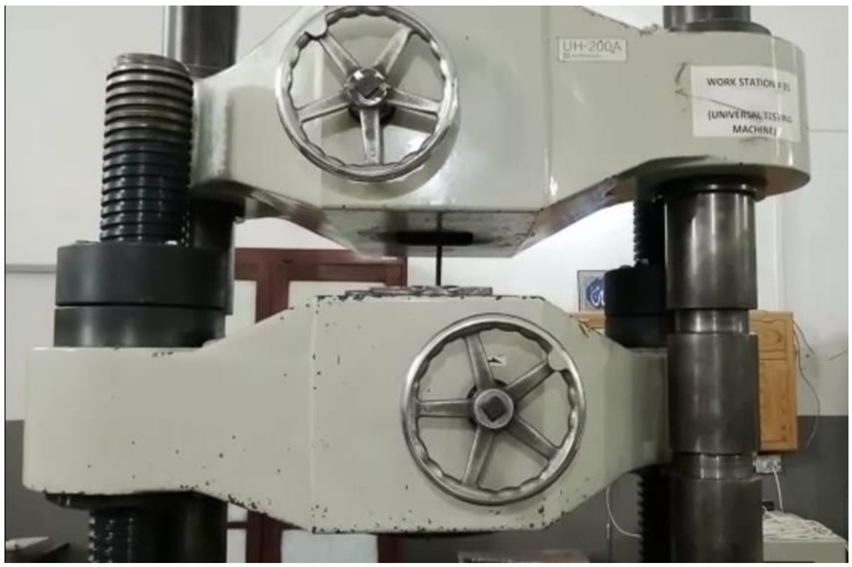


Figure 3-4 Tensile Testing of Steel in UTM

Table 3-3 Properties of Main Steel bars

Specimen	Yield strength (MPa)	Tensile Strength (MPa)
01	298.2	437.0
02	297.0	436.0
03	297.5	436.5
Average	297.57	436.5

3.1.5 Aluminum Alloy Sheet

Aluminum Alloy 1050-H14 having thickness of 1.5mm employed during this investigation, depending on the materials' accessibility in the local marketplace. Aluminum alloy 1050 is of moderate strength. It has excellent corrosion resistance and high ductility. The properties of AA 1050 are presented below.

- It has excellent workability.
- Weldability with both Gas and Arc is excellent.
- Brazability and Solderability is also excellent.
- Machinability is slightly poor.

Composition of AA 1050

Besides Aluminum, other main elements are iron and silicon whose allowable percentage is 0-0.40% and 0-0.25% respectively. Other elements are zinc, magnesium, titanium, manganese, copper etc are present in very small amount (in less than 0.1% each).

Aluminum Alloy Coupon Test

Three dog-bone-shaped aluminum alloy 1050 plates were made using ASTM E8. Sample length measures 375 mm, gauge length measures 225 mm, and grip length measures 75 mm on each side. The gauge length of the test setup is 75 mm, loaded at a pace of 0.5 mm per minute. The test sample ruptured within the gauge length depicted in the image. The table displays the values for elongation, yield strength, and tensile strength. An average of yield strength, tensile strength and elongation obtained from test of three sample are 105Mpa, 145Mpa and 12.1% respectively.

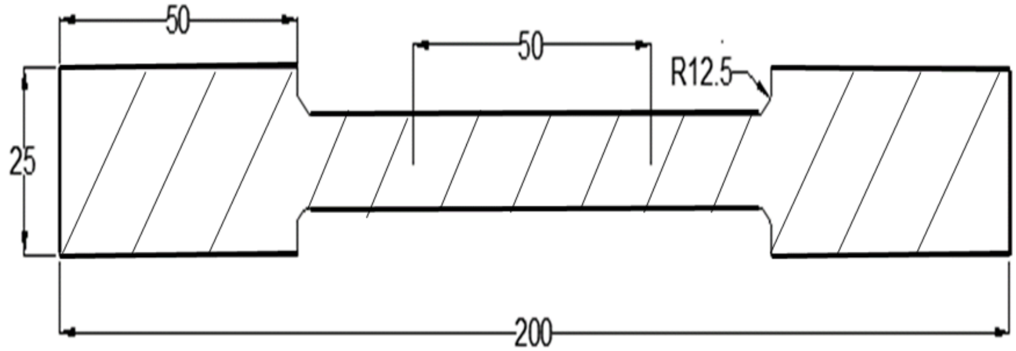


Figure 3-5a Dimensions of Coupon

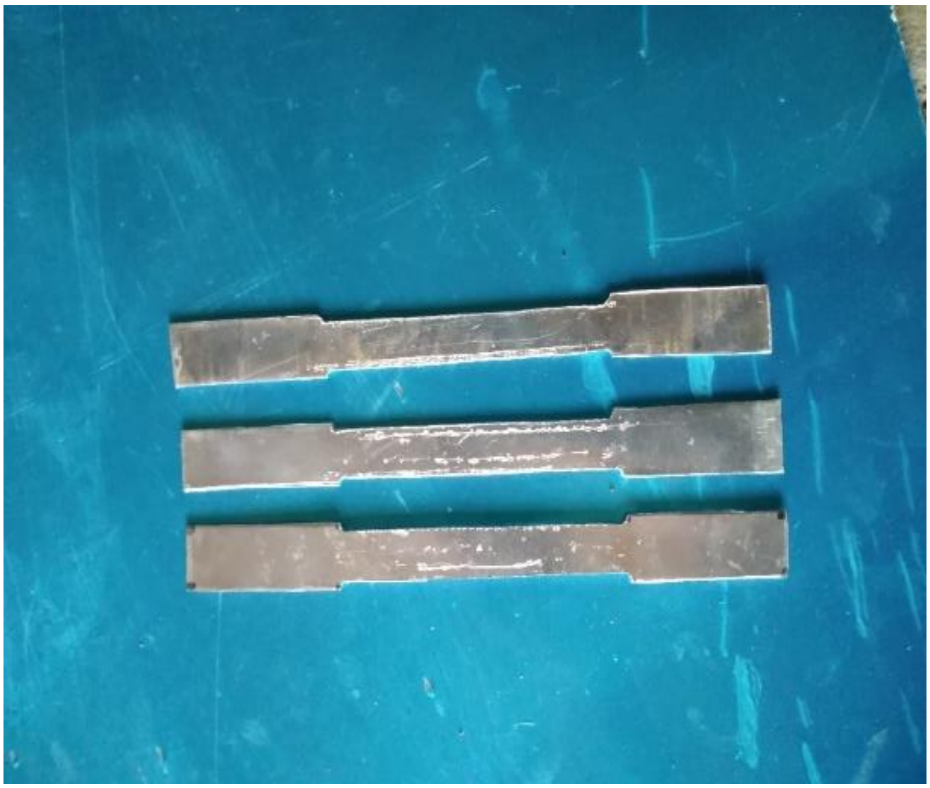


Figure 3-5b Samples of Coupon Test

Table 3-4 Properties of Aluminum Alloy

Tensile Strength	145 MPa
Yield Strength	105MPa
% Elongation	12.1% min

3.1.6 Epoxy Glue

The two ingredients of magic epoxy are hardener and resin. Part A is a liquid bisphenol that resists heat, corrosion, and adhesion better than other types. Its viscosity varies from 17,000 to 20,000 cps at 25 °C. Part B is a low molecular weight modified curing agent designed to be used with epoxy resins. It is composed of radicals of amino, carboxyl, and amide as well as a chain of mono-saturated fatty hydrocarbons. Epoxy resin will be used to cross-link it during the cementation process. It is more inert, insulating, and possesses higher adhesion. Its viscosity ranges from 500,000 to 700,000 cps. Part B to component A has a design ratio of 10:8.

Figure 3-6 Epoxy Glue Part A and B

Table 3-5 Mechanical Properties of Epoxy Glue

Compressive Strength	118Mpa
Tensile Strength	21Mpa
Lap shear Strength	14.5Mpa
Tensile Elongation	5%-6%

3.1.7 Epoxy Sikadur 30LP

Sikadur 30LP is used in one category of samples for bonding. Following are the properties of Sikadur 30LP.

Table 3-6 Mechanical Properties of Sikadur 30LP

Compressive Strength	185Mpa
Tensile Strength	45Mpa
Lap shear Strength	29Mpa
Tensile Elongation	1.5%
Colour of Component A	white
Colour of Component B	black
Colour of mixture	light grey
Mix Ratio	3:1

3.1.8 Expansion Anchor Bolts

The Aluminum Alloy plate is fastened to the concrete cylinder with the help of 10mm anchor bolts. The sample was drilled in accordance with the specifications listed in the Index Bolts standard. The washer that held the plate to the concrete bottom was tightened with a wrench after the bolt was driven into the hole.

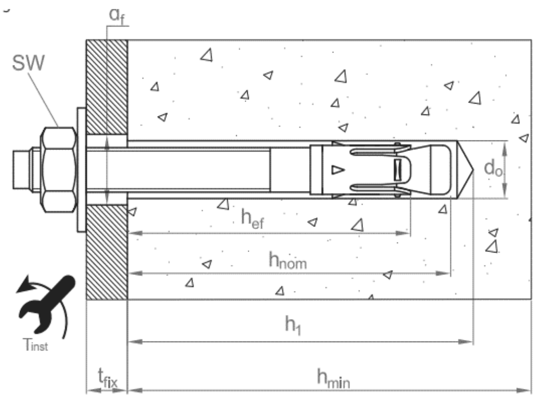


Figure 3-7a Schematic Diagram of Expansion Anchor Bolt

Figure 3-7b Expansion Anchor Bolt

(Above Images are taken from Expansion Anchor Bolts Manual provided by manufacturer)

Table 3-7 Mechanical Properties of Bolts

Diameter	10mm
Tensile Strength	600Mpa
Yield Strength	480 Mpa
Nominal Installation depth	68mm

3.2 Concrete Cylinder Test

Mix design ratio used in concrete was 1:1.5:1.5. Water to cement ratio was 0.45.

Figure 3-8a Batching Fine Aggregate

Figure 3-8b Batching Coarse Aggregate

Figure 3-8c Batching of Cement

Figure 3-8d Concrete Mixing

Slump value obtained from slump test according to ASTM C143/C143M-15, of fresh mix came out to be 105 mm.

Compressive Strength of concrete Cylinders is determined according to the ASTM-C39. This standard describes a method for exerting an axial compressive load to concrete specimens with cylindrical shapes until failure occurs in order to evaluate their compressive strength. The investigation's specimens measured four inches in diameter and eight inches high.

Figure 3-9 Cylinder Testing

Table 3-8 Results of Compression Test

S No:	CYLINDER	COMPRESSION STRENGTH (MPA)
1	C1	22.4
2	C2	22.8
3	C3	23.6
Average	**=**	**22.93**

CHAPTER 4: EXPERIMENTAL PROGRAM

The experimental program is initiated for the inspection of viability of utilizing locally available aluminum alloy AA1050 for confinement of reinforced concrete. It comprises assessment of the effect of varying the number of layers of an aluminum alloy sheets used for confinement of reinforced concrete on the strength and ductility.

This chapter includes the details of experimental program. It includes details of preparation of samples and testing procedure.

4.1 Test Samples' Detail

The details of all the specimen have been discussed. Two specimen were casted for each category. All specimens were casted with an average concrete strength (f'c) and steel yield strength (fy) of 22.93 and 280 MPa, respectively. Longitudinal reinforcement consists of 6 no# 4 bars, while transverse tie (circular ties) are of no# 3 bar provided at 100mm c/c space. All specimens were cured for fourteen days.

4.1.1 Control Specimen

It is denoted by CS. Control specimens have diameter of 200mm and height of 350mm.

4.1.2 Modified Sample 01

It is denoted by H350L1B1. These specimens have diameter of 200mm and height of 350mm. These are modified by single layer of Aluminum Alloy (AA) sheet (H350L1B1). AA sheet is connected by using a bolt at the center. In order to have proper bonding between concrete and AA sheet epoxy is used for transfer of stresses properly.

4.1.3 Modified Sample 02

It is denoted by H350L1B2. These specimens have diameter of 200mm and height of 350mm. These are modified by single layer of Aluminum Alloy (AA) sheet (H350L1B2). AA sheet is connected by using two bolts having clear spacing of 130mm. Edge distance of each bolt is 100mm. In order to have proper bonding between concrete and AA sheet epoxy is used for transfer of stresses properly.

4.1.4 Modified Sample 03

It is denoted by H350L2E. These specimens have diameter of 200mm and height of 350mm. These are modified by double layer of Aluminum Alloy (AA) sheet (H350L2E). AA sheet is connected by using epoxy Sikadur 30LP.

4.1.5 Modified Sample 04

It is denoted by H350L2B2. These specimens have diameter of 200mm and height of 350mm. These are modified by double layer of Aluminum Alloy (AA) sheet (H350L2B2). AA sheet is connected by using two bolts having clear spacing of 130mm. Edge distance of each bolt is 100mm.

4.1.6 Modified Sample 05

It is denoted by H450L2B2. These specimens have diameter of 200mm and height of 450mm. These are modified by double layer of Aluminum Alloy (AA) sheet (H450L2B2). AA sheet is connected by using two bolts having clear spacing of 180mm. Edge distance of each bolt is 125mm.

4.1.7 Modified Sample 06

It is denoted by H450L2B3. These specimens have diameter of 200mm and height of

450mm. These are modified by double layer of Aluminum Alloy (AA) sheet (H450L2B2). AA sheet is connected by using three bolts having clear spacing of 110mm. Edge distance of each bolt is 100mm.

CS H350L2E H350L1B1 H350L2B2

H350L1B2 H450L2B2 H450L2B3

Figure 4-1 Test Samples

4.2 Nomenclature of Modified Samples

In the nomenclature, four English alphabets are used which are:

H = Height

L= layer of AA Sheet

B= Bolts

E= Epoxy

Digits next to English alphabet represents the value of that parameter. Height is shown in mm, whereas digits next to “L and B” shows the number of layers of AA Sheet and number of bolts respectively. For example, H350L1B2 shows that this sample has height of 350mm, single layer of AA Sheet and two number of bolts. Following table shows the details of all the specimen.

Table 4-1 Sample's Specifications

Sample	Height (mm)	No. of Layers of AA Sheet	Type of connection	No. of Bolts
CS	350	-	-	-
H350L1B1	350	1	Bolt	1
H350L1B2	350	1	Bolt	2
H350L2E	350	2	Epoxy	-
H350L2B2	350	2	Bolt	2
H450L2B2	450	2	Bolt	2
H450L2B3	450	2	Bolt	3

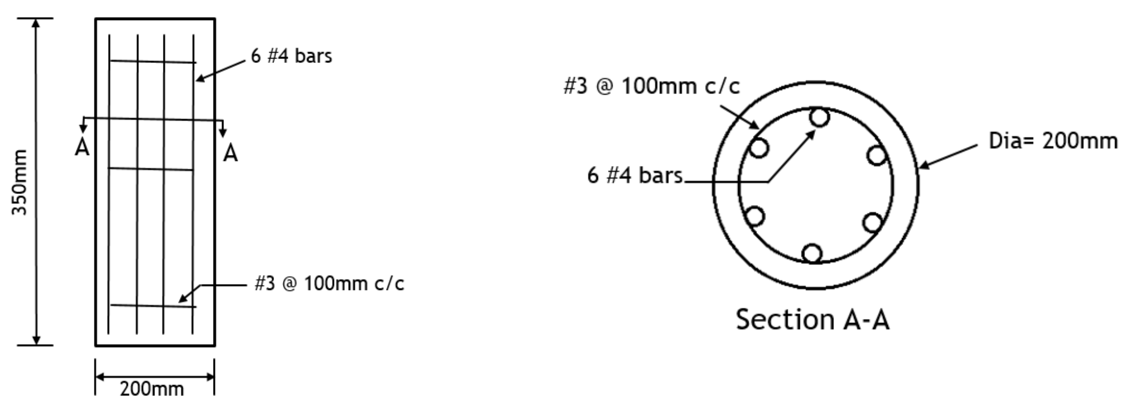


Figure 4-2 Sample's Dimensions

4.3 Confinement of Samples

Prior to strengthening, the surfaces of the aluminum alloy sheet and concrete were roughened with an electrical grinder. As a result, the bond between the sheet and the epoxy was stronger, resulting in an ideal surface profile and efficient stress transfer.

Two methods were employed to prepare the surfaces of aluminum alloy plates and concrete. An electrical grinder was utilized up until the appearance of aggregates, per the ACI-546. Air blow was utilized to eliminate any dust or loose particles in order to increase the bond's efficiency. An electrical grinder was used to roughen aluminum alloy sheet.

Then, in order to avoid drilling through reinforcement, locations for the bolt installation on the AA sheet and the concrete surface were marked out using a drawing. As per the Index Bolts specification, hammer drill predrilling was carried out up to the embedded depth. Two different types of drill bits—drill bit for concrete and for AA, steel drill bit—were utilized to prevent excessive damage. Pressurized air blow was used to eliminate any dust and loose air particles in order to facilitate easy installation and provide an efficient contact between the expansion anchor bolt sleeve and the inner surface of the hole. To stop galvanic corrosion, 10mm indices expansion anchor bolts were carefully hammered into the hole without coming into touch with the internal reinforcement. The cylinders' surfaces were coated with a mixture of 10:8 parts A and B epoxy adhesive. Then Aluminum Alloy sheet is wrapped by hand. To hold the sheet in position firmly, ½ inch screws are used in scattered form. Before drilling, Jubilee clamps are fixed and tightened on cylinders. After that, drilling is done through the sheet and concrete using two different drill bits. Bolts are installed, keeping in view the recommended torque.

One sample was strengthened only by using sikadur 30LP epoxy. So in that case, jubilee clamps were fixed and tightened on cylinder for 24 hours. At the end edges are made smooth by using electric grinder.

4.4 Organization of Loading Assembly

All of the cylinders were tested under axial compression loading until they failed. A 5000KN Compression testing machine was employed to apply the load with a rate of 0.3KN/s. The entire applied load was measured using an electric load cell. To evenly distribute the applied load, both ends were leveled after stuffing pores and lastly steel collars of 100 mm width and 10 mm thickness were positioned over it. Deformation gauge was inserted under upper steel plate by using magnetic field and calibrated to measure the axial deformation.

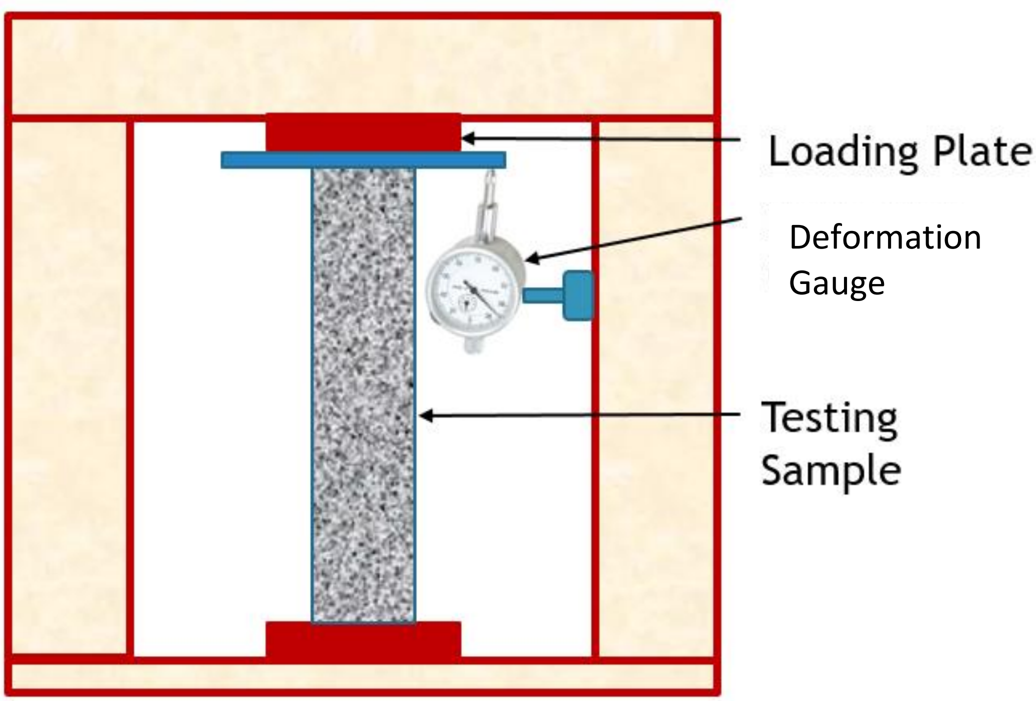


Figure 4-3a Schematic Diagram of Loading Assembly

Figure 4-3b Testing Assembly

Figure 4-3c Compression Testing

CHAPTER 5: RESULT AND DISCUSSION

This chapter includes the results of all the experimental samples reinforced with an aluminum alloy sheet. All the samples are tested in uniaxial compression testing machine of Structural Lab of National University of Sciences and Technology NUST, Islamabad. Cracking pattern, load vs axial deflection curve, and ultimate load and ultimate deformation are presented and illustrated in this chapter. The impact of varying no. of layers of Aluminum Alloy sheet, number of bolts and change in height on the performance of strengthened reinforced concrete cylinders are discussed.

The modified and control samples' ultimate strength and deformation at yield, ultimate, and failure points are displayed in the experimental program results. The ultimate load is the maximum force a column can support before collapsing completely. "Ultimate deformation" refers to the deformation at the ultimate point caused by the peak performance load. The yield deformation is the result of the internal steel bars in the concrete reaching the yield stage, which is known as the yielding point.

In order to analyze the suitability of proposed strengthening technique, increase in the strength and ductility of modified samples is compared to the control sample. The increase in strength is illustrated by using the value of ultimate load of samples modified with the control sample. Ductility of samples is determined as the ratio of the ultimate deformation (Δu) to the yield deformation (Δy). Yield deformation is taken as the deformation corresponding to 75% loading.

At the end, the failure mechanism of the tested samples has been described. Generally, column failed due to the sheet rupture and crushing of concrete.

5.1 Axial Load Vs Axial Deformation Graphs

The performance of all the tested sample is represented by Load vs deformation graphs. Following are some key features of these graphs.

- All the curves have initial linear elastic region followed by non-linear portion.
- Curves of modified samples are steeper as compared to control sample representing high stiffness of modified sample because of lateral confinement.
- Stiffness of samples with height of 350mm is greater as compared to that of 450mm.
- Stiffness is not disturbed by number of layers or number of bolts.
- Curves of modified samples do not have clear yield point as control sample has. More over their response is more non-linear.
- Yield point of modified samples is higher than control sample. It shows that modified samples have better resistance to initial cracking as compared to control sample.

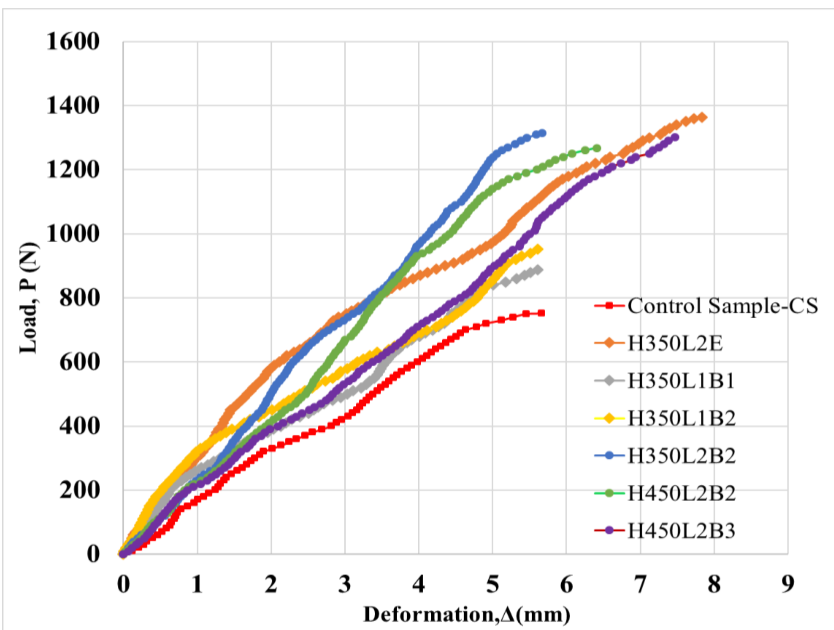


Figure 5-1 Load Vs Deformation Curve

Table 5-1 Peak Response of Tested Samples

Sample	Ultimate Load, P (KN)	Ultimate deformation, Δ (mm)	%age increase in load w.r.t CS
CS	751.4	5.67	
H350L1B1	900.25	5.61	19.81%
H350L1B2	966.7	6.09	28.65%
H350L2E	1352.8	7.94	80.04%
H350L2B2	1302.0	6.24	73.28%
H450L2B2	1282.85	6.74	70.73%
H450L2B3	1293.4	7.51	72.13%

5.2 Ultimate Load

- The maximum increase in strength is 80.04% that is observed for cylinder strengthen by double layers Aluminum Alloy sheet with sikadur 30LP epoxy (H350L3E) without any bolts.
- Bolted connection has slightly reduced the strength as compared to epoxy but that is only 7 to 9%.
- By doubling the layers of Aluminum Alloy sheet, increase in strength is more than twice as compared to single layer.
- It is observed that by changing the number of bolts has not affected the strength as much.
- This strengthening technique is not affected by change in height of samples.

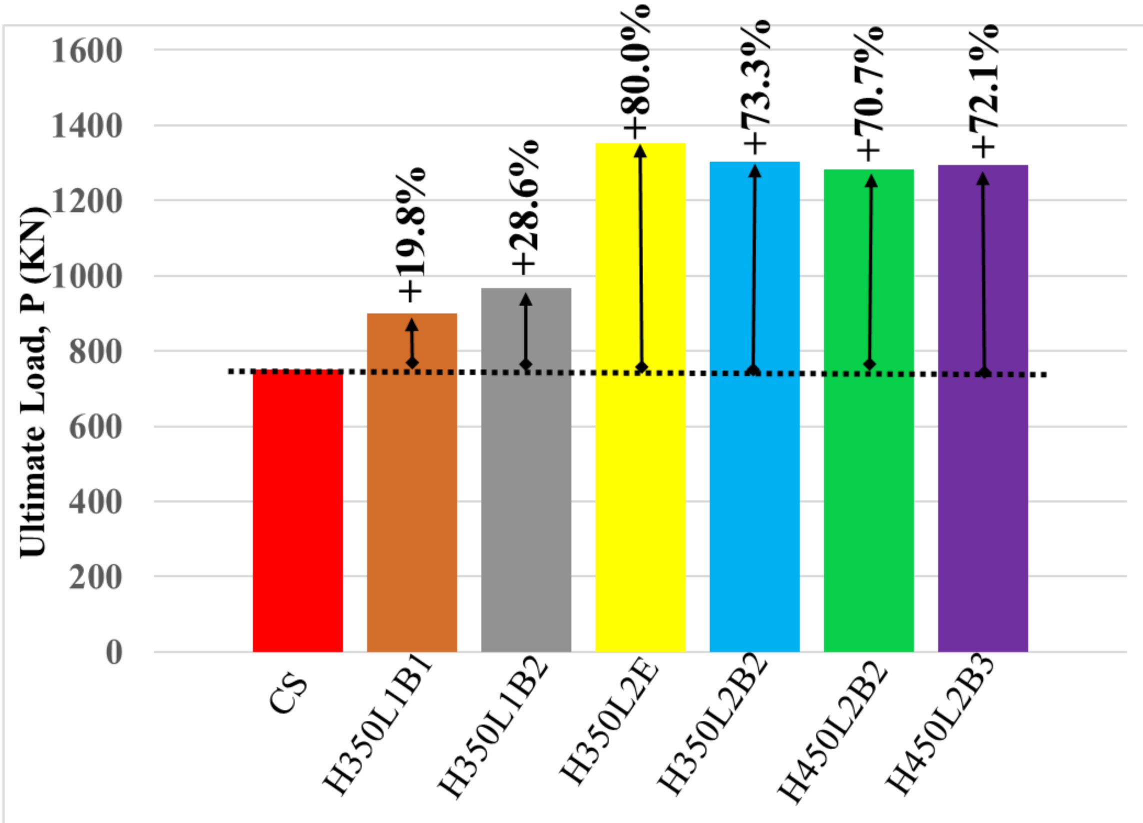


Figure 5-2 Ultimate Load Comparison

5.3 Ultimate Deformation

- Ultimate deformation is not disturbed by single layer of aluminum alloy sheet but samples with double layers of aluminum alloy sheet has higher ultimate deformation.
- It is also observed that increase in height has also increased the ultimate deformation of samples. But sample H350L2E has shown different response in this regard.

Table 5-2 Ultimate Deformation Comparison

Sample	Ultimate Load, P (KN)	Ultimate deformation, Δu (mm)	%age increase in Deflection w.r.t CS
CS	751.4	5.67	-
H350L1B1	900.25	5.61	-1.06%
H350L1B2	966.7	6.09	7.41%
H350L2E	1352.8	7.94	40.04%
H350L2B2	1302.0	6.24	10.05%
H450L2B2	1282.85	6.74	18.87%
H450L2B3	1293.4	7.51	32.45%

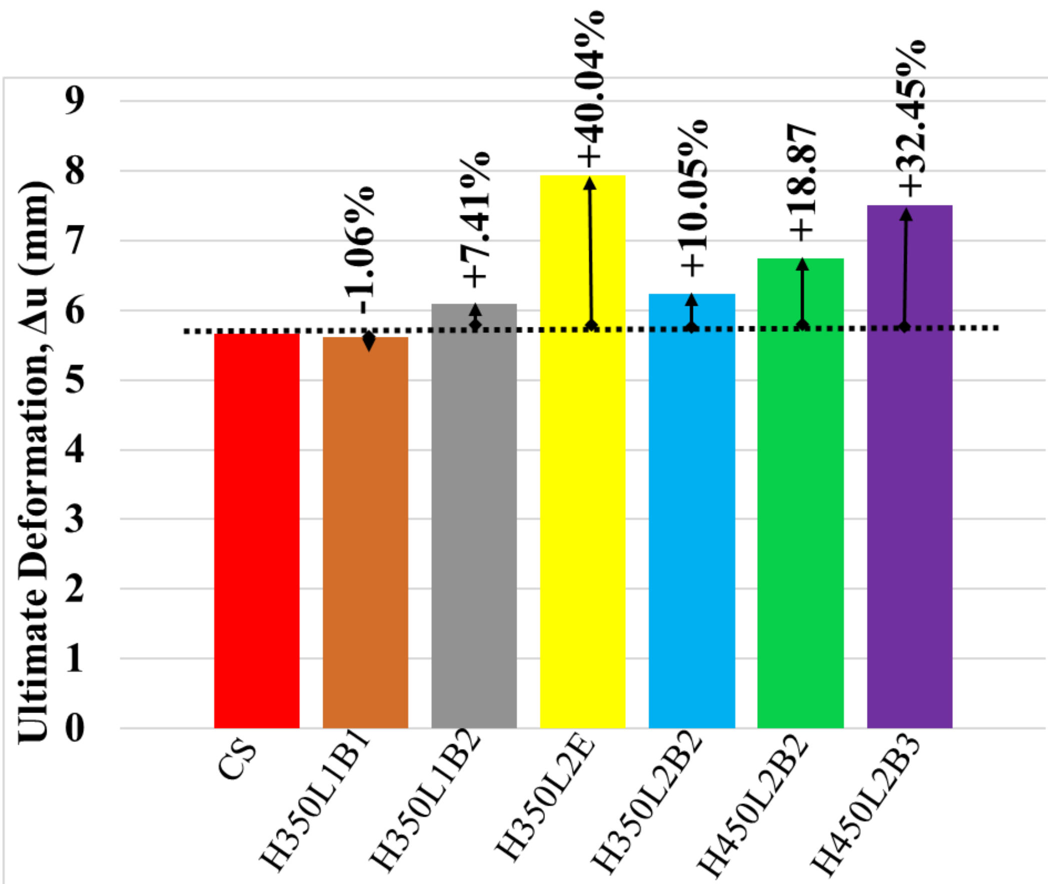


Figure 5-3 Ultimate Deformation Comparison

5.4 Ductility Index

Design guidelines place a strong emphasis on making sure reinforced concrete (RC) elements have enough ductility to avoid brittle collapses and give early notice of impending collapse. The yield deformation, Δy, and ultimate deformation, Δu, are used to determine the ductility index. It is the fraction of ultimate deformation (Δu) to the yield deformation (Δy). Yield deformation is taken as the deformation corresponding to 75% loading.

Ductility index of most of the modified samples is less than control sample because of lateral confinement. But this reduction is value is very small, as it can be seen that maximum decrease is 14.29% for sample H350L2E. Moreover, ductility index is not affected by number of layers of aluminum alloy sheet, number of bolts and height of sample. Type of connection also not affected ductility index considerably.

Table 5-3 Ductility Index of all the samples

Sample	Yield deformation, Δy (mm)	Ultimate deformation, Δu, (mm)	Ductility Index, I
CS	3.73	5.67	1.52
H350L1B1	3.87	5.61	1.45
H350L1B2	4.51	6.09	1.35
H350L2E	5.46	7.94	1.45
H350L2B2	4.34	6.24	1.44
H450L2B2	4.23	6.74	1.59
H450L2B3	5.46	7.51	1.37

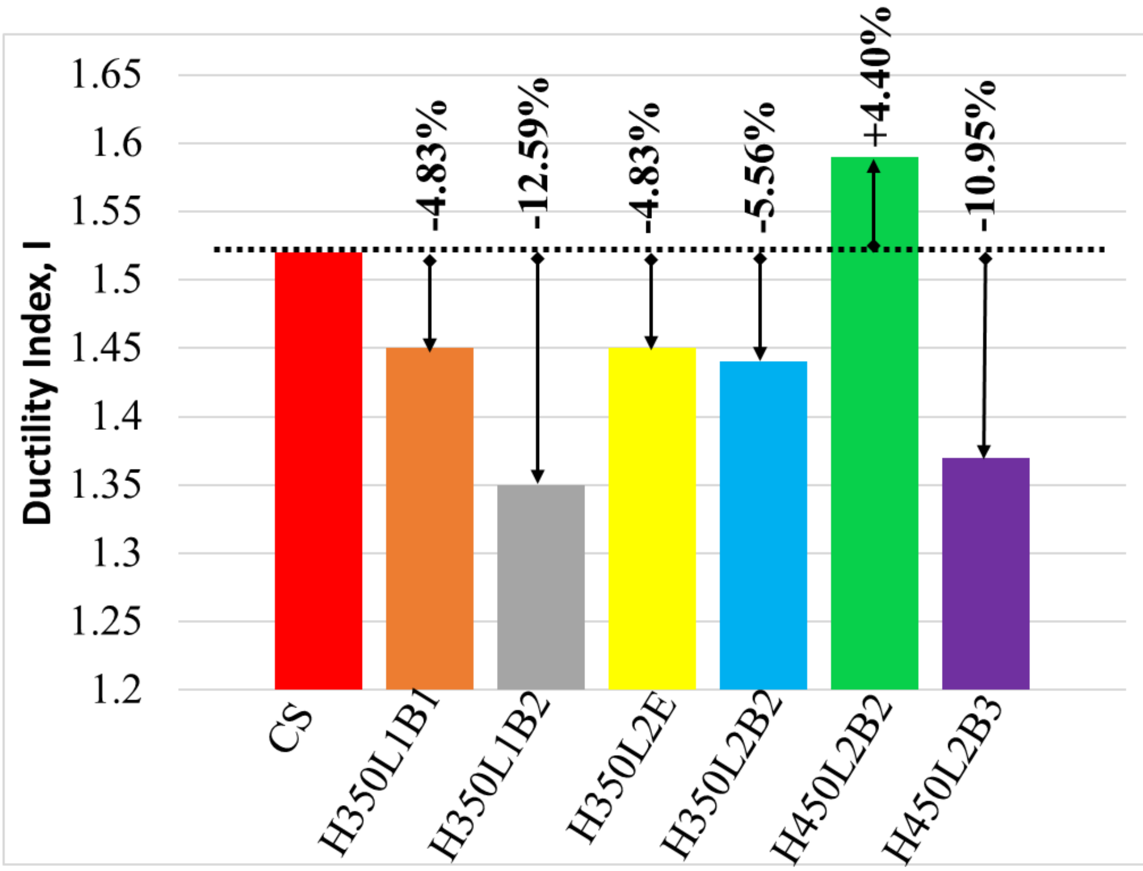


Figure 5-4 Comparison of Ductility Index

5.5 Failure Mechanism

The cracks appeared to initiate in the upper half region of all the specimens. During the application of axial load, until the 75% of the peak strength, the casted columns remained elastic, and the confinement rupture was not initiated. With further increase in the applied load, cracking of Aluminum Alloy sheet initiated with delicate feeble sound, and longitudinal thin crack began at the upper region of the tested columns. As the application of load was further intensified, the width of minor cracks amplified until the maximum value was reached. At the maximum applied loading, vertical deflection of the specimens amplified at an increased speed triggering extended ruptures along the columns’ height. At this stage, the spalling of concrete initiated, and leading to failure of the lateral ties.

H350L2B2 H350L1B2 H450L2B2

Figure 5-5 Failure Mechanism

5.6 Analytical Models

Analytical models proposed by different researchers for strengthened reinforced compression element are used to find the compressive strength of strengthened samples. The results of analytical models are obtained by using variable height and number of layers of aluminum alloy sheet. These results are then compared with respective experimental results. Mean Absolute Percentage error (MAPE) is then calculated to find the most suitable analytical model.

Following are the different analytical models used in this study:

5.6.1 Mander’s Model

This model is developed for concrete confined by transverse reinforcement and is subjected to uniaxial compression. This model can be effectively used for various types of confinements and different loading conditions. Parameters are defined in this model to incorporate full scale compression members of different cross sections. (By J. B. Mander, 1988)

The basic equation of this model is:

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

Where;

f'_{cc} = Confined Concrete Compressive Strength

f'_{co} = Unconfined Concrete Compressive Strength

f'_l = Effective Lateral Confining Stress

5.6.2   ACI 440.2- R17

This section of ACI code incorporates design guidelines for concrete strengthening with FRPs. chapter 12 is related to compression elements. It only incorporates completely confined sections not partial confinement. Parameters are defined to account non-circular sections. It is based on Lam and Teng model (2003). Below equation of ACI 440.2- R17 is basically for circular compression element strengthened by using FRP and tested under uniaxial compression. (440, 2017)

$$f'_{cc} = f'_{co} + 3.3\Psi_f k_a f_l \ldots\ldots\ldots\ldots \quad \text{Equation 2}$$

Two new factors in this equation are:

Ψ_f = 0.95 (Reduction factor)

$$f_l = \frac{2E_A n t_A \varepsilon_{Ae}}{D} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Equation 3}$$

k_a = accounts for the geometry of the section (for circular section its value is 1)

Where;

E_A = 71000 MPA

n = number of layers = 2

t_A = thickness of AA sheet

ε_{Ae} = effective strain in AA sheet at failure

D = Diameter of the section

5.6.3 Canadian Standard Association- CSA-S806

Ultimate strength on confined concrete can be calculated by following equation suggested by CSA S806-02.

$$f'_{cc} = 0.85 f'_c + k_l k_s f_l \quad \text{………….. Equation 4}$$

Parameter, k_l is defined by Razvi et al. (1992) for circular shaped section tested under static loading. Equation is given as $k_l = 6.7 f_l^{-0.17}$. Second parameter ks is used to account for non-circular shaped section. For circular section k_s = 1. (Nanni, 2008)

5.6.4 Model Proposed by T.M Pham and Hadi

This model is also proposed for FRP in 2014. It is based on round shaped cross section. Along with normal concrete it also covers high strength concrete. Two new parameters are defined in this model which are stiffness and strain ratios that also influence the confinement. (Thong M. Pham 1, 2014)

$$f'_{cc} = 0.7 f'_{co} + 1.8 f_l + 5.7 \frac{t}{d} + 13 \quad \text{……… Equation 5}$$

Where t/d is thickness of confining sheet to diameter of section ratio.

5.6.5 Model Proposed by Fatimeh Shirmohammadi

Fatimeh et. al proposed a model for Reinforced concrete strengthened by FRP and tested under uniaxial compression. This model can be used for FRP confinement as well as lateral steel confinement.

$$f'_{cc} = f'_{co}(1.1 + 2.5\left(\frac{f_{lf}}{f'_{co}}\right)^{0.8} \times \left(\frac{f_{ls}}{f'_{co}}\right)+3.5\left(\frac{f_{ls}}{f'_{co}}\right)^{0.2}\left(\frac{d_c^2}{D^2}\right)^4 \quad \text{..........} \quad \text{Equation 6}$$

In the above mentioned equation, f_{lf} is the confining pressure due to externally added material whereas, f_{ls} is due to lateral reinforcement. Following are the equation that can be used to predict these pressures. (Fatemeh Shirmohammadi a, 2015)

$$f_{lf} = \frac{2nt_A f_A}{D} \quad \text{................} \quad \text{Equation 7}$$

$$f_{ls} = \frac{2A_{st} f_{ys}}{s \times d_c} \quad \text{................} \quad \text{Equation 8}$$

d_c = diameter of concrete core

D= diameter of gross cross section

s= spacing between transverse reinforcement

f_A = strength of Aluminum Alloy sheet

f_{ys} = Yield stress of steel reinforcement

5.6.6 Model Proposed by G Wu et. al

This model is also based on uniaxial compressive strength of concrete cylinders strengthened with FRP. The uniqueness of this model is that it accounts for poison ratio of strengthened concrete. Equations are also defined to calculate the peak response of the samples. Following equation is used to determine the peak stress of modified sample. (G. Wu 2006)

$$f'_{cc} = f'_{co}(0.75 + 2.5\frac{f_l}{f'_{co}}) \quad \text{................} \quad \text{Equation 9}$$

Where;

$$f_l = \frac{1}{2}\rho_A f_A \quad \text{..............................} \quad \text{Equation 10}$$

$\rho_A = \frac{4t_A}{D}$ (Volumetric ratio to AA sheet to concrete)

5.6.7 Model Proposed by Kaushik & Singh

This model is proposed for ultimate strength of reinforced concrete circular column confined with ferrocement. In this model equations for peak responses are proposed. Following equation is used to determine the peak stress of strengthened element tested under concentric compression loading. (A.B.M.A. Kaish a, 2018)

$$f'_{cc} = f'_c + k_1 f_l \quad \ldots\ldots\ldots\ldots \quad \text{Equation 11}$$

Where, k_1 is strength increasing factor having value of 4.2.

5.6.8 Model Proposed by Chastre et al.

This model is also proposed for circular reinforced concrete column strengthened with FRP. Along with external confinement, this model also included confinement due to transverse steel reinforcement. (Carlos Chastre∗, 2010)

$$f'_{cc} = \alpha f'_{co} + k_1(f_{ju} + f_{shu}) \quad \ldots\ldots\ldots\ldots \quad \text{Equation 12}$$

k_1 = 5.29

Confining pressure of AA sheet is: $f_{ju} = \frac{2t}{D} E_A \varepsilon_A$

Confining pressure of Transverse steel is: $f_{shu} = \frac{2A_s}{d_s \times s} f_{ys}$

5.6.9 Model Proposed by Samaan et al.

This model is based on the models of reinforced concrete columns. It also incorporates bilinear loading in both compression as well as lateral direction. (By Michel Samaan, 1998)

Ultimate strength of confined concrete is given as:

$$f'_{cc} = f'_c + k_1 f_r \quad \ldots\ldots\ldots\ldots\ldots \quad \text{Equation 13}$$

Where

k_1 = 4.1

$$f_r = \frac{2nt_A f_A}{D} \quad \ldots\ldots\ldots\ldots\ldots \quad \text{Equation 14}$$

5.6.10 Model Proposed by Youssef et al.

This model was developed by experimental data of different geometrical shapes. It has included variety of factors like peak response, geometry of section, jacketing parameters. (Marwan N. Youssef, 2007)

Ultimate strength of confined concrete is given as:

$$f'_{cc} = f'_{co}(1.0 + 2.25\left(\frac{f_{lu}}{f'_c}\right)^{5/4} \quad \ldots\ldots\ldots\ldots \quad \text{Equation 15}$$

Where;

$$f_{lu} = \frac{1}{2}\rho_A f_A \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Equation 16}$$

$\rho_A = \frac{4t_A}{D}$ (confinement ratio to AA sheet to concrete)

5.7 Results of all Analytical Models

Analytical results obtained for the height of 350mm and single layer of AA are compared with the experimental result of H350L1B2. Results of 350mm height and double layers of AA are compared with both H350L2E and H350L2B2. Values obtained for 450mm height and double layer of AA are compared with H450L2B3. For each type of sample percentage error is calculated. Then Mean Absolute Percentage Error (MAPE) is calculated to check the overall suitability of models.

Table 5-4 Analytical Models Results

		Experimental Results (Mpa)								
		H350L1B2	30.79	H350L2E	43.08	H350L2B2	41.46	H450L2B3	41.19	
S.NO	Model	Analytical Result (Mpa)	Percentage Error	Analytical Result (Mpa)	Percentage Error	Analytical Result (Mpa)	Percentage Error	Analytical Result (Mpa)	Percentage Error	MAPE
1	Mander Model	32.55	-6%	46.12	-7%	46.12	-11%	46.12	-12%	**9%**
2	ACI 440.2-R17	26.49	14%	30.06	30%	30.06	28%	30.06	27%	25%
3	CSA	34.69	-13%	44.62	-4%	44.62	-8%	44.62	-8%	**8%**
4	T.M Pham & Hadi	33.01	-7%	36.92	14%	36.92	11%	36.92	10%	11%
5	Fatemeh Shirmohammadi	47.11	-53%	49.16	-14%	49.16	-19%	49.16	-19%	26%
6	G. Wu et al.	24.78	20%	30.22	30%	30.22	27%	30.22	27%	26%
7	Kaushik & Singh	34.93	-13%	44.06	-2%	44.06	-6%	44.06	-7%	**7%**
8	Chastre et al.	39.23	-27%	50.73	-18%	50.73	-22%	49.28	-20%	22%
9	Samaan et al.	36.13	-17%	42.58	1%	42.58	-3%	42.58	-3%	**6%**
10	Youssef et al.	28.43	8%	32.07	26%	32.07	23%	32.07	22%	20%

Analytical models presented by Mander (1988), Canadian Standard Association (CSA) S806-02, Kaushik & Singh (1999), and Samaan et al. (1998) are predicting the results almost equal to experimental data as mean absolute percentage error (MAPE) of these models is below 10%.

Hence, Results have shown considerable increase in ultimate strength, greater initial stiffness and delayed initial cracking of modified members. It is also observed that external confinement has reduced the ductility of members slightly.

CHAPTER 6: CONCLUSIONS

As stated earlier, old Reinforced Concrete (RC) structures have been strengthened and repaired using a variety of materials. Steel plates, which are prone to corrosion, and carbon fiber reinforced polymer (CFRP), which is brittle by nature, are two materials that are frequently used. An innovative method that makes use of aluminum alloy sheet has been researched to overcome the drawbacks of these materials. Because of their reputation for being ductile and resistant to corrosion, aluminum alloys offer a viable way around the drawbacks of CFRP and steel plates.

Examining and understanding the usefulness of aluminum alloy sheets as confining materials for strengthening columns was the main goal of this study, which also focused on how these materials affected the ductility and strength of the modified structures. Tension coupon tests were performed in order to assess the mechanical characteristics of the aluminum alloy sheet. These tests produced vital information that is needed to evaluate the material's performance, such as the values of deformation at failure, tensile strength, and modulus of elasticity. Analytical equations proposed by different researchers are used to compare and validate the experimental results. The aim was to ensure the most suitable analytical model that closely align with the actual performance observed in the experiments.

Following are the conclusions from experimental results:

- Aluminum Alloy sheet wrapping has considerably increased the axial strength of concrete cylinders.
- It has seen that bolts can be used for bonding along with filler.

- Percentage increase in strength is not affected by changing the height of sample.
- Ductility Index is slightly reduced due to confinement.
- Analytical models presented by Mander (1988), Canadian Standard Association (CSA) S806-02, Kaushik & Singh (1999), and Samaan et al. (1998) are predicting the results almost equal to experimental data.

Although confinement of concrete cylinders with Aluminum Alloy sheets has shown greater increase in properties and found suitable technique for use. Still there are many factors that need to be investigated in detail. Therefore, in future, several other parameters that can be investigated such as:

- Investigate the suitable number and spacing of bolts by testing full scale columns.
- Investigate the cheap filler such as cement grout.
- Investigate partial wrapping of column with Aluminum Alloy sheet.
- Investigate post peak response of column strengthen with this technique.

REFERENCES

1. 440, A.C.I (2017). Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. *American Concrete Institute (ACI)*.
2. A.B.M.A. Kaish a, M. Jamil, S.N. Raman b, M.F.M. Zain b, Lutfun Nahar. (2018). Ferrocement composites for strengthening of concrete columns. *Construction and Building Materials*.
3. Alshimmeri, A. (2016). Structural behavior of confined concrete filled aluminum tubular (cft) columns under concentric load.,. . *Journal of Engineering, 22(8),* , 125-139. doi:https://doi.org/10.31026/j.eng.2016.08.08
4. Aref A. Abadel, M. I. K., Radhouane Masmoudi. (2021). Axial capacity and stiffness of post-heated circular and square columns strengthened with carbon fiber reinforced polymer jackets. *Structures*.
5. Ashraf, M. (2010). Development of Cost-effective and Efficient Retrofitting Technique for Masonry Buildings in Pakistan.
6. Bashir, A. (2024). Investigation of the buckling behavior of square hollow columns fabricated from 7a04-t6 aluminum alloy through numerical analysis... . doi:https://doi.org/10.21203/rs.3.rs-4343148/v1
7. By J. B. Mander, M. J. N. P., 2 and R. Park,3 Fellow, ASCE. (1988). THEORETICAL STRESS-STRAIN MODEL FOR CONFINED CONCRETE "*Structural Engineering*."
8. By Michel Samaan, A. M. M., ASCE, and Mohsen Shahawy. (1998). MODEL OF CONCRETE CONFINED BY FIBER COMPOSITES "*Structural Engineering"*.
9. C. Del Vecchio, M. D. L., A. Balsamo, A. Prota, and E. Cosenza,. (2018). “Experimental response and fiber-reinforced cement composites strengthening of real reinforced concrete columns with poor-quality concrete,. *Int. Fed. Struct.*, 1168–1181.
10. Carlos Chastre∗, M. A. G. S. (2010). Monotonic axial behavior and modelling of RC circular columns confined with CFRP "*Engineering Structures"*.
11. Chahardoli, S., Attar, A., Ziaie, M., & Marashi, S. . (2022). Introducing new nested absorbers with square cross-sections and optimization of their performance using response surface method under quasi-static loading. *Journal of Materials Design and Applications,, 236(8)*,. doi:https://doi.org/10.1177/14644207221075836
12. Chellapandian, M., Prakash, S., & Sharma, A. . (2019). Experimental investigations on hybrid strengthening of short reinforced concrete column elements under eccentric compression. *Structural Concrete*,. doi:https://doi.org/10.1002/suco.201800311
13. Ding, F., Lyu, F., Wang, E., Xu, Y., Liu, Y., Feng, Y., … & Shang, Z. (2021). Numerical investigation of the composite action of axially compressed concrete-filled circular aluminum alloy tubular stub columns. . *Materials, 14(9)*,. doi: https://doi.org/10.3390/ma14092435
14. Fan, M. (2024). Research on the mechanical properties of some new aluminum alloy composite structures in construction engineering. *Korean Journal of Materials Research, 34(2)*,. doi: https://doi.org/10.3740/mrsk.2024.34.2.72
15. Fatemeh Shirmohammadi a, Asad Esmaeily b, Zohreh Kiaeipour. (2015). Stress–strain model for circular concrete columns confined by FRP and conventional lateral steel *Engineering Structures*.

16. Fengqin Wang, J. W., Hua Yang, Qihan Shen. (2021). Axial compressive behaviour of RC columns strengthened with rectangular steel tube and cementitious grout jackets. *Structures*.
17. G. Wu , Z. T. L., Z.S. Wu. (2006). trength and ductility of concrete cylinders confined with FRP composites *Construction and Building Materials*.
18. Guo, Y., Xiao, S., Luo, J., Ye, Y., & Zeng, J. (2018). Confined concrete in fiber-reinforced polymer partially wrapped square columns: axial compressive behavior and strain distributions by a particle image velocimetry sensing technique. *Sensors, 18(12), 4118*. doi:https://doi.org/10.3390/s18124118
19. Ismail, F., Azmi, D., & Jauhari, Z. (2021). Structural evaluation and strengthening strategy of the law faculty hall building in andalas university, padang, indonesia. . *Advanced Science Engineering and Information Technology*. doi: https://doi.org/10.18517/ijaseit.11.4.11613
20. Janwaen, W., Barros, J., & Costa, I. (2019). A new strengthening technique for increasing the load carrying capacity of rectangular reinforced concrete columns subjected to axial compressive loading. . *engineering composites*.
21. Kim, S., Park, J., Jung, W., & Kang, J. . (2021). Strengthening effect of the external prestressing method that simulated a deterioration bridge. *Applied Sciences*. doi: https://doi.org/10.3390/app11062553
22. Kozman, N., El-Attar, M., & Elnady, A. (2023). Strengthening of short reinforced concrete columns by using pre-tensioned steel. *Engineering Research Journal - Faculty of Engineering, 52(2),* , 37-43. doi:https://doi.org/10.21608/erjsh.2023.181846.1123
23. L.N.K. Sai Madupu, K. S. S. R. (2020). Performance of axially loaded reinforced concrete rectangular columns strengthened with GFRP strips. *Materials Today: Proceedings*.
24. Lee, D., Dong, Z., & Kikuchi, N. (2009). Foa (first-order analysis) model of a granule-filled tube for vehicle crash energy absorption. , . *Mechanics of Materials, 41(6),*. doi: https://doi.org/10.1016/j.mechmat.2009.01.016
25. Li, S., Li, Q., Jiang, H., Zhang, H., & Zhang, L. (2017). Experimental research on seismic performance of a new-type of r/c beam-column joints with end plates. ,. *Shock and Vibration*. doi: https://doi.org/10.1155/2017/3823469
26. M. Chellapandian, S. S. P., Akanshu Sharma. (2017). Strength and Ductility of Innovative Hybrid NSM Reinforced and FRP Confined Short RC Columns under Axial Compression. *Composite Structures*.
27. Marwan N. Youssef, M. Q. F., Ayman S. Mosallam (2007). Stress–strain model for concrete confined by FRP composites. *composite Engineering*.
28. Meda A, P. G., Rinaldi Z, Martinola G. (2008). Strengthening of R/C existing columns with high performance fiber reinforced concrete jacket. *Concrete Repair. Rehabilitation and Retrofitting II*.
29. Mohammed A. Al-Osta, A. M. S., A.C. Mohamed Suhoothi, Syed Khaja Najamuddin. (2021). Strengthening of axially and eccentrically compression loaded RC columns with UHPC jacketing system: Experimental investigation and finite element modeling. *Engineering Structures*.
30. Nanni, S. R. N. G. a. A. (2008). Review of Design Guidelines for FRP Confinement of Reinforced Concrete Columns of Noncircular Cross Sections *composite Construction*.
31. Parametric studies on the moment resistant beamcolumn connection behavior of concrete filled double steel tubular columns and i steel beams.. (2022). doi: https://doi.org/10.18057/icass2020.p.284
32. Park, J., Park, S., & Hong, S. (2021). Evaluation of flexural behavior of textile-reinforced mortar-strengthened rc beam considering strengthening limit. , . *Materials, 14(21), 6473*. doi: https://doi.org/10.3390/ma14216473

33. Pascual, A., Romero, M., & Tizani, W. (2015). Fire performance of blind-bolted connections to concrete filled tubular columns in tension. *Engineering Structures, 96*.
34. Pham, N. (2023). Application of american aluminum specification in design of cold-rolled aluminum alloy channel columns. ,. *Key Engineering Materials,, 942*. doi:https://doi.org/10.4028/p-06zy91
35. Rohilla, I. (2023). A review on the performance of concrete filled tubular columns under axial compression: emphasis on geometrical parameters and various concrete infills and encasings. . *The Structural Design of Tall and Special Buildings*. doi: https://doi.org/10.1002/tal.2088
36. Rosalia, C., Putra, I., Dirgantara, T., Jusuf, A., & Hadi, B. (2020). Experimental study on the crashworthiness response of hybrid al/gfrp crash-box structures under axial compression loading. *Materials Science and Engineering*.
37. Teng, J., Chen, J., Smith, S., & Lam, L. (2003). Behaviour and strength of frp-strengthened rc structures: -. *Structures and Buildings,*. doi: https://doi.org/10.1680/stbu.2003.156.1.51
38. Teng, J., Yu, T., & Fernando, D. (2012). Strengthening of steel structures with fiber-reinforced polymer composites. *Journal of Constructional Steel Research, 78*, 131-143. doi:. https://doi.org/10.1016/j.jcsr.2012.06.011
39. Theodoros Chrysanidis, I. A. T. (2020). Axial and transverse strengthening of R/C circular columns: Conventional and new type of steel and hybrid jackets using high-strength mortar. *Journal of Building Engineering*.
40. Thong M. Pham 1, M. N. S. H. (2014). Confinement model for FRP confined normal- and high-strength concrete circular columns. *Construction and Building Materials*.
41. Tizani, W., Cabrera, M., Mahmood, M., Ninić, J., & Wang, F. (2022). The behaviour of anchored extended blind bolts in concrete-filled tubes. *Steel Construction, 15(S1)*.
42. Varinder Kumar , P. V. P. (2016). Strengthening of axially loaded circular concrete columns using stainless steel wire mesh (SSWM) – Experimental investigations "*Construction and Building Materials"*.
43. Wang, Y., Lin, S., Fan, F., Zhai, X., & Qian, H. . (2016). Numerical simulation of aluminum alloy 6082-t6 columns failing by overall buckling. . *Advances in Structural Engineering,, 19(10)*, . doi: https://doi.org/10.1177/1369433216643899
44. Wang, Z., Wang, Y., Yun, X., Gardner, L., & Hu, X. (2020). Experimental and numerical study of fixed-ended high-strength aluminum alloy angle-section columns. . *Journal of Structural Engineering,, 146(10)*. doi:. https://doi.org/10.1061/(asce)st.1943-541x.0002773
45. Wu, G., Wu, Z., Wei, Y., Jiang, J., & Cui, Y. (2012). Flexural strengthening of rc beams using distributed prestressed high strength steel wire rope: theoretical analysis. . *Structure and Infrastructure Engineering,*. doi:https://doi.org/10.1080/15732479.2012.715174
46. Wu, Y. a. Z., Q. (2011). Experimental investigation and design of aluminum columns with longitudinal welds., . *Frontiers of Architecture and Civil Engineering in China, , 5(3)*.
47. Xie Jian, F. Q., Yan Jia-Bao. . (2019). Compressive behaviour of stub concrete column strengthened with ultra-high performance concrete jacket. *Construction and Building Materials*(204:643–58.).
48. Yan, X., Ahmed, M., Hassanein, M., & He, M. (2023). Performance analysis and design of circular high-strength concrete-filled double-skin aluminum tubular short columns under axial loading. , . *Structural Concrete,, 24(5)*.
49. Zhou, C., Li, X., Wang, D., & Xia, S. (2019). Analysis of bearing capacity and seismic performance of circular RC columns strengthened with externally wrapped

steel plates. *Advances in Civil Engineering* doi:https://doi.org/10.1155/2019/2515091

50. Zhou, F. a. Y., B. (2009). Concrete-filled aluminum circular hollow section column tests. ,*Thin-Walled Structures*,, *47(11)*, 1272-1280. doi: https://doi.org/10.1016/j.tws.2009.03.014
51. Zhu, J. a. Y., B. . (2006). Aluminum alloy tubular columns, parametric study and design using direct strength method., , . *Thin-Walled Structures, 44(9)*.