PERFORMANCE OF FERROCEMENT ANGLE TO RETROFIT THE PARTIALLY DAMAGED RC COLUMN



By

A. K. M. Masum

13MCE004P

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER of ENGINEERING in CIVIL ENGINEERING

Department of Civil Engineering

CHITTAGONG UNIVERSITY OF ENGINEERING & TECHNOLOGY

AUGUST 2025

The thesis titled "**PERFORMANCE OF FERROCEMENT ANGLE TO RETROFIT THE PARTIALLY DAMAGED RC COLUMN**" submitted by **A. K. M. Masum**, Roll No: **13MCE004P**, Session 2013-2014, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of **Master of Engineering in Civil Engineering** on 17 August, 2025.

BOARD OF EXAMINATIONS

Dr. Md. Rabiul Alam
Professor
Department of Civil Engineering
CUET, Chattogram-4349

Chairman
(Supervisor)

Dr. Aysha Akter
Head
Department of Civil Engineering
CUET, Chattogram-4349

Member
(Ex-officio)

Dr. Md. Moinul Islam
Professor
Department of Civil Engineering
CUET, Chattogram-4349

Member

Dr. Md. Saiful Islam
Professor
Department of Civil Engineering
East West University, Dhaka-1212.

Member
(External)

Declaration

I hereby declare that the work contained in this Thesis has not been previously submitted to meet the requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the Thesis contains no material previously published or written by another person except where due reference is cited. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulations of CUET.



A. K. M. MASUM

Student ID: 13MCE004P

Department of Civil Engineering

Chittagong University of Engineering & Technology (CUET)

Copyright © A. K. M. Masum, 2025.

This work may not be copied without the permission of the author or Chittagong University of Engineering & Technology.

Dedication

To my beloved parents, especially my mother, whose constant encouragement for higher education shaped my journey. When I was serving in Dhaka and envisioned studying abroad, she reminded me that true learning can happen anywhere—even in Bangladesh—if one has access to books, a syllabus, dedicated teachers, and, most importantly, the intention and effort to strive for excellence. Her words remained with me and became a source of strength throughout this journey.

To my teachers at CUET, especially my thesis supervisor, for their support, mentorship, and for always encouraging research and critical thinking.

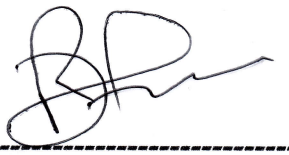
To the KAFCO authority, whose understanding and support allowed me to pursue higher studies alongside professional responsibilities, and to my Civil Maintenance staff at KAFCO, whose cooperation helped in the practical aspects of this work.

And to my wife, whose constant encouragement and belief in the lifelong journey of learning have inspired me every step of the way.

This work stands as a reflection of their faith, support, and sacrifices.

Approval/Declaration by the Supervisor

This is to certify that A. K. M. Masum has carried out this research work under my supervision and has fulfilled the relevant Academic Ordinance of the Chittagong University of Engineering and Technology, so that he is qualified to submit the following Thesis in the application for the degree of MASTER of ENGINEERING in Civil Engineering. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulations of CUET.



Dr. Md. Rabiul Alam

Professor

Department of Civil Engineering

Chittagong University of Engineering & Technology

Acknowledgment

All praise is due to Almighty Allah, whose mercy and blessings have enabled me to complete this thesis work successfully.

I would like to express my deepest gratitude to my supervisor, Prof. Dr. Rabiul Alam, for his continuous guidance, support, encouragement, and invaluable advice throughout the entire period of my research. His patience, motivation, and insightful feedback have shaped the direction and depth of this work.

My sincere thanks also go to Prof. Dr. Abdur Rahman Bhuiyan, Prof. Dr. Asiful Hoque and Dr. Md. Aftabur Rahman for their continued kind support, valuable guidance, and encouragement during my academic journey. I shall always be thankful to all of my above-mentioned teachers. I am also thankful to Prof. Dr. G.M. Sadiqul Islam for his support.

I gratefully acknowledge the KAFCO authority for permitting me to pursue higher studies while holding a management position with specific responsibilities. Special thanks go to the Late Mr. Sk. Shafi Ahmed, former COO of KAFCO, for his role in facilitating this opportunity, as well as to Mr. Azizur Rahman Chowdhury, then GM Maintenance (later COO), for his continued support. I also thank Mr. Manzur Zahed, DGM (Civil) for encouraging me to complete this academic endeavor.

I would like to extend my appreciation to the dedicated staff of the Civil Maintenance Department of KAFCO, particularly Mr. Zahedull Islam (Civil Supervisor), Mr. Shahjahan (Carpenter), and Mr. Bipul, Mr. Ali, and Mr. Anis from the mason group, for their active cooperation in preparing test samples and assisting during the experimental work on-site.

Special thanks are also due to Mr. A.H.M. Shahidul Islam, research assistant, IEER, CUET and Mr. Shakwat Karim Maher, research assistant, Department of Civil Engineering, CUET, for their technical assistance and support during laboratory experiments.

I am forever indebted to my parents, spiritual guides, and wife for their endless prayers, unwavering support, and encouragement throughout my academic journey.

Abstract

Reinforced concrete (RC) columns are the most crucial building component in concrete buildings, resisting both gravity and lateral loads. Therefore, their effective retrofitting technique is a burning topic in the scientific community. This research investigates the performance of prefabricated ferrocement angles (PFAs) as a retrofitting solution for damaged RC columns. A total of 18 scaled-down square columns of three different concrete strengths of 36.40 MPa, 34.20 MPa and 31.40 MPa were experimentally investigated. The strength of the ferrocement used to make the PFAs was 39 MPa. Each concrete strength group consists of 6 columns: 1 control, 1 control pre-cracked, 2 retrofitted with single-layer wire mesh PFAs and 2 retrofitted with double-layer wire mesh PFAs. The complete retrofitting procedures involved the external application of PFAs at the column corners with bonding agents, joining the PFAs with each other by sewing wire meshes and filling the voids between PFAs with high-strength mortar. The specimens were tested under displacement-controlled axial loading and performance in regard to ultimate load capacity, stiffness, energy absorption, ductility and failure patterns were evaluated.

The application of PFAs significantly increased the axial load capacity of the pre-cracked RC columns. Increasing the layer of wire mesh also increased the gain of axial load capacity by almost 50%. This increase was found to be more for RC columns of the higher concrete strength group, indicating the dependence of the axial load capacity increase after PFA jacketing on the actual concrete strength of the RC columns. PFA jacketing also helped to retain the stiffness of the pre-cracked samples while allowing greater lateral and axial deformation. Jacketing the pre-cracked columns with PFAs increased their energy absorption capacity by more than 100%. The proposed jacketing method of RC columns with PFAs

also improved their ductility via the confinement effect, ensuring higher plastic deformation and preventing brittle failure.

Key Words: Pre-fabricated ferrocement angle (PFA), Retrofitting, RC columns.

সারসংক্ষেপ

যেকোন কনক্রিটের তৈরী ভবনের সর্বাপেক্ষা গুরুত্বপূর্ণ অংশ হলো কলাম, যেটি একইসাথে অভিকর্ষ চাপ ও পার্শ্বীয় চাপ উভই প্রকারের বল প্রতিরোধ করে। তাই বৈজ্ঞানিক মহলে এসব কলামের কার্যকর রেট্রোফিটিং পদ্ধতি নিয়ে গবেষণা একটি আলোচিত বিষয়বস্তু। এই গবেষণায় প্রিফেব্রিকেটেড ফ্যারোসিমেন্ট এঙ্গেল (পি.এফ.এ.) ব্যবহার করে ক্ষতিগ্রস্ত আর.সি. কলামে এই রেট্রোফিটিং পদ্ধতির কার্যকারিতা পরীক্ষা করা হয়েছে। মোট ১৮ টি ক্ষুদ্রাকৃতির বর্গাকার কলাম পরীক্ষামূলকভাবে বিশ্লেষণ করা হয়, যেখানে ৩৬.৪০, ৩৪.২০ এবং ৩১.৪০ মেগাপ্যাসকেল বিশিষ্ট এই তিন ধরনের কনক্রিট ব্যবহার করা হয়। পি.এফ.এ. তৈরিতে ব্যাবহৃত কনক্রিটের শক্তিমাত্রা ছিল ৩৯ মেগাপ্যাসকেল। প্রতিটি কনক্রিট গ্রুপে ৬ টি করে কলামের নমুনা ছিল - ১ টি স্বাভাবিক কলাম, ১ টি ক্ষতিগ্রস্ত কলাম, ২ টি এক স্তর তারের জাল বিশিষ্ট পি.এফ.এ. রেট্রোফিটেড কলাম এবং ২ টি দুই স্তর তারের জাল বিশিষ্ট পি.এফ.এ. রেট্রোফিটেড কলাম।সম্পূর্ণ রেট্রোফিটিং পদ্ধতিতে কলামের কোনায় পি.এফ.এ. গুলো বাইন্ডিং ক্যামিক্যাল দ্বারা আটকানো হয় এবং পি.এফ.এ গুলো পরস্পর পরস্পরের মধ্যে বুনন তার দ্বারা যুক্ত করে অবশিষ্ট ফাঁকা স্থান উচ্চশক্তিসম্পন্ন মর্টার মিশ্রণ দিয়ে পূর্ণ করা হয়। কলামের নমুনা সমূহ এক্সিয়াল চাপ প্রয়োগপূর্বক ডিসপ্লেসমেন্ট কন্ট্রোল কর্মপদ্ধতি অনুসারে এদের চূড়ান্ত ভার বহন ক্ষমতা, কাঠামোগত দৃঢ়তা, শক্তি শোষণ ক্ষমতা, নমনীয়তা সূচক এবং কলাম ক্ষতিগ্রস্ত হওয়ার ধরণ যাচাই করা হয়। এটি পরিলক্ষিত যে পি.এফ.এ. ব্যবহার করে ক্ষতিগ্রস্ত কলাম সমূহ রেট্রোফিটিং করার ফলে এসকল কলামের এক্সিয়াল চাপ বহন ক্ষমতা উল্লেখযোগ্যভাবে বৃদ্ধি পায়। তারের জালের তৈরি স্তর সংখ্যা বৃদ্ধি করার ফলে এক্সিয়াল চাপ বহন ক্ষমতা ৫০ শতাংশ পর্যন্ত বৃদ্ধি পেয়েছে। কংক্রিটের শক্তিমাত্রা বৃদ্ধির সাথে সাথে এটি আরো বেশি মাত্রায় বৃদ্ধি পায়, যা প্রমাণ করে যে কলামগুলোর এক্সিয়াল চাপ বহন ক্ষমতা কলামে ব্যবহৃত কনক্রিটের শক্তিমাত্রার উপর নির্ভরশীল। এছাড়াও পি.এফ.এ. ব্যহারের ফলে ক্ষতিগ্রস্ত কলাম সমূহে অধিকতর অক্ষীয় এবং পার্শ্ব বিকৃতির পাশাপাশি এদের কাঠামোগত দৃঢতা বৃদ্ধি পায়। পি.এফ.এ. জ্যাকেটিং পদ্ধতিতে এসকল কলামের শক্তি শোষণ মত্রা ১০০ শতাংশ এর চেয়েও বেশি বৃদ্ধি পেয়েছে। প্রস্তাবিত এই পি.এফ.এ. জ্যাকেটিং পদ্ধতি কলাম গুলোতে কনফাইনমেন্ট প্রভাব সৃষ্টি করে, অধিকতর

প্লাস্টিক বিকৃতি নিশ্চিত করে এবং ভঙ্গুরতা প্রতিরোধ করার মাধ্যমে আর.সি. কলামের নমনীয়তা বৃদ্ধি করে।

মূল শব্দ: প্রি-ফ্যাব্রিকেটেড ফেরোসিমেন্ট অ্যাঙ্গেল (পি. এফ. এ), রেট্রোফিটিং, আর. সি কলাম।

TABLES OF CONTENTS

Abstract vii
সারসংক্ষেপ ix
TABLES OF CONTENTS xi
LIST OF FIGURES xiii
LIST OF TABLES xvii
Nomenclature xviii
Chapter 1 : INTRODUCTION 1
1.1 GENERAL 1
1.2 BACKGROUND 1
1.3 OBJECTIVES OF THE RESEARCH 3
1.4 SCOPE OF THE STUDY 4
1.5 THESIS OUTLINE 5
Chapter 2 : LITERATURE REVIEW 6
2.1 GENERAL 6
2.2 ROLE OF RC COLUMNS IN EXISTING STRUCTURES 6
2.2.1 Common Causes of RC Column Failures 7
2.2.2 Regional Context 7
2.3 FAILURE MODES OF RC COLUMNS 8
2.3.1 Flexural Failure 8
2.3.2 Shear Failure 8
2.3.3 Flexure Shear Failure 9
2.3.4 Compression Failure 9
2.3.5 Buckling Failure 9
2.4 TRADITIONAL RETROFITTING TECHNIQUES 9
2.4.1 RC Jacketing 10
2.4.2 Steel Jacketing 11
2.4.3 Concrete Encasement 13
2.4.4 Epoxy Injection and Surface Repair 14
2.4.5 External Binding 15
2.4.6 Shotcrete Jacketing 16
2.5 FERROCEMENT 17
2.6 FERROCEMENT IN STRUCTURAL REPAIR AND RETROFITTING 18
2.6.1 Prefabricated Ferrocement Angle (PFA) for Column Retrofitting 21
2.6.2 Relevance in Developing Countries 24
2.7 RESEARCH GAP 25

Chapter 3 : MATERIALS AND METHODOLOGY 26

3.1 GENERAL 26

3.2 MATERIALS 26

3.3 FORMWORK PREPARATION 27
3.3.1 Wooden Formwork for RC Column 27
3.3.2 Wooden Formwork for PFA Casting 29

3.4 REBAR PREPARATION 30

3.5 CONCRETE PREPARATION 30

3.6 PRE-CRACK PREPARATION of RC COLUMN 31

3.7 RC COLUMN CASTING 32

3.8 PREFABRICATED FERROCEMENT ANGLE (PFA) CASTING 35

3.9 JOINING PFAs WITH EACH OTHER 37

3.10 JACKETING OF PRE-CRACKED RC COLUMNS 38
3.10.1 Contact Surface Preparation 38
3.10.2 Application of Bonding Chemical 39
3.10.3 Application of High Strength Mortar 42

3.11 EXPERIMENTAL SETUP 46

Chapter 4 : RESULTS & DISCUSSIONS 49

4.1 GENERAL 49

4.2 COMPRESSIVE STRENGTH TEST OF CONCRETE 49

4.3 COMPRESSIVE STRENGTH TEST OF FERROCEMENT MORTAR 51

4.4 AXIAL COMPRESSION TEST OF COLUMN SPECIMENS 51
4.4.1 Load Displacement Behaviour and Stiffness 51
4.4.2 Energy Absorption and Ductility 64

4.5 FAILURE PATTERN 69

4.6 LATERAL DEFLECTION 81

4.7 COMPARISON WITH PREVIOUS RESEARCH 82

Chapter 5 : CONCLUSION 84

5.1 GENERAL 84

5.2 KEY OUTCOMES 84

5.3 LIMITATIONS 86

5.4 FUTURE RECOMMENDATION 86

BIBLIOGRAPHY 87

LIST OF FIGURES

Figure 2. 1: Typical strengthening of RC columns by RC jacketing[60] 10
Figure 2. 2: Steel jacketing applied to RC columns[67] 12
Figure 2. 3: Concrete encasement example[70].....13
Figure 2. 4: Epoxy injection for structural crack repair[74] 14
Figure 2. 5: FRP wrapping of RC column[81].....16
Figure 2. 6: Shotcrete application.....17
Figure 2. 7: Types of wire mesh used in ferrocement applications; (a) welded wire mesh; (b) hexagonal wire mesh; (c) woven wire mesh; (d) expanded metal [85].....18
Figure 2. 8: Prefabricated jacket, (a) "L" shape jacket, (b) "C" shape jacket[119] 23
Figure 2. 9: Design of (a) L-shape and (b) U-shape jackets[120] 23
Figure 2. 10: Confined specimens[120] 24

Figure 3. 1: Workflow diagram.....26
Figure 3. 2: Wooden formwork for RC column.....28
Figure 3. 3: Assembled wooden formwork for RC column.....28
Figure 3. 4: (a)WPM formwork, (b) Complete WPM formwork for PFA casting.....29
Figure 3. 5: Rebar orientation of column 30
Figure 3. 6: Manual concrete mixing.....31
Figure 3. 7: Packing paper profile for pre-crack preparation 31
Figure 3. 8: Plan view of packing paper inside the column for pre-crack preparation 31
Figure 3. 9: Placement of packing paper inside the formwork 32
Figure 3. 10: (a) Column without pre-cracking under axial load, (b) Column with pre-cracking under axial load. 32
Figure 3. 11: (a) Half casting of column and placement of packing paper, (b) Full casting of column after placement of packing paper.....33
Figure 3. 12: Slump test 34

Figure 3. 13: Concrete cube for compressive strength testing 34
Figure 3. 14: Curing of concrete cube and RC columns 35
Figure 3. 15: Casting of PFAs 36
Figure 3. 16: Curing of PFAs 36
Figure 3. 17: Joining of PFAs using GI wire 37
Figure 3. 18: Three sides joined and one side open PFAs 38
Figure 3. 19: Prepared surface of the RC column. 39
Figure 3. 20: Application of Nitobond EP to RC column surface 41
Figure 3. 21: Application of Nitobond EP to PFA surfaces 41
Figure 3. 22: Mixing of Renderoc HSXtra 42
Figure 3. 23: Application of Renderoc HSXtra on the inside portion of the wire mesh joint as a pre-place layer 43
Figure 3. 24: Application of Renderoc HSXtra on the remaining thickness at outside of the retrofitted column 44
Figure 3. 25: RC column retrofitted with PFA 45
Figure 3. 26: Detailed section of the retrofitted RC column 45
Figure 3. 27: Setup for determining compressive strength of (a) Concrete and (b) Ferrocement 47
Figure 3. 28: Experimental setup for column axial compression test 48

Figure 4. 1: Concrete cube failure pattern 50
Figure 4. 2: Load-displacement curve of specimen A1 52
Figure 4. 3: Load-displacement curve of specimen A2 53
Figure 4. 4: Load-displacement curve of specimen A3 53
Figure 4. 5: Load-displacement curve of specimen A4 54
Figure 4. 6: Load-displacement curve of specimen A5 54
Figure 4. 7: Load-displacement curve of specimen A6 55
Figure 4. 8: Load-displacement curve of specimen B1 55
Figure 4. 9: Load-displacement curve of specimen B2 56
Figure 4. 10: Load-displacement curve of specimen B3 56
Figure 4. 11: Load-displacement curve of specimen B4 57

Figure 4. 12: Load-displacement curve of specimen B5 57
Figure 4. 13: Load-displacement curve of specimen B6 58
Figure 4. 14: Load-displacement curve of specimen C1 58
Figure 4. 15: Load-displacement curve of specimen C2 59
Figure 4. 16: Load-displacement curve of specimen C3 59
Figure 4. 17: Load-displacement curve of specimen C4 60
Figure 4. 18: Load-displacement curve of specimen C5 60
Figure 4. 19: Load-displacement curve of specimen C6 61
Figure 4. 20: Comparison of the ultimate load capacity of the specimens 62
Figure 4. 21: Stiffness comparison of the specimens 64
Figure 4. 22: Total energy absorption 66
Figure 4. 23: Elastic energy absorption of the specimens 67
Figure 4. 24: Plastic energy absorption of the specimens 68
Figure 4. 25: Failure mode of specimen A1 69
Figure 4. 26: Failure mode of specimen A2 69
Figure 4. 27: Failure mode of specimen A3 70
Figure 4. 28: Failure mode of specimen A4 70
Figure 4. 29: Failure mode of specimen A5 71
Figure 4. 30: Failure mode of specimen A6 71
Figure 4. 31: Failure mode of specimen B1 72
Figure 4. 32: Failure mode of specimen B2 73
Figure 4. 33: Failure mode of specimen B3 73
Figure 4. 34: Failure mode of specimen B4 74
Figure 4. 35: Failure mode of specimen B5 74
Figure 4. 36: Failure mode of specimen B6 75
Figure 4. 37: Failure mode of specimen C1 76
Figure 4. 38: Failure mode of specimen C2 76
Figure 4. 39: Failure mode of specimen C3 77
Figure 4. 40: Failure mode of specimen C4 77
Figure 4. 41: Failure mode of specimen C5 78
Figure 4. 42: Failure mode of specimen C6 78

Figure 4. 43: Crushing failure of concrete 79
Figure 4. 44: Tearing of wire mesh in specimen 80
Figure 4. 45: Debonding of PFA from RC column surface 80
Figure 4. 46: Lateral deflection of different categories of specimens 82

LIST OF TABLES

Table 3. 1: Composition of Cement 27
Table 3. 2: Details of test specimens 46

Table 4. 1: Concrete compressive strength test results 49
Table 4. 2: Slump values for different types of concrete 50
Table 4. 3: Ferrocement mortar compressive strength test results 51
Table 4. 4: Summary of ultimate load capacity and stiffness 62
Table 4. 5: Energy absorption of the tested specimens 65
Table 4. 6: Lateral deflection of the tested specimens 81
Table 4. 7: Summary of performance comparison 83

Nomenclature

Symbols, Acronyms and Abbreviations

RC = Reinforced Concrete

PFA = Prefabricated Ferrocement Angles

ACI = American Concrete Institute.

ASCE = American Society of Civil Engineers.

BNBC = Bangladesh National Building Code.

LVDT = Linear Variable Differential Transformer

UTM = Universal Testing Machine

WPM = Wooden Packaging Materials

UTM = Universal Testing Machine

Chapter 1 : INTRODUCTION

1.1 GENERAL

In today's era of rapid infrastructural development, the selection of a proper structural system and a compatible material combination to serve the intended purpose is crucial for safe and sustainable development. In this regard, reinforced concrete (RC) contributed tremendously, becoming a cornerstone in the modern construction practice[1]. This was due to the excellent mechanical properties, economy and formability of RC. The combined effect of excellent compressive strength of concrete and superior tensile capacity of reinforcement encouraged versatile construction practice with the ability to withstand a wide range of load conditions[2]. The typical RC frame is made up of beams as horizontal elements and columns as the vertical structural elements. RC columns are essential for carrying the gravity loads of the structure and their performance under lateral loads like earthquake and wind is of greater importance. RC columns carry the load from the superstructure and transfer the same to the foundation. RC columns are given high importance as their failure can lead to disastrous consequences. As a result, the design and rehabilitation of RC columns are a critical focus in both the practical field and academia[3].

1.2 BACKGROUND

Like any other structural element, an RC column fails when the service load exceeds the capacity of the column[4]. There are two likely scenarios- one is where the column is well-conditioned, but the load exceeds under severe conditions like overloading of the gravity load, earthquake load, wind load, snow load, e.tc. Another one is where the column itself also deteriorated. These can be due to initial imperfection and material degradation[5–8], rebar corrosion[9–14], poor construction practice, especially inefficient detailing of rebar in a seismically

active region[15–18], chemical attack[19–24], biological degradation[25–28], etc. Another key parameter is the age of the constructed RC column. Usually, concrete structures are designed to serve for a specific period. After the completion of the design life, the performance of the RC structures diminishes significantly[29–31]. In the case of developing countries such as Bangladesh, this issue is more concerning as the adherence of structures built to proper seismic provisions and standard construction practice is questionable. As a result, there is a global demand for well-performing, cost-effective and easy-to-construct methods to repair damaged or partially damaged structural elements, with the main focus on RC columns.

Retrofitting in structural engineering refers to techniques adopted to restore or enhance the capacity of an existing structural component. When there is a lack of adequate capacity of a structural element due to a change in design requirements or damage to overstress, the first thought that comes to mind is demolishing and reconstructing the existing structure. However, it may not always be suitable, considering the occupancy, economy, logistical complexity or historical significance. Furthermore, retrofitting is a more sustainable solution compared to demolition and reconstruction[32, 33]. Therefore, retrofitting may be the main solution to be considered in this regard, particularly for strengthening of RC columns. Different types of retrofitting methods are available in current engineering practice. The selection of a particular method depends on the type of structure, damage intensity, capacity requirement, environmental considerations, etc[34–36]. The most common retrofitting methods are concrete jacketing and steel jacketing. The other innovative techniques include fibre reinforced polymer (FRP) and carbon fibre reinforced polymer (CFRP) jacketing, glass fibre reinforced polymer (GFRP), shape memory alloy, etc[37–43]. The most emerging alternative for structural retrofitting is the use of ferrocement.

This study aims to investigate the performance of prefabricated ferrocement angles (PFAs) in the retrofitting of RC columns, bonded by applying a chemical bonding agent between the column and the PFA. Gaps between the prefabricated segments were filled with high-strength mortar. R.C.C columns were cast with 3 (three) different strengths of concrete, which were made from three different mixing proportions. PFA segments were reinforced with one-layer and two-layer wire mesh to find the impact of increased reinforcement layer on the performance of PFA. The pre-cracked condition of the RC columns was simulated by inserting degradable thick papers, maintaining a definite profile during casting of the columns. For a single mix-ratio, one column was cast without any pre-cracking to identify actual column strength, one pre-cracked damaged column kept without jacketing to find the load-carrying capacity of a damaged column, 2 (two) pre-cracked columns were jacketed with PFAs, reinforced with 1(one) and 2(two) layers of wire mesh. For each mix ratio of concrete, a total of 6(six) columns were cast. A total 18 (eighteen) number of columns were prepared for three different concrete casting ratios. A universal testing machine (UTM) was used to apply displacement-controlled compressive load to the columns for strength testing and the axial load and relevant displacement were recorded in a computerized environment. The lateral deflection was recorded using two external strain gauges placed in orthogonal directions at the mid-height of the columns.

1.3 OBJECTIVES OF THE RESEARCH

This study aims to evaluate the effectiveness of PFAs as a retrofitting technique in restoring and enhancing the axial load-carrying capacity of partially damaged RC columns.

The specific objectives include-

i. To determine and compare the axial load-carrying capacity of scaled-down control columns, damaged columns and retrofitted columns.

ii. To determine the load displacement characteristics.

iii. To determine the stiffness, ductility and energy dissipation of the control, pre-cracked and retrofitted columns.

iv. To investigate the failure pattern of control columns, damaged columns and retrofitted columns.

1.4 SCOPE OF THE STUDY

A clear definition of the scope of scientific study is required to clarify the boundaries of a research and highlight its practical relevance. The works considered in this study are noted below-

i. This research studies the performance of scaled-down RC square columns for control columns, damaged columns and retrofitted columns.

ii. This study considers partially cracked RC columns by the placement of thick paperboard inside the column.

iii. This study used PFA at the corners of the damaged columns for retrofitting purposes.

iv. This study concentrates on the short-term, displacement-controlled axial loading only for laboratory testing, which is the primary load capacity for column elements.

1.5 THESIS OUTLINE

There are five chapters in this thesis. The study's background, problem statement, objectives and scope, relevant works, experimental setup, findings and detailed analysis, conclusions, etc., are presented systematically in this thesis.

Chapter 01 lays the foundation of the entire research. It explains the problem context, the importance of retrofitting and the significance of ferrocement as a retrofitting material. It outlines the objectives and the scope of this study clearly.

Chapter 02 presents a comprehensive review of past works in structural retrofitting of RC structures and various techniques available at the present time. It systematically introduces the research gap – the lack of studies on the performance of PFAs for RC column retrofitting.

Chapter 03 describes the complete experimental program, starting from the specimen details to the final test setup for the compressive test in the UTM.

Chapter 04 contains the results from the experiment and relevant discussions on load-displacement behaviour, load capacity, failure pattern and energy dissipation.

Chapter 05 summarizes the key outcomes of this research and discusses its practical implications with future recommendations.

Chapter 2 : LITERATURE REVIEW

2.1 GENERAL

RC columns are the most important part of reinforced concrete structures. For the safety of structures and to perform well in design load conditions as well as in unexpected and rare conditions, like an earthquake, it is necessary to realize the crucial role of RC columns. This chapter discusses the details regarding this topic and sheds light on the current practice of retrofitting of RC columns and emphasizes the importance of the study in question by finding out the literature gap.

2.2 ROLE OF RC COLUMNS IN EXISTING STRUCTURES

RC columns are the primary load-bearing elements in building structural systems. Their failure due to overloading, design deficiencies, or natural hazards such as seismic events, cyclones, and landslides can result in catastrophic consequences. Therefore, understanding the vulnerability of RC columns is important to develop effective and economical strategies for retrofitting purposes, especially for aging infrastructures and seismically active zones.

RC columns transfer loads such as axial load, bending loads, or a combination of loads from the superstructure to the foundation. In case of a multistorey building, columns are a key component in consideration to resist both the gravity load and the lateral load[44]. The performance of the whole structure as a whole depends on the ductility, strength and integrity of columns. Failure of even a single column, especially on the first floor of a multistorey building, can cause severe disruption in the load path of the system and bring down the whole structure[45]. The post-disaster investigation after the 1999 Izmit earthquake, Turkey and the 2015 Gorkha earthquake, Nepal, showed the catastrophic effects of inadequate

column detailing and degradation on the widespread collapse of RC buildings[46, 47].

2.2.1 Common Causes of RC Column Failures

Some of the common reasons for RC column susceptibility to failure are noted below-

i. Aging and Environmental Deterioration from carbonation-induced corrosion of reinforcement, freeze-thaw cycle, chloride ingress and poor construction management. These factors degrade the concrete and reduce the bond strength between the rebar and the surrounding materials[48].

ii. The inadequate design and detailing of columns resulting from wrong stirrups spacing, insufficient longitudinal rebar, lack of anchorage and low maintenance of development length. This is very true for buildings constructed before the 1980s, where gravity load resistance was given preference over ductility[49].

iii. Buildings may be subjected to increased service load due to a change in occupancy category, vertical extension or other unauthorized structural alterations. This may cause overloading of columns, leading to gradual or sudden failure.

iv. Dynamic actions occurring during an earthquake, such as reversal of cyclic loads, can significantly reduce the strength and stiffness of RC columns.

2.2.2 Regional Context

Bangladesh is a developing country where most of the buildings are constructed following the old building codes. The latest building code, Bangladesh National Building Code-2020 (BNBC-2020)[50], came into effect very recently. This code contains details guidelines regarding the seismic detailing of RC structures. Therefore, old structures built before the application of BNBC-

2020 pose a severe risk for the community and its people, particularly for areas in high seismic zones. In this scenario, cost-effective retrofitting strategies can greatly mitigate the regional seismic risk and improve the resilience of the community in question.

2.3 FAILURE MODES OF RC COLUMNS

RC columns can fail in various ways, which can be broadly categorized as flexural failure, shear failure and flexure-shear failure[51]. The details of failure modes of columns are discussed below-

2.3.1 Flexural Failure

Flexure failure in columns occurs when the bending moment due to external load exceeds the capacity of the column. The bending moment leads to the exceedance of the tensile capacity of the column reinforcement. This is characterized by the cracks developing on the tension side of the column and eventually crushing the concrete on the compressive side[51, 52]. This failure is typically ductile and allows for energy dissipation and deformation before collapse. Factors such as reinforcement details, axial load, steel ratio and material properties play a crucial role in influencing the flexural failure of RC columns[53–55].

2.3.2 Shear Failure

Shear failure of RC columns is a critical concern, particularly under dynamic loading conditions. This occurs when the shear force acting on the column exceeds the shear capacity of the column. Shear failure often results from diagonal cracking, invalidating the plane section condition and complicating the stress evaluation procedures. Unlike flexural failure, shear failure is often brittle, leading to catastrophic consequences[56].

2.3.3 Flexure Shear Failure

Flexure shear failure results from the combines action of bending and shearing force. This failure mode is brittle in nature and may result in sudden collapse. This failure mode is of high importance in seismic design as columns can be subjected to significant lateral load and deformation under seismic loads[57]. This failure mode is influenced by column aspect ratio, rebar detailing, loading conditions and material properties. Short columns with low aspect ratios and insufficient transverse rebar are more prone to shear failure after the yielding of flexural reinforcement[58].

2.3.4 Compression Failure

Compressive failure is a crucial failure to consider in the design of RC columns, as Columns are usually subjected to compression load under normal conditions over their entire service life. When the service axial load exceeds the column's capacity to resist, it leads to the crushing of concrete or yielding of reinforcement. This phenomenon is quite common for short column.

2.3.5 Buckling Failure

Buckling failure of RC columns is a critical issue, leading to sudden collapse most of the time. This failure is more prominent in slender columns, where buckling may occur before the failure of materials[59]. Loading conditions also play a vital role in the buckling of columns. A column designed for a concentric axial load may fail for an eccentric load of the same magnitude, due to the extra moment associated with the eccentricity. Therefore, any possibility of eccentric loading should be thoroughly analysed in the column design procedure.

2.4 TRADITIONAL RETROFITTING TECHNIQUES

Retrofitting of RC columns has always been a focal area of research in structural engineering due to their high vulnerability and critical role in load-bearing systems of buildings. Over the decades, several retrofitting techniques

have been developed to restore and enhance the strength, stiffness and ductility of RC columns. The traditional retrofitting techniques in practice are discussed briefly in the following section.

2.4.1 RC Jacketing

In this method, the existing RC column in encased in a new layer of reinforced concrete. The combined effect of old concrete and the new RC layer is ensured by the placement of shear connectors between them. When the question is about the retrofitting of RC columns, this is the primary solution applied. Figure 2.1 shows the typical cross-sections of RC jacketing for different column shapes.

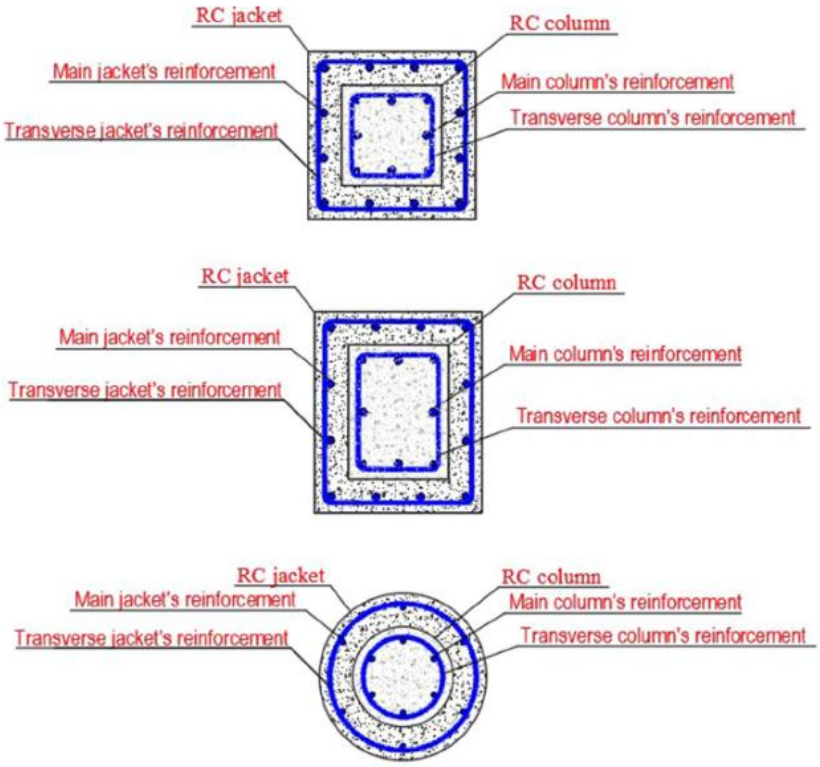


Figure 2. 1: Typical strengthening of RC columns by RC jacketing[60]

This technique is well favoured for its simplicity, easy design procedure, economy and the ability to significantly boost the structural performance of the retrofitted columns. It increases the load-carrying capacity tremendously. This increase can be up to 290% with the jacketed column behaving as a monolithic

component, without noticeable displacement between the original column and the outer jacket[61, 62]. It also increases the lateral stability during seismic events by reducing lateral displacements. The increased column ductility allows better energy dissipation in seismic events[60, 63]. The increase in the column section due to the outer layer of jacket increases stiffness and provides more confinement for the core concrete, increasing its capacity to withstand service loads[64].

While RC jacketing provides several advantages, it also has some major demerits. It requires proper surface preparation, shear dowels and bonding agent for effective action with the old concrete. The outer jacket increases the dead load on the structure. The increased cross-section may sometimes collide with the building's serviceability by reducing the effective areas available. Also, this jacketing process disrupts the regular operation of the building undergoing a retrofitting operation.

2.4.2 Steel Jacketing

It is a method of strengthening and repairing RC columns by encasing them in steel plates or a steel cage and the gap between the RC columns and steel is filled with grout or epoxy to ensure bond and confinement. This increases the load-bearing capacity, ductility and resistance to shear and compressive force of the column[65]. The confinement can be full or partial. Full encasement involves completely encasing the column with steel plates, leaving small gap between the steel plates and the RC column for grouting. In another method, steel angles are placed at the corners of the RC columns and those angles are welded together with steel straps or plates at a regular interval, forming a cage-like structure. In some cases, the steel plate wrapping also further strengthened using a stiffener. These partially stiffened steel jackets are very efficient in preventing shear brittle failure at the joint and greatly improve the ductility of the column, leading to an ultimate drift ratio of more than 8%[66]. Figure 2.2 shows the elevation of typical steel jacketing of RC columns.



Figure 2. 2: Steel jacketing applied to RC columns[67]

Steel jacketing also significantly increases the lateral performance of the RC columns, providing a more stable load-displacement curve. Increasing the length of the corner angles effectively boosts the lateral strength and ductility of the retrofitted columns[64]. Experimental studies showed that the latticed steel jacketing can effectively repair the shear-controlled columns, enhancing stiffness, strength and energy dissipation[68]. Steel jacketing is also found to enhance the performance of eccentrically loaded RC columns under monotonic loading[69].

Steel jacketing is widely popular as a retrofitting technique due to its effective confinement of core concrete, prevention of spalling or cracking of concrete cover, ease of application and cost-effectiveness. However, the initial cost of steel material may be an issue sometimes. Also, the application of steel jacketing may not always be aesthetically pleasing. The biggest disadvantage of steel jacketing is the susceptibility of steel to corrosion, making this technique almost impractical in a humid environment.

2.4.3 Concrete Encasement

Concrete encasement is a technique where a section in question is encased within a new layer of concrete to form a composite section. The addition of reinforcement or wire mesh is not compulsory in this method. In case of RC members, the surface is prepared first and then the high-strength concrete is poured in a formwork, either full encasement or partial encasement, and properly compacted. Proper curing is also necessary for achieving the desired strength of the new layer of concrete. This method is simpler and faster as plain or lightly reinforced concrete is used. The typical concrete encasement of a steel profile is shown in Figure 2.3.

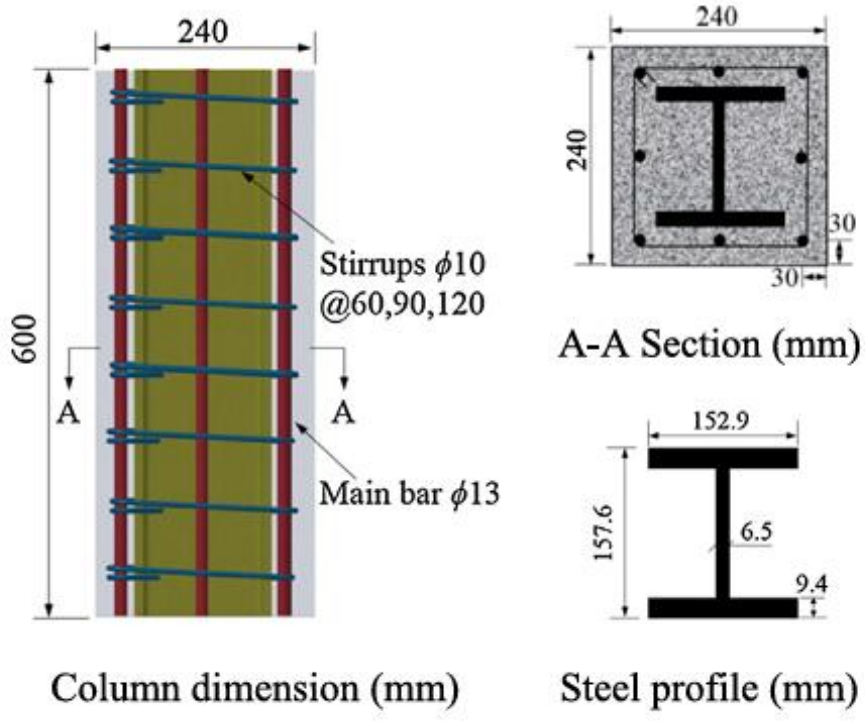


Figure 2. 3: Concrete encasement example[70]

Concrete encasement improves ductility by providing confinement. Use of special detailing in concrete-encased steel columns showed a significant increase in ductility, as an increase in displacement ductility factors and plastic hinge rotations was observed[71]. A study on the fire performance of concrete-encased

concrete-filled steel tube (CFST) showed high fire resistance and an increase in strength as well as retention of post-fire residual strength of the column[72]. Furthermore, the encasement of steel columns further improves the corrosion resistance, a common drawback of steel constructions.

The major drawback of this method is that the gain in strength is low as compared to RC jacketing, where proper reinforcement detailing is prioritized. Also, there is a risk of debonding of the new concrete layer and the original column section. In short, it can be said that only concrete encasement is a lower version of RC jacketing, primarily suitable for low-scale retrofitting works.

2.4.4 Epoxy Injection and Surface Repair

For repairing the cracks and voids in concrete components, epoxy injection is widely used to restore the structural integrity of the concrete. This process seals the existing crack and prevents further crack propagation, protecting the inner reinforcement from other moisture intrusion, harmful chemicals and other deterioration agents. Epoxy injection can restore the concrete structural component to its original strength, particularly for narrow cracks[73]. Figure 2.4 shows the epoxy injection technique for repairing the existing structural cracks.



Figure 2. 4: Epoxy injection for structural crack repair[74]

Epoxy injection can effectively restore structural integrity and moisture resistance, provided that the cracks are stable and not subjected to ongoing stress. If there is a possibility of subsequent movement, then this method of repair will not be effective[75]. Before epoxy injection can be initiated, a proper investigation of the cracks must be done. The crack width and depth will affect the choice of epoxy. Usually, low viscosity epoxies are preferred when the penetration depth is high for better restoration of strength[76]. Also, the number of drilling holes and epoxy application pressure play a vital role in the repair success.

It should be kept in mind that this process is not suitable for large-scale retrofitting where the capacity demand is high. This method can only treat the existing cracks for better performance of the structure. It cannot increase the ductility or strength higher than the design strength of the original section. Furthermore, this surface treatment is not applicable for severely damaged and yielding members[77].

2.4.5 External Binding

Another technique of retrofitting is to externally bind the structural component. The binding material can be fibre reinforced polymer (FRP), glass fibre reinforced polymer (GFRP), carbon fibre reinforced polymer (CFRP), etc. FRP wrapping is particularly effective in increasing the shear capacity, ductility and overall load-bearing capacity of RC columns. The column shape also plays a key role in FRP wrapping success. FRP wrapping was found to be more effective in circular columns due to the uniform distribution of confinement pressure, whereas the effectiveness for rectangular columns was limited. The attempt to increase the confinement of rectangular columns using post-tensioned CFRP showed a poor performance in this regard[78]. A study on the CFRP wrapping performance on a rectangular column with a large corner radius indicated an enhancement in the ultimate load-bearing capacity by delaying the rupture of the FRP[79]. Finite element analysis of GFRP wrapping of RC column showed up to

34% increase in load-carrying capacity and ductility of the wrapped column section[80]. FRP wrapping can also be full or partial wrapping. The effectiveness of partial wrapping depends on the arrangement and the number of FRP strips employed. The arrangement of partial wrapping also influences the failure mode of the column section[81]. Figure 2.5 shows the full and partial wrapping of RC columns with FRP.

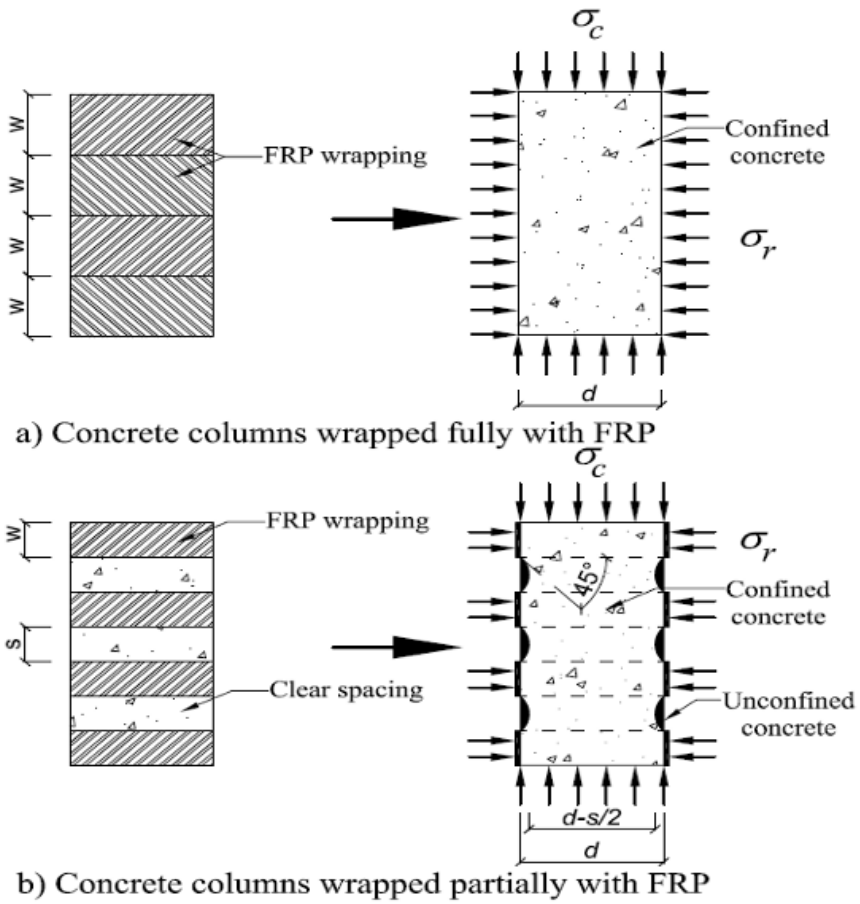


Figure 2. 5: FRP wrapping of RC column[81]

FRP wrapping is aesthetically poor, which some stakeholders find displeasing. The cost of FRP wrapping is very high and requires skilled labour for implementation. FRPs are also moisture sensitive during the installation process.

2.4.6 Shotcrete Jacketing

Shotcrete, also known as sprayed concrete, is a variant of concrete jacketing where concrete is applied pneumatically at high velocity, as shown in Figure 2.6, allowing it to be placed in complex shapes and hard-to-reach surfaces without

using any formwork. This process is very suitable for speedy construction and quick post-disaster recovery. However, it may suffer from poor bonding, internal voids and surface cracking, particularly in humid and poorly ventilated environments.



Figure 2. 6: Shotcrete application

2.5 FERROCEMENT

Ferrocement was first conceptualised by P. L. Nervi and is now widely used in a variety of fields for its outstanding crack resistance, tensile strength and free shape moulding opportunity. Ferrocement is a composite matrix of cementitious material reinforced with one or more layers of metallic or non-metallic wire mesh[82]. The wire mesh is typically made up of galvanised or stainless steel. In case of conventional reinforced concrete, reinforcements are provided in locations where the tensile stress is more likely to be generated, whereas in ferrocement, the uniform distribution of the wire mesh across the cross-section creates a multi-directional reinforcement system, which is the primary reason for the excellent performance of ferrocement against cracking and impact loading[82]. The typical thickness of ferrocement components is from 10mm to 30mm or more, making them extremely lightweight[83, 84]. Figure 2.7 shows the different types of wire mesh used in ferrocement.

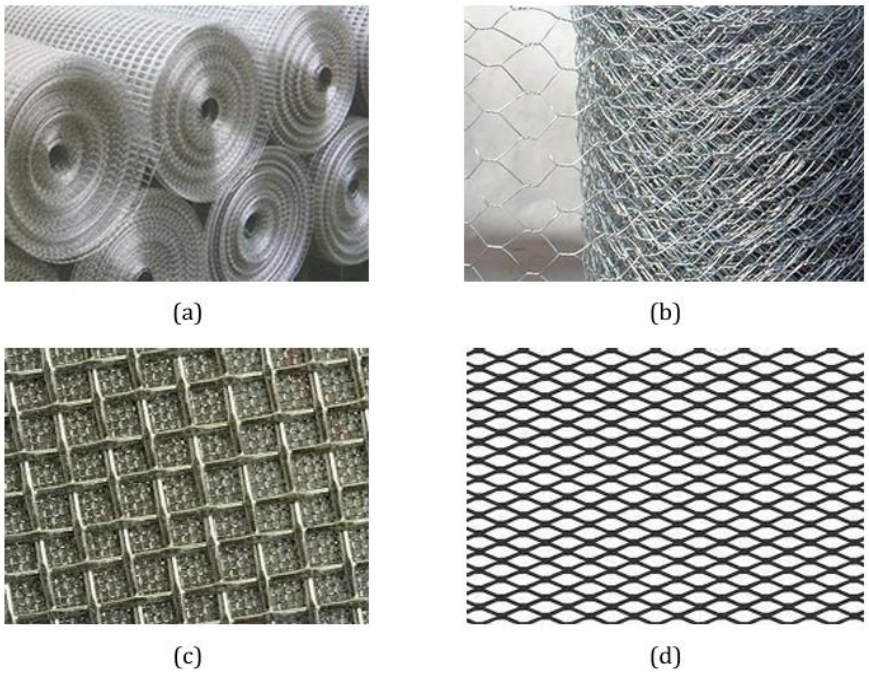


Figure 2. 7: Types of wire mesh used in ferrocement applications; (a) welded wire mesh; (b) hexagonal wire mesh; (c) woven wire mesh; (d) expanded metal [85]

2.6 FERROCEMENT IN STRUCTURAL REPAIR AND RETROFITTING

Outside the use of traditional methods discussed above, another technique that gained popularity in the retrofitting industry is the use of ferrocement. In search of an efficient, economical and easily constructible method for RC structure repair and retrofitting, ferrocement technology emerged as a promising alternative. Ferrocement is formed using-

i. A mortar mix of cement-sand ratio of 1 to 2.5 by weight and water-cement ratio of 0.4-0.6[86].

ii. A steel wire mesh, usually woven wire, expanded metal or welded wire.

iii. Admixtures if needed

It must be pointed out that no coarse aggregate is used in the mix design of ferrocement. Despite that, it shows a high tensile strength of 30-50 MPa due to steel mesh distribution and superior crack resistance controlled by the fine mesh system. Also, it absorbs a significant amount of energy and shows ductile

behaviour. All these benefits may come from a thin section of 10-25mm ferrocement cast in a regular or irregular shape[87]. The most important benefit of using ferrocement is its formability and workability. Due to its thin shape and flexible wire mesh system, it can be moulded into any desired shape. This property is extremely useful while thinking about retrofitting of irregular or non-standard sections, where the traditional approach can be costly and sometimes impractical. Also, its high surface-to-volume ratio makes it an ideal solution for surface treatment and overlays[88]. The other key benefits are[83, 89] :

i. High tensile strength and toughness.
ii. Excellent crack resistance and fatigue resistance.
iii. Light-weight structure.
iv. Readily available raw material.
v. Less formwork for construction.
vi. Rapid construction.
vii. More sustainable than a conventional RC structure.
viii. No skilled labour required.

Despite its wide popularity, ferrocement application has some minor drawbacks, like-

i. Low resistance to punching.
ii. More susceptible to wire mesh corrosion if the mortar cover is inadequate.
iii. Fastening bolts, screws, welding and nailing operations are not easy.
iv. High cost of labour for intricate construction.

Over the years, several research works have been conducted on the suitability and performance of ferrocement retrofitting. While used in the retrofitting of RC members, ferrocement showed a moderately high performance. It can significantly increase the ductility and load-carrying capacity of RC columns[90–93]. Ferrocement is also found to increase the flexural capacity, shear capacity and ductility of RC beams[94–99]. Dhanoa et al.[100] examined the performance of ferrocement on RC beam strengthening and observed an increase of 45% compared to the control beam and the stiffness was also improved as depicted by the moment rotation curve. Makki[101] used bolts to join ferrocement to the RC beam to eliminate the debonding of ferrocement from the beam face. He reported a staggering increase of 69.8-175% in the ultimate load-carrying capacity of the strengthened RC beam. He also reported a positive effect of an increase in wire mesh diameter in the ultimate strength of the beam. Muhit et al.[98] conducted an experiment on 20 RC beams of size 203mmx203mmx1000mm with a shear deficiency employing different layers of wire mesh. They found a 46% increase in the ultimate load-carrying capacity of the sample with three layers of wire mesh. The retrofitted beams' failure mode was flexural despite the shear deficiency in the original design. Beams retrofitted with ferrocement exhibited reduced crack width, increased deflection at higher ultimate load, indicating better ductility and crack control compared to normal RC beams[102].

Al-Rawe et al.[103] experimented on six biaxially loaded RC columns of size 150mmx150mmx1700mm retrofitted with ferrocement jacketing. The retrofitted columns showed a 38.8% increase in ultimate load-carrying capacity compared to the control column. Islam and Kabir[104] studied the behaviour of the RC column of size 152mmx152mmx1524mm under axial load. They showed that the capacity of the column with double wire ferrocement increased by 58% and ductility by 78% compared to that of the single-layer wire mesh. Abdullah and Takiguchi[105] experimented on six identical columns retrofitted with circular or

square ferrocement orientation. All confined columns showed a significant performance boost, increasing ductility tremendously. Bari et al.[106] investigated the performance of ferrocement on the retrofitting of fire-damaged columns. Their study showed a 46% decrease in the load capacity of the column after a fire incident, which was increased by 23% and 49% by ferrocement retrofitting after the fire damage with one layer and two layers of wire mesh, respectively. Kaish et al.[107] studied square jacketing with single-layer wire mesh and rounded column corners (RSL), square jacketing using single-layer wire mesh with shear keys at the centre of each face of the column (SKSL) and square jacketing with single-layer wire mesh and two extra layers of mesh at each corner (SLTL). All three types of retrofitting with ferrocement effectively overcame the stress concentration problem related to square column retrofitting and SLTL showed the most superior performance under concentric loading and RSL under eccentric loading. Amala et al.[108] experimented on the effectiveness of high-performance ferrocement mortar mix as a retrofitting material for square columns, where the mix proportion of 1:1.5 displayed a higher load-carrying capacity of 8.85% compared to the control column. R et al.[109] studied the performance of full and strip wrapping employing ferrocement. Indeed, the full wrapping system showed a much higher load-carrying capacity and lower deflection compared to the strip wrapping technique.

2.6.1 Prefabricated Ferrocement Angle (PFA) for Column Retrofitting

Prefabrication refers to the manufacturing of building elements or modules in a controlled environment in a factory setting and later transportation and on-site assembly of those components[110, 111]. This offers automation and mechanisation of the construction process and significantly reduces the construction time compared to traditional in-situ construction. This reduction in time can be up to 73%[112]. It also contributes to improving quality control, cost

reduction, risk reduction and waste minimisation as well as sustainable construction practice[113–115].

While the prefabrication process is combined with ferrocement technology, it presents a promising and efficient development, especially for the retrofitting works of RC structures. On top of that, focusing on the corners of RC square or rectangular columns with PFA will provide effective confinement and crack arrest, as corners are the critical areas where stress concentration occurs and are more prone to cracking[116, 117]. This way, the amount of material used will also be minimised and will require minimal surface preparation. Furthermore, this will ensure better strengthening of the RC columns for superior performance under various loads, including seismic loads and better crack prevention[118]. Therefore, the idea of retrofitting partially cracked RC columns using PFA is a relatively novel concept with significant promise.

As for the inclusion of the prefabricated concept with ferrocement jacketing, very few studies are found. Kaish et al.[119] presented a prefabricated ferrocement jacketing system for semi-automated strengthening of RC columns. In their study, they presented the importance of prefabricated retrofitting technique and discussed various possible jointing methods for the prefabricated "L"and "C" shaped jackets, as shown in Figure 2.8, where the "C" shape showed higher ultimate load carrying capacity.

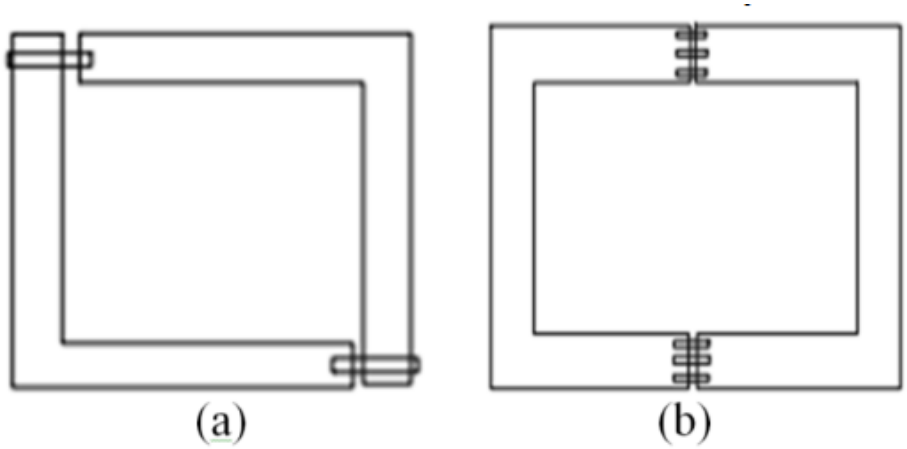


Figure 2. 8: Prefabricated jacket, (a) "L" shape jacket, (b) "C" shape jacket[119]

Mahmood et al.[120] proposed "L" shaped and "U" shaped wearable prefabricated ferrocement jackets. Their proposed arrangement is shown in Figure 2.9 and the attachment method to the RC column is shown in Figure 2.10.

5

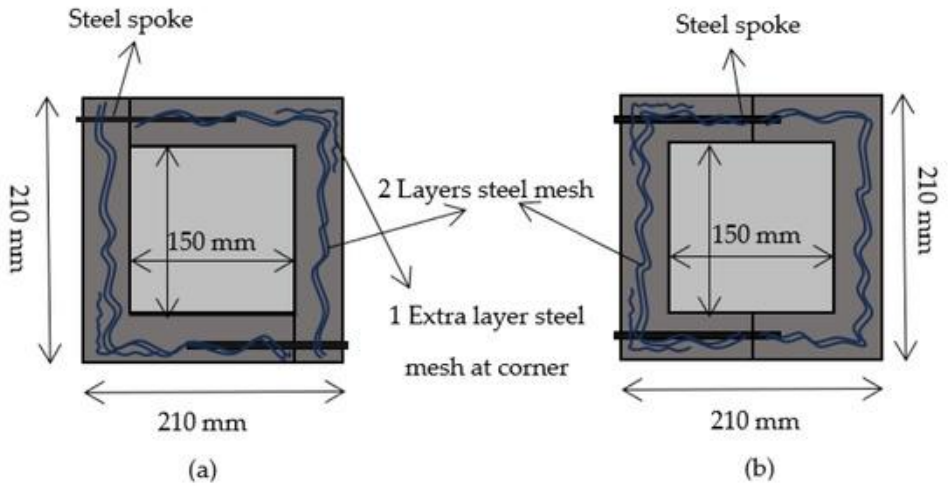


Figure 2. 9: Design of (a) L-shape and (b) U-shape jackets[120]

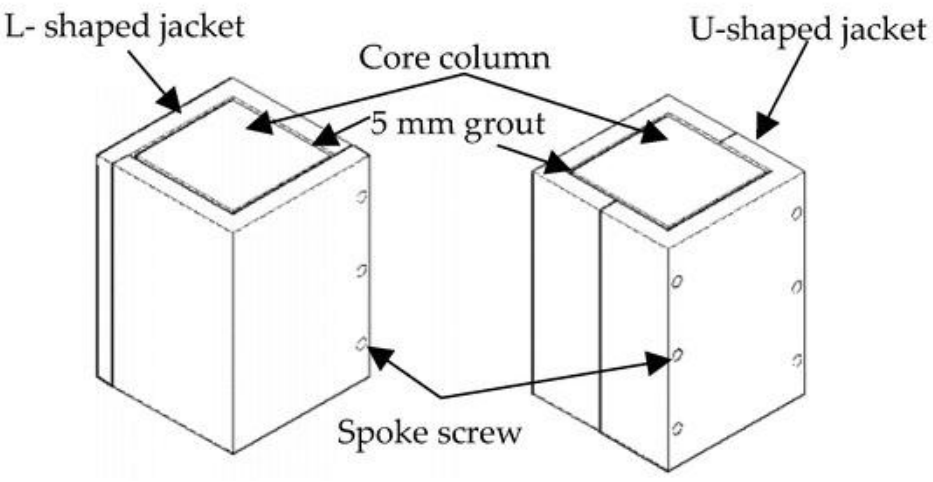


Figure 2. 10: Confined specimens[120]

They observed that the "U" shaped jacket was more effective in repairing and strengthening square columns.

2.6.2 Relevance in Developing Countries

From a practical standpoint, the innovation of PFA holds significant relevance for developing countries like Bangladesh. Here, construction quality is often poor and the use of advanced technology and skilled labour is scarce. Most of the time, any retrofitting works depend on simple tools, locally available materials, an easy construction sequence and economically viable methods.

Moreover, the consideration for post-disaster recovery is often neglected in the planning and design of structures. This is particularly important for the old buildings and other structures situated in those regions, especially for seismically active zones. In this scenario, a rapid retrofitting solution will play a crucial role in the disaster resilience of these regions and significantly increase the safety of life and assets. Therefore, PFA not only contributes to the retrofitting of structures but also increases the social and economic security of the people. This hybrid innovative method will combine modern enhanced performance with the low-tech construction practice of the developing countries, leading to sustainable

and accessible structural retrofitting practice for RC structures, particularly for columns.

2.7 RESEARCH GAP

From the reviewed literature on the retrofitting procedures of partially damaged RC columns, it is seen that most of the techniques are costly and time-consuming procedures that do not support the quick retrofitting of damaged RC columns. Some of the methods need sophisticated materials that are not readily available in Bangladesh. Considering these limitations, it is evident that ferrocement opens a gate with vast potential in the field of structural engineering as a retrofitting material. On top of that, the inclusion of a prefabricated system will make retrofitting work using ferrocement faster, efficient and dynamic. As evident from the literature review, this field still needs more research. Therefore, in this thesis, the performance of prefabricated ferrocement "angles" as a retrofitting method to strengthen pre-cracked RC square columns is investigated using locally available materials. This novel research also incorporated the effect of column concrete strength and the effects of single-layer and double-layer wire mesh in this study.

Chapter 3 : MATERIALS AND METHODOLOGY

3.1 GENERAL

This chapter presents the methodology and experimental setup that have been implemented to investigate the performance of prefabricated ferrocement angles (PFAs) to retrofit partially damaged RC columns. A quantitative approach was adopted with the focus on the structural behaviour of the RC columns under axial loading. The general steps are shown in Figure 3.1-

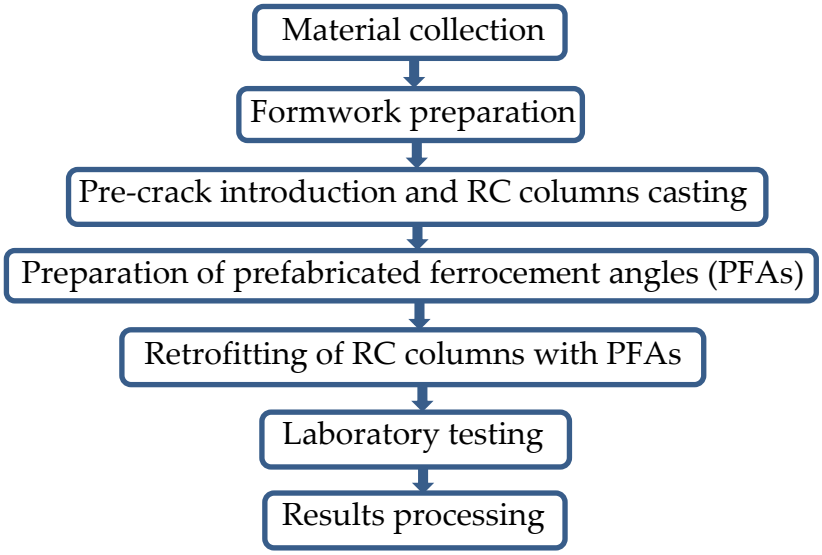


Figure 3. 1: Workflow diagram

3.2 MATERIALS

The research utilized the local materials available in Bangladesh. The local sand available was used as fine aggregate and stone chips were used as coarse aggregate. Portland composite cement, supplied by Heidelberg Cement Group, was used as the binding material. The specifications of the binding material are given in Table 3.1.

Table 3. 1: Composition of Cement

Property	Specifications
Product Type	BDSEN-CEM II/B-M(S-V-L)
Grade	425 N
Clinker	65-79%
Slag, Fly ash and Limestone	21-35%
Gypsum	5%

60-grade rebar was used both for the longitudinal and lateral reinforcement. The wire mesh used in the making of PFA was the locally available one, which is usually used for sieving sand or chips. The mesh size was 3.85mmx3.7mm and the wire size was 24 SWG (0.6mm)

For binding the PFA to the column surface, an epoxy resin bonding agent, named Nitobond EP[121], was used. This is a two-part epoxy system consisting of base and hardener. To fill in the portion between the PFAs and the column surface, a highly consistent repair mortar, called Renderoc HSXtra[122] , was used. For rapid curing, a water-based concrete curing compound, named Concure WB[123], was used.

3.3 FORMWORK PREPARATION

3.3.1 Wooden Formwork for RC Column

The formwork for the RC column was prepared using 1-inch-thick wooden planks. The top side was kept open and the other three sides were joined to make a form work that could be easily disassembled and reused. The inside dimension of the formwork was 900mmx150mmx150mm, as shown in Figures 3.2 and 3.3.

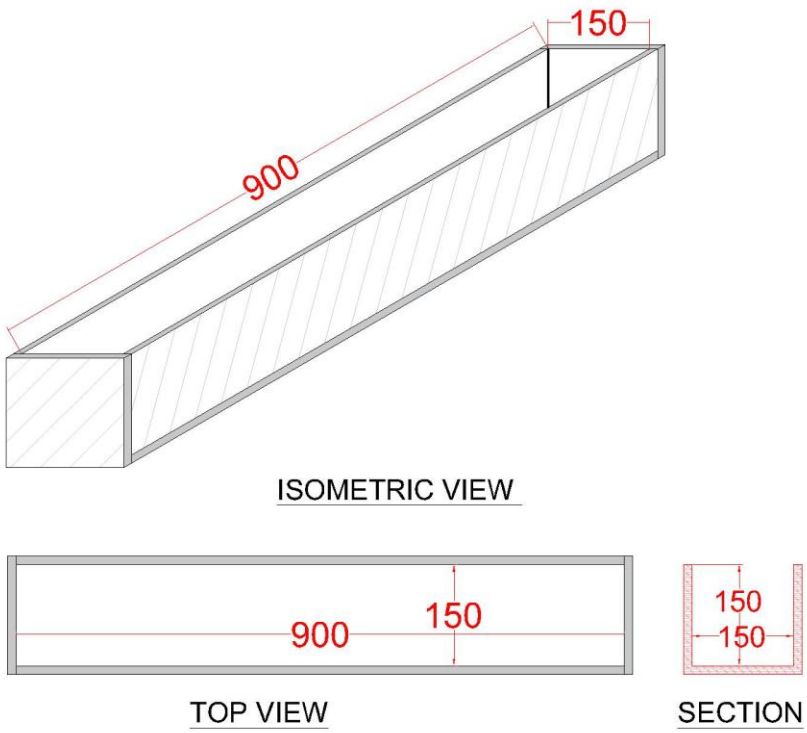


Figure 3. 2: Wooden formwork for RC column



Figure 3. 3: Assembled wooden formwork for RC column

The inside surfaces and edges of the formwork were well finished for accuracy of dimensions, smooth concrete surfaces and minimizing the gaps for better water tightness. The inside planes of the formwork were coated with shutter oil for smooth finishing, good compaction and easy removal of formwork. At the top open surface, some wooden battens were also placed to preserve the shape

of the formwork and remove the possible displacement of the sides during compaction activity.

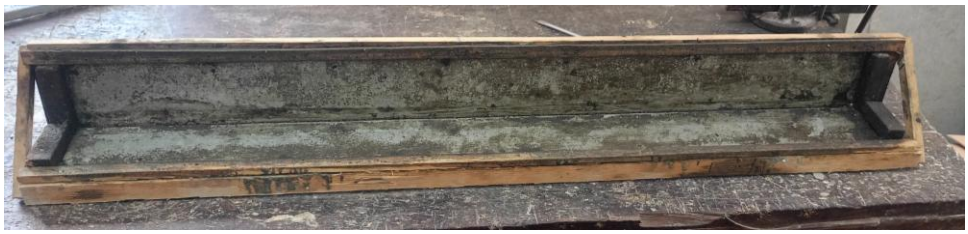
3.3.2 Wooden Formwork for PFA Casting

This work can be divided in two consecutive steps-

i. At first, the wire mesh was prepared. The wire mesh was cut into the desired size using a wire cutter. The length of the mesh was 870mm and width was 200mm. Some portion of the wire mesh was kept outside of the formwork so that the extra portion can be used for sewing two side-by-side place PFA.

ii. Then, the formwork was made with wooden packaging materials (WPM), which is a prefinished material. These comparatively soft materials were used for making accurate angles and for precision fabrication. The inside surface was metallized with an aluminum sheet, which was coated with shutter oil before casting, for smooth finishing and easy removal of the PFAs after casting, as shown in Figure 3.4. The dimension of PFA angles was 890 mm in length with two 75 mm legs. This dimension was maintained by fixing wooden battens around the casting form.

(a)



(b)

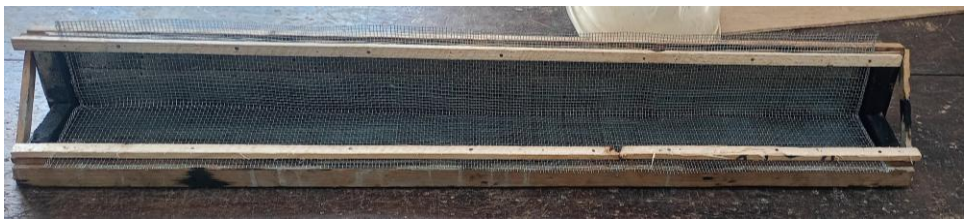


Figure 3. 4: (a)WPM formwork, (b) Complete WPM formwork for PFA casting

2 (two) layers of battens of thickness 8 mm each were fixed at the ends of the formwork. At the first step, one layer of batten was fixed. In the second step, the wire mesh layer is fixed in position with an extended width greater than the PFAs, which will be used later for binding the angles together for jacketing. In the final step, fixing of 2nd layer of battens, all with small nails with extensions to remove them easily during the formwork striking. Angle battens were also fixed at the two short ends to hold the angle in position firmly.

3.4 REBAR PREPARATION

The rebars used in this experiment were Extreme-500W manufactured by BSRM. Two different diameters of rebar were used. For longitudinal reinforcement, 4 nos. of DB10mm bars and for stirrups, 7 nos. of DB8mm @ 133mm c/c spacing were used. Clear cover for all rebar was 25mm from the stirrup and at the end of the longitudinal bar. The rebar detail is shown in Figure 3.5.

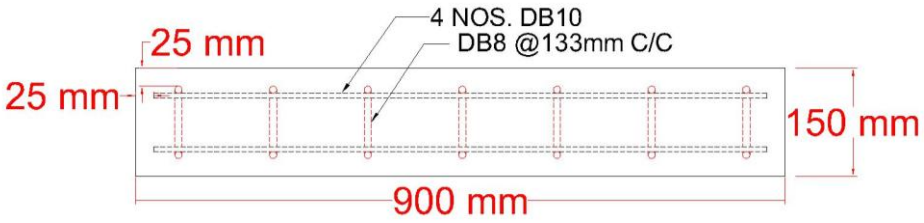


Figure 3. 5: Rebar orientation of column

3.5 CONCRETE PREPARATION

In this study, three different types of concrete mix ratios were utilized. The proportions were (Cement: Sand: Stone Chips) 1:2:3, 1:2.5:4, 1:2.5:3.5 on a volume basis. The sand mixture contains 50% local sand and 50% Sylhet Sand. The concrete paste was prepared using hand mixing, as regularly employed in local construction, thoroughly, to get a homogeneous mixture. Figure 3.6 shows the mixing process, which was conducted on a clean platform to avoid the intrusion of any foreign materials.



Figure 3. 6: Manual concrete mixing

3.6 PRE-CRACK PREPARATION OF RC COLUMN

To introduce cracks in the casted columns for simulating cracked columns, 2mm thick packing paper was used, as experimental formation of cracks is very difficult in the laboratory. The profile of the packing papers and their positions are shown in Figures 3.7 to 3.9.

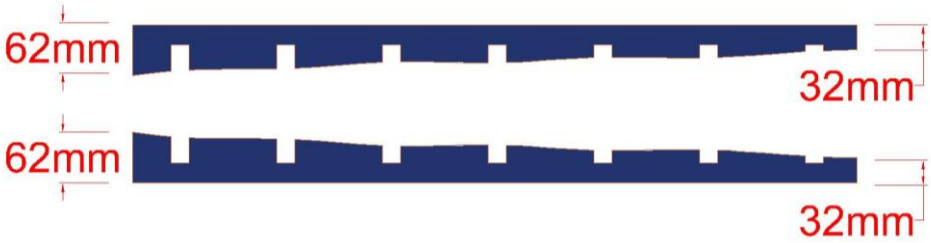


Figure 3. 7: Packing paper profile for pre-crack preparation

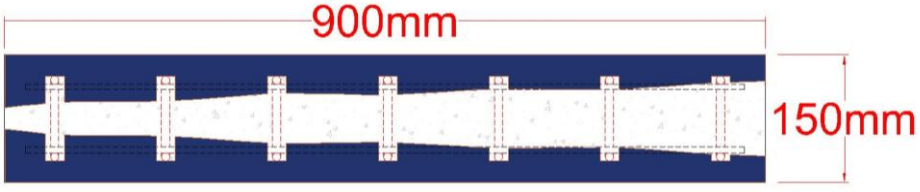


Figure 3. 8: Plan view of packing paper inside the column for pre-crack preparation

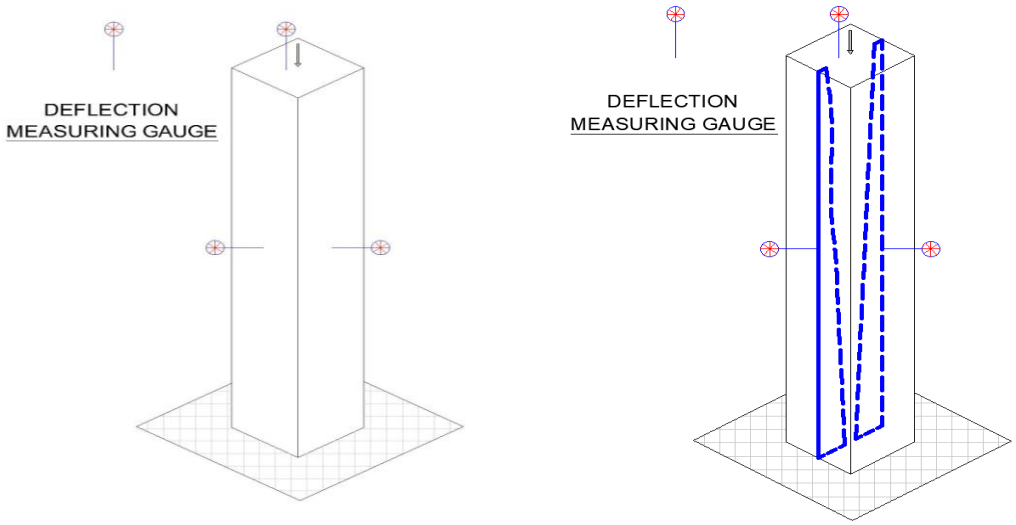


Figure 3. 9: Placement of packing paper inside the formwork

The packing paper was placed in the middle depth of the column with both the 62mm ends at one end of the column and the 32mm ends at the other end of the column.

3.7 RC COLUMN CASTING

The rebars were placed into the prepared formwork, maintaining a 25mm clear cover on all sides. Wet concrete is placed into the formwork using a trowel and simultaneously compacted with the trowel and rebar. Each batch of casting was used for casting a total of 6 (six) specimen columns. One sample was cast without any pre-cracking. The rest of the five specimens were pre-cracked with the above-mentioned packing paper inserted into a profile. The general idea of the precracked and uncracked column is shown in Figure 3.10.



(a) (b)

Figure 3. 10: (a) Column without pre-cracking under axial load, (b) Column with pre-cracking under axial load.

In the first step, as shown in Figure 3.11, casting of half the depth of the formwork was done, then placement of the paper profile and then the rest of the depth casting was done.

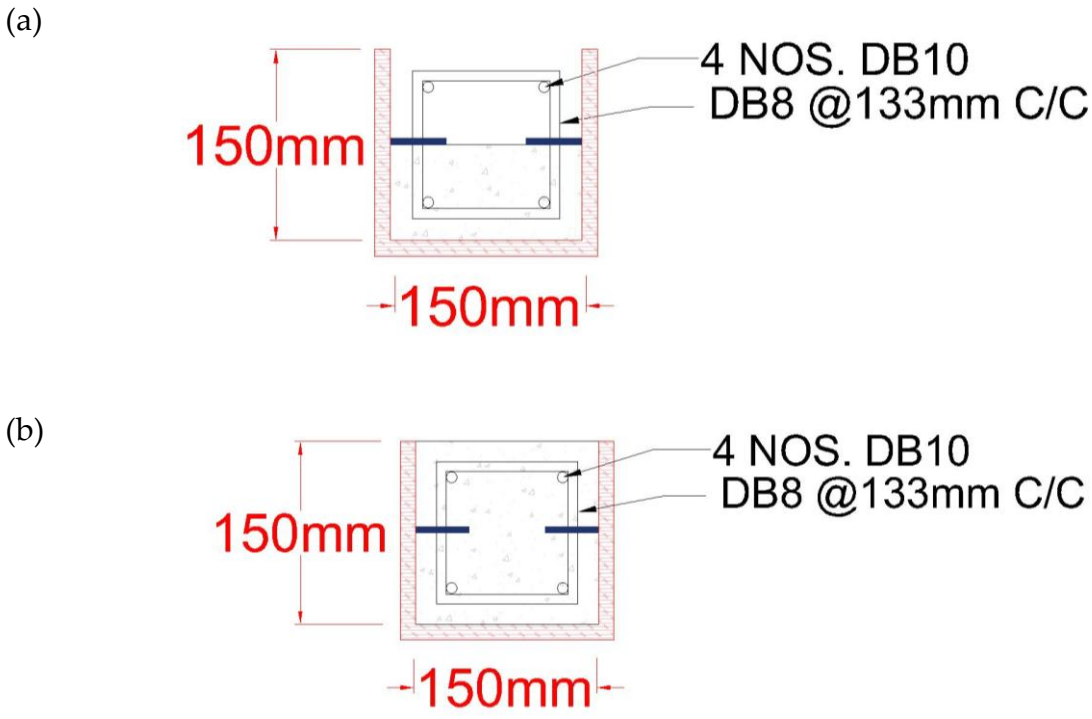


Figure 3. 11: (a) Half casting of column and placement of packing paper, (b) Full casting of column after placement of packing paper.

The specimens were left for setting up until the setting time. After almost 48 hours, the formwork was removed. The same procedures were followed for column casting with different mix ratios. After removal of formwork, the specimens were left for submerged curing in the curing pit for 28 days. Slump values were checked during casting using a slump cone as shown in Figure 3.12. Also, 3 concrete cubes of size 6"x6"x6", shown in Figure 3.13, from each set were taken to confirm the concrete compressive strength. The curing procedure for all test specimens is shown in Figure 3.14.



Figure 3. 12: Slump test



Figure 3. 13: Concrete cube for compressive strength testing



Figure 3. 14: Curing of concrete cube and RC columns

3.8 PREFABRICATED FERROCEMENT ANGLE (PFA) CASTING

At first, cement and sand were mixed with a ratio of 1:1.5. The water-cement ratio used for ferrocement mortar was 0.45. The measured water was gradually mixed with the mixture of cement and sand to make a homogeneous paste. The paste was then poured into the WPM formwork with a previously fixed single or double layer of wire mesh. A steel towel was used to press and compact the ferrocement paste in the formwork slowly. PFA casting is shown in Figure 3.15.



Figure 3. 15: Casting of PFAs

As the PFA consists of two legs, one leg was placed horizontally and cast first and left for a while to set. After hardening of one leg, the ferrocement mortar was poured into the other leg in the same way. This process was followed for all the PFAs casting. The formwork was removed after 48 hours and was left in a curing pond for 28 days, shown in Figure 3.16. 10 cubes of size 50mmx50mmx50mm of the ferrocement mortar were also prepared, which were later tested in the laboratory for their compressive strength.



Figure 3. 16: Curing of PFAs

3.9 JOINING PFAS WITH EACH OTHER

The RC column studied in this research was square in shape. Therefore, for easy attachment of PFAs to the square RC column surface, 4 PFAs were joined together, keeping one side open (Figure 3.18).



Figure 3. 17: Joining of PFAs using GI wire

The joining operation was done by sewing the overlapping extended portions of the wire mesh of the PFAs with each other using 24SWG GI wire in both directions, as shown in Figure 3.17. The stitching was done in a spiral form.



Figure 3. 18: Three sides joined and one side open PFAs

The side that was left open was joined following the same process using GI wire after surrounding the RC column.

3.10 JACKETING OF PRE-CRACKED RC COLUMNS

3.10.1 Contact Surface Preparation

Before the application of the chemical bonding agent to join the PFAs to the RC column surface, the surface of the RC column was prepared using the following 5 steps-

i. Wiping of the RC column surface using dry hessian cloths.

ii. Chipping the concrete surface by applying about 20 strikes per square foot surface area of the column. The depth of the chipping was not more than 1-2mm.

iii. Rubbing off the chipped-off surface with a wire brush and wiping with a dry hessian cloth.

iv. Wiping the surface with a wet hessian cloth.

v. Drying of the RC column surface completely.

The prepared surface of the RC column before the fixing of the PFAs is shown in Figure 3.19.



Figure 3. 19: Prepared surface of the RC column.

Similarly, the surface of the PFAs that will be in contact of the column was prepared using the following steps-

i. Wiping the surface with dry hessian cloths.

ii. Rubbing off the surface with a wire brush and wiping with a dry hessian cloth.

iii. Wiping the surface with a wet hessian cloth.

iv. Complete surface drying of the PFAs.

3.10.2 Application of Bonding Chemical

An epoxy resin was used as a bonding agent between the RC column surface and the PFA, called Nitobond EP, manufactured by Berger Fosroc

Limited. Before application, the two parts of the bonding agent, base and hardener, were mixed well with each other according to the specified proportion. The mixture was prepared for each column separately as it sets within a very short time.

The steps in the mixing operation are as follows-

i. Taking 100 mL of base in a premeasured jar after stirring the container well to mix the deposition at the bottom of the container homogeneously.

ii. Taking 56 ML of hardener in another premeasured jar after stirring the container well to mix the deposition at the bottom of the container homogeneously.

iii. Pour both of the components into a mixing jar and mix thoroughly with a steel stirrer.

After the mixture was prepared, it was applied to the prepared dry surface of the RC columns and the PFAs using a brush. The brush application of the Nitobond EP to the prepared surfaces included the following steps-

i. The brush was dipped in the prepared mixture and gently applied the epoxy resin to the surfaces of the RC columns and the PFAs.

ii. Wait for 30-40 minutes for the transformation of the applied mixture to gel.

iii. Apply a 2nd coat of Nitobond EP in the same process.

The application of Nitobond EP to RC columns and PFA surfaces is shown in Figures 3.20 and 3.21.



Figure 3. 20: Application of Nitobond EP to RC column surface



Figure 3. 21: Application of Nitobond EP to PFA surfaces

3.10.3 Application of High Strength Mortar

To fill the gaps between PFAs to PFAs and to fill gaps between the PFAs and the column surface, a high-strength repair mortar, called Renderoc HSXTra, was used. The mixing process of the Renderoc HSXtra for one column treatment included the following steps-

i. 4.5 kg dry powder was taken in a plastic container.

ii. 625 mL of water was taken in a jar.

iii. The water was gradually mixed with the dry powder in the container by a low-rpm power-operated paddle mixture machine, as shown in Figure 3.22, until complete mixing of the ingredients and obtaining a flowable mixture.



Figure 3. 22: Mixing of Renderoc HSXtra

For the ease of application and jacketing of the RC column, the application of the high-strength mortar can be divided into two separate operations. In the first step-

i. Applying the mortar on the inside bonding agent-coated surface of the PFAs in a thin layer to minimize the gaps between the angles and the concrete columns.
ii. Applying the mortar in the inside portion of the wire mesh joint in a thick layer as a preplaced layer so that the gap below the wire mesh can be minimized, as shown in Figure 3.23.

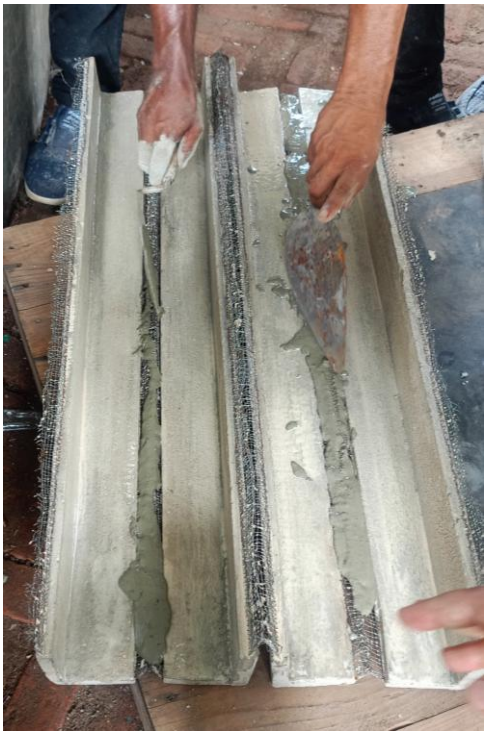


Figure 3. 23: Application of Renderoc HSXtra on the inside portion of the wire mesh joint as a pre-place layer

In the second step (Figure 3.24)-

i. The mortar applied PFAs were attached to a pre-cracked, Nitobond EP-coated column.
ii. Joining the side that was kept open of the PFAs bundle using GI wires.
iii. Applying the mortar on the remaining thickness of the wire mesh joint.

iv. Application of curing chemical (ConcureWB) on the exposed surfaces of the applied mortar of the assembled retrofitted column



Figure 3. 24: Application of Renderoc HSXtra on the remaining thickness at outside of the retrofitted column

After the end of the curing period, the retrofitting operation of the pre-cracked columns was complete. The final longitudinal section and cross sections are shown in Figures 3.25 and 3.26.

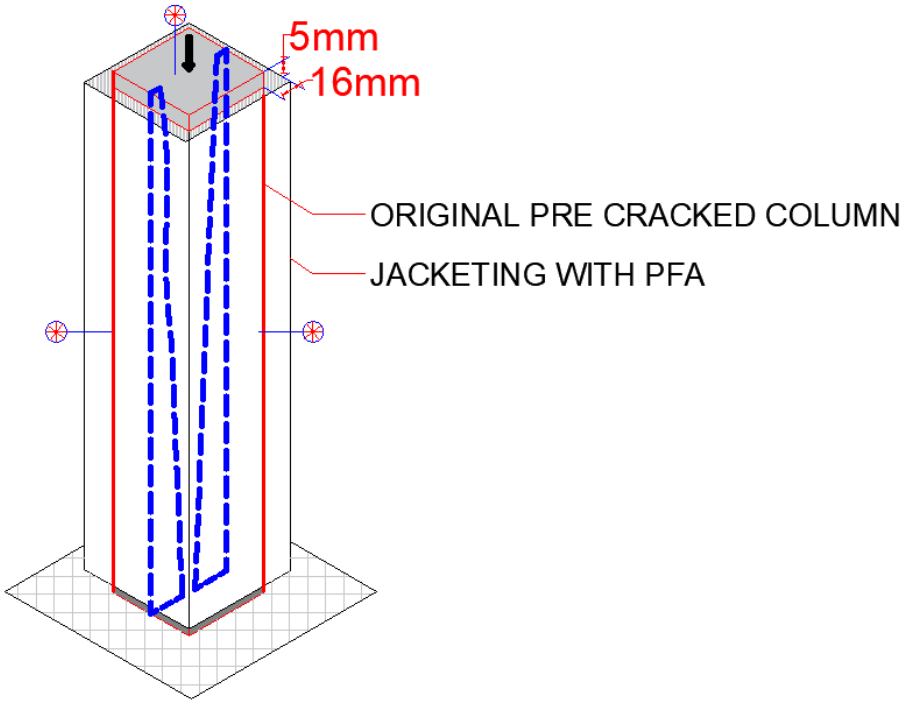
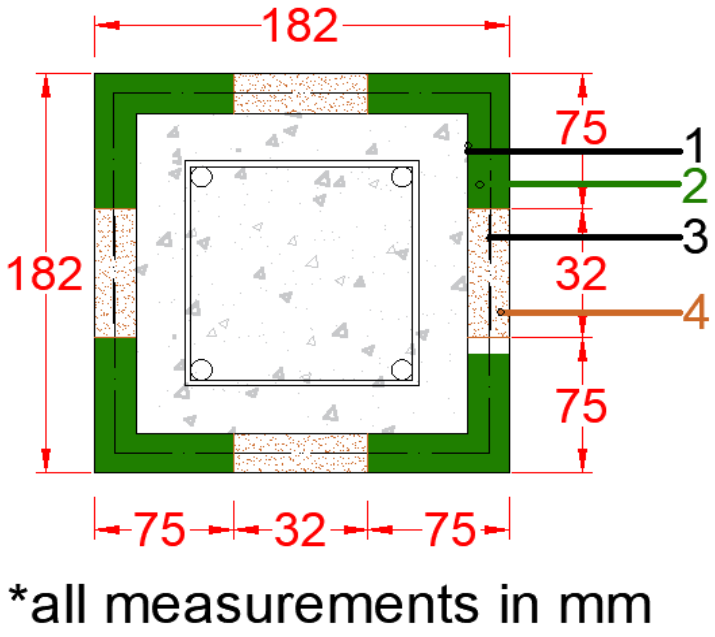


Figure 3. 25: RC column retrofitted with PFA



1. BONDING AGENT (NITOBOND EP)
2. 16 MM THICK P.F.A
3. SINGLE/DOUBLE LAYER WIRE MESH
4. MORTAR (RENDEROC HSXtra)

Figure 3. 26: Detailed section of the retrofitted RC column

3.11 EXPERIMENTAL SETUP

The procedures discussed in the previous section were repeated to prepare a total of 18 test specimens (3 control,3 control with pre-crack (control PC), 12 retrofitted). Specimen details are shown in Table 3.2.

Table 3. 2: Details of test specimens

Concrete Group	Date of Casting	Concrete Mix Ratio	Sample Name	Prepared Specimens		
				Specimen Characteristics	Jacketing Information	Wire Mesh
M1	10-03-2025	1:2:3	A-1	Control Specimen without precracking	Without Jacketing	No Mesh
			A-2	Control Specimen with precracking	Without Jacketing	No Mesh
			A-3	Specimen with precracking	Jacketed	Single Layer
			A-4	Specimen with precracking	Jacketed	Single Layer
			A-5	Specimen with precracking	Jacketed	Double Layer
			A-6	Specimen with precracking	Jacketed	Double Layer
M2	17-03-2025	1:2.5:3.5	B-1	Control Specimen without precracking	Without Jacketing	No Mesh
			B-2	Control Specimen with precracking	Without Jacketing	No Mesh
			B-3	Specimen with precracking	Jacketed	Single Layer
			B-4	Specimen with precracking	Jacketed	Single Layer
			B-5	Specimen with precracking	Jacketed	Double Layer
			B-6	Specimen with precracking	Jacketed	Double Layer
M3	19-03-2025	1:2.5:4	C-1	Control Specimen without precracking	Without Jacketing	No Mesh
			C-2	Control Specimen with precracking	Without Jacketing	No Mesh
			C-3	Specimen with precracking	Jacketed	Single Layer
			C-4	Specimen with precracking	Jacketed	Single Layer
			C-5	Specimen with precracking	Jacketed	Double Layer
			C-6	Specimen with precracking	Jacketed	Double Layer

The specimens were categorized into three groups according to the mix ratio M1, M2 and M3. Each group consists of 6 columns named A1-A6, B1-B6 and C1-C6. The details of the test specimens are shown in Table 3.2.

The concrete cubes were tested on the compressive strength testing machine and the ferrocement cubes were tested on the double dial gauge compressive strength testing machine one after another.



(a) (b)

Figure 3. 27: Setup for determining compressive strength of (a) Concrete and (b) Ferrocement

The RC columns were tested in the universal testing machine (UTM). Axial load was applied to the columns and load-displacement values were collected from the computer. For the lateral displacement, two dial gauges were fitted on the two orthogonal axes of the column at mid-height. The complete test setup is shown in Figure 3.28.



Figure 3. 28: Experimental setup for column axial compression test

Chapter 4 : RESULTS & DISCUSSIONS

4.1 GENERAL

The compressive strength test of concrete cubes with 3 (Three) different mix ratios, mortar cubes and the axial compression test of the prepared column samples were carried out in the strength of materials laboratory of the Department of Civil Engineering, CUET. The results obtained from the experiments are presented and discussed in detail in this chapter.

4.2 COMPRESSIVE STRENGTH TEST OF CONCRETE

3 cubes of size 150mmx150mmx150mm were prepared for each mix ratio. A total of 9 cubes were tested in the compressive strength testing machine. The observed dial gauge reading was adjusted from the calibration chart of the testing machine and the final result was calculated.

The test results are presented in Table 4.1.

Table 4. 1: Concrete compressive strength test results

Concrete Group	Concrete Mix Ratio	Area (mm^2)	Dial Reading	Calibrated Load (KN)	Concrete Strength (MPa)	Average Concrete Strength (MPa)
M1	1:2:3	22500	138	807.32	35.88	36.40
		22500	140	819.32	36.41	
		22500	142	831.32	36.95	
M2	1:2.5:3.5	22500	131	765.31	34.01	34.20
		22500	132	771.31	34.28	
		22500	132	771.31	34.28	
M3	1:2.5:4	22500	121	705.30	31.35	31.40
		22500	123	717.30	31.88	
		22500	120	699.30	31.08	

It can be seen that all the mix ratios used arbitrarily in this study led to a high concrete strength gain with very little difference in value between the 3 mix ratios. The M1 samples showed the highest concrete compressive strength of 36.40 MPa and the lowest value was observed for the M3 samples (31.40 MPa). Overall, the high strength for the 3 mix ratios was achieved via excellent quality control during the casting process and proper curing of the samples. It can also be said that the locally employed mix ratio by the general people without any expert opinion may have the potential to gain high concrete strength. The slump values of the three concrete groups are shown in Table 4.2.

Table 4. 2: Slump values for different types of concrete

Concrete Group	**Mix Ratio**	**Slump Value 1 (mm)**	**Slump Value 2 (mm)**
M1	1:2:3	55	56
M2	1:2.5:3.5	25	27
M3	1:2.5:4	27	30

All the concrete cubes that were crushed in the concrete compressive strength testing machine showed a typical shear failure pattern, as depicted in Figure 4.1.



Figure 4. 1: Concrete cube failure pattern

4.3 COMPRESSIVE STRENGTH TEST OF FERROCEMENT MORTAR

A total of 10 cubes of size 50mmx50mmx50mm were prepared for testing the strength of the ferrocement mortar used in the making of PFAs. The cubes were crushed in a small double dial gauge compressive strength testing machine and the dial gauge readings were adjusted from the machine calibration chart and then the compressive strength was calculated.

The test results are presented in Table 4.2.

Table 4. 3: Ferrocement mortar compressive strength test results

Serial	Concrete Mix Ratio	Area (mm^2)	Dial Reading	Calibrated Load (KN)	Ferrocement Strength (MPa)	Average Ferrocement Strength (MPa)
1	1:1.5	2500	110	116.70	46.68	39
2			90	96.94	38.77	
3			90	96.94	38.77	
4			80	87.05	34.82	
5			110	116.70	46.68	
6			75	82.11	32.84	
7			80	87.05	34.82	
8			100	106.82	42.73	
9			95	101.88	40.75	
10			75	82.11	32.84	

The ferrocement mortar achieved a high strength of 39 MPa with a mix ratio of cement: sand = 1:1.5. It shows the scope of using ferrocement in important works requiring high strength.

4.4 AXIAL COMPRESSION TEST OF COLUMN SPECIMENS

The column specimens were axially loaded until they failed in the compressive strength testing machine. Based on the output of the experiments, their load-displacement behaviour, stiffness and ductility were calculated.

4.4.1 Load Displacement Behaviour and Stiffness

The load vs displacement graphs of the test specimens are shown in Figures 4.2 to 4.19. From the graphs, their linear behaviour region and the non-linear

behaviour region, the ultimate load-carrying capacity and associated displacement are determined. Furthermore, the elastic stiffness of the specimens is obtained by fitting a linear trendline in the initial linear portion of the graph and the slope value of that trendline was recorded. The obtained slope values will represent the elastic stiffness of the samples.

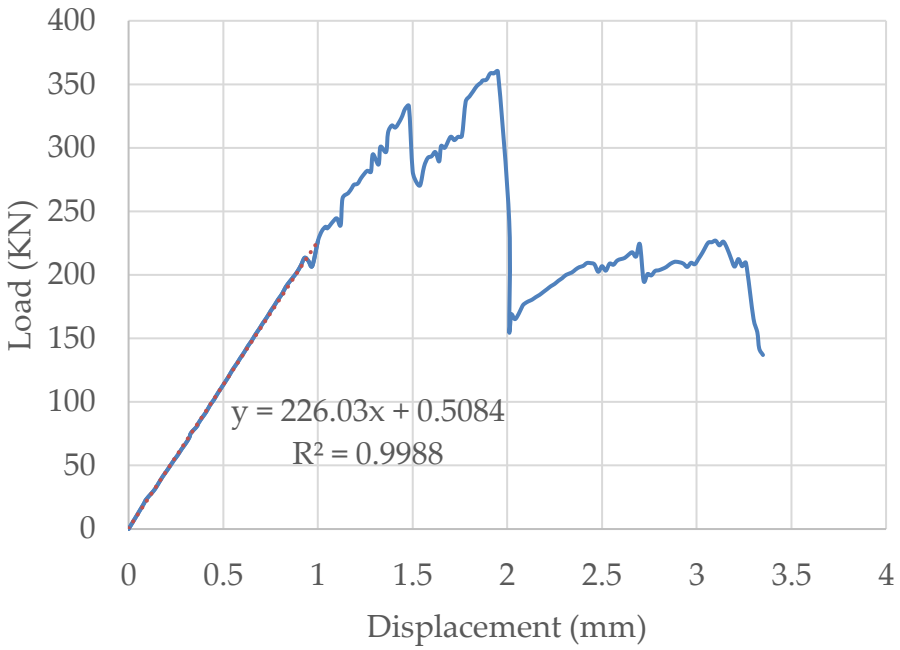


Figure 4. 2: Load-displacement curve of specimen A1

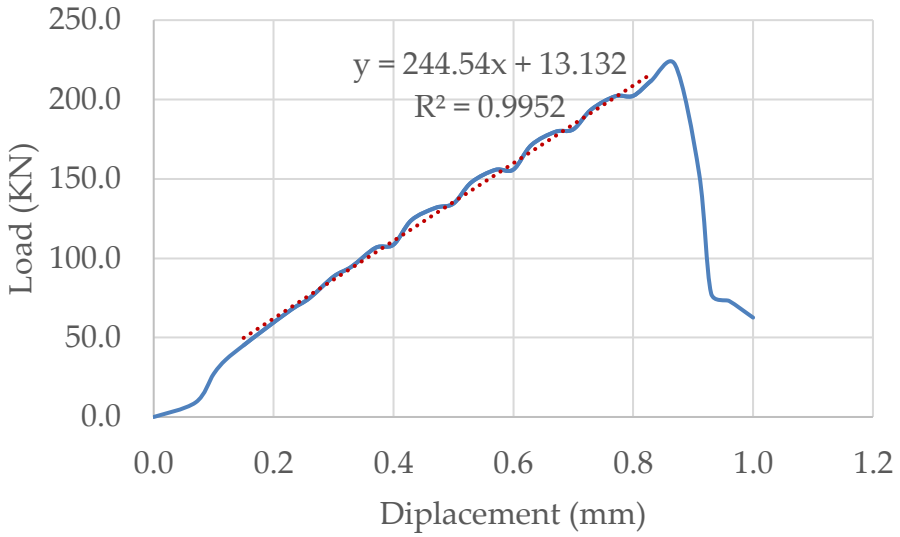


Figure 4. 3: Load-displacement curve of specimen A2

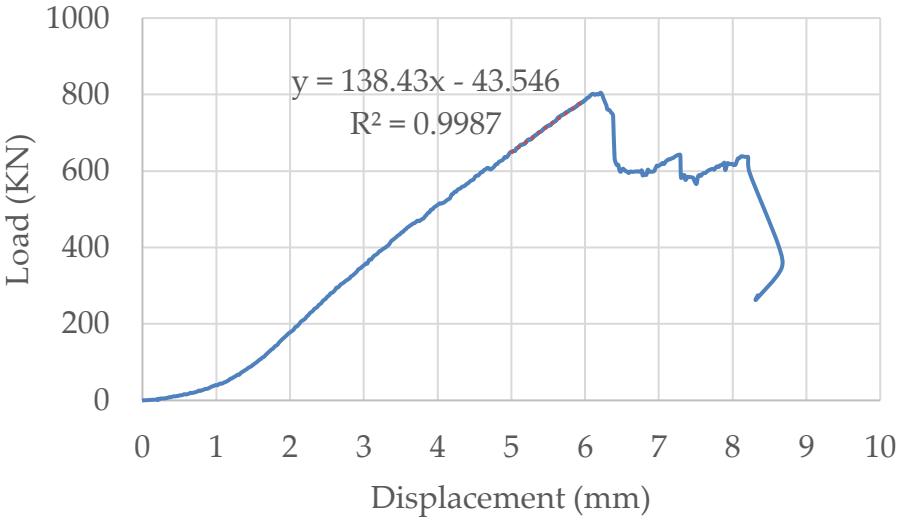


Figure 4. 4: Load-displacement curve of specimen A3

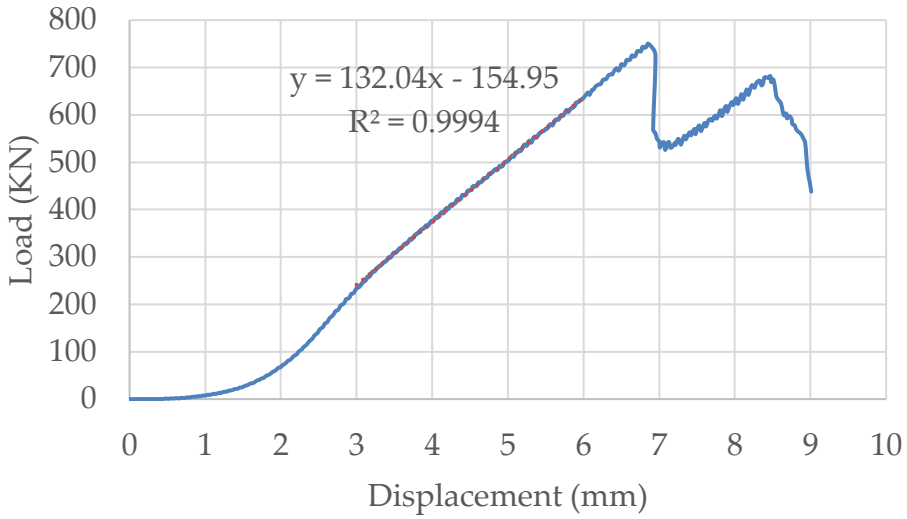


Figure 4. 5: Load-displacement curve of specimen A4

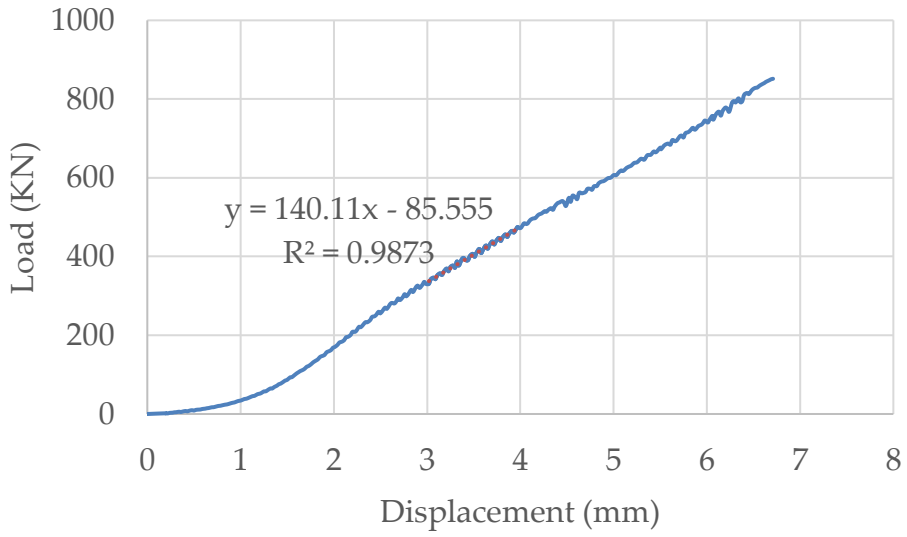


Figure 4. 6: Load-displacement curve of specimen A5

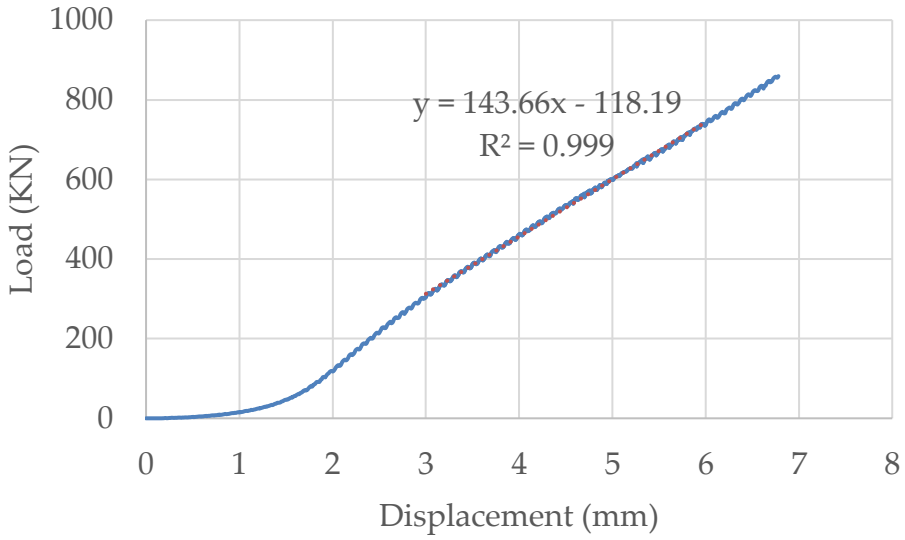


Figure 4. 7: Load-displacement curve of specimen A6

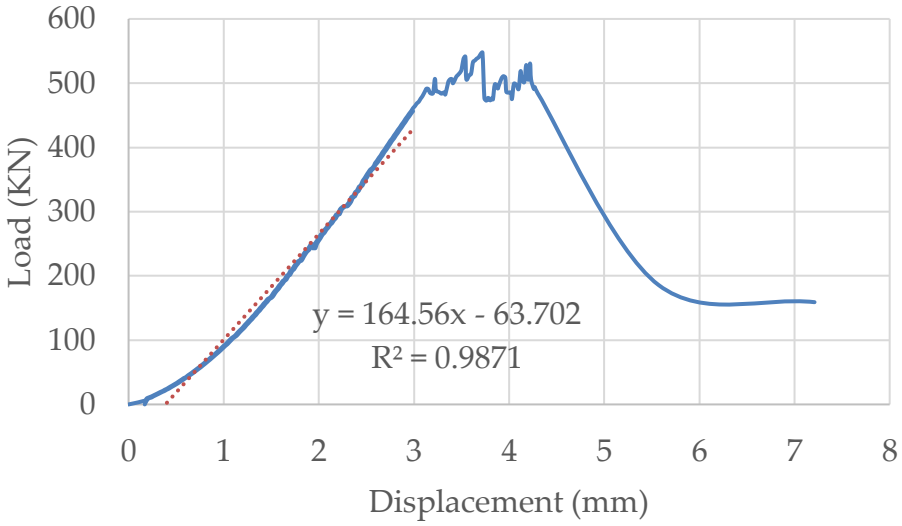


Figure 4. 8: Load-displacement curve of specimen B1

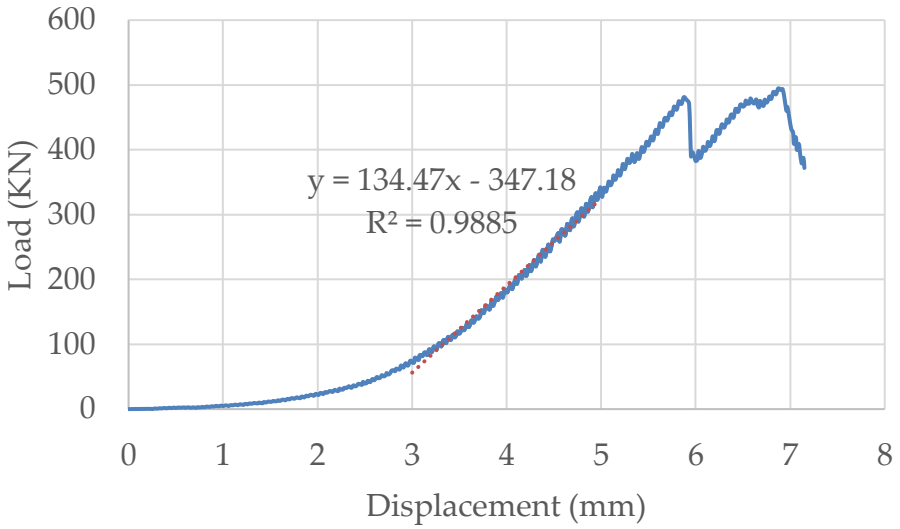


Figure 4. 9: Load-displacement curve of specimen B2

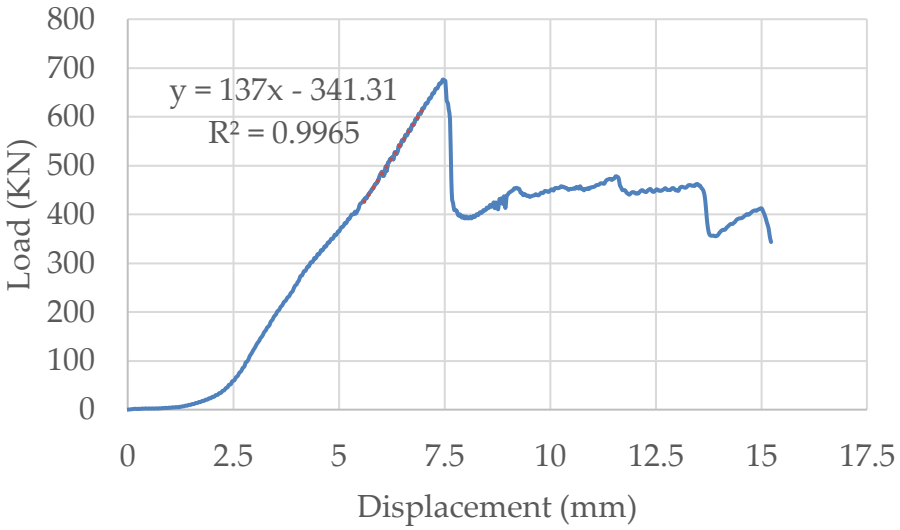


Figure 4. 10: Load-displacement curve of specimen B3

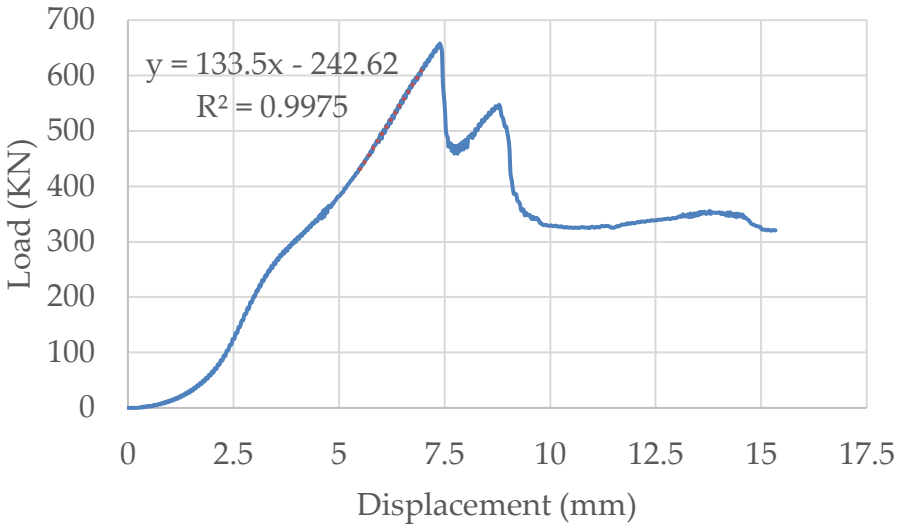


Figure 4. 11: Load-displacement curve of specimen B4

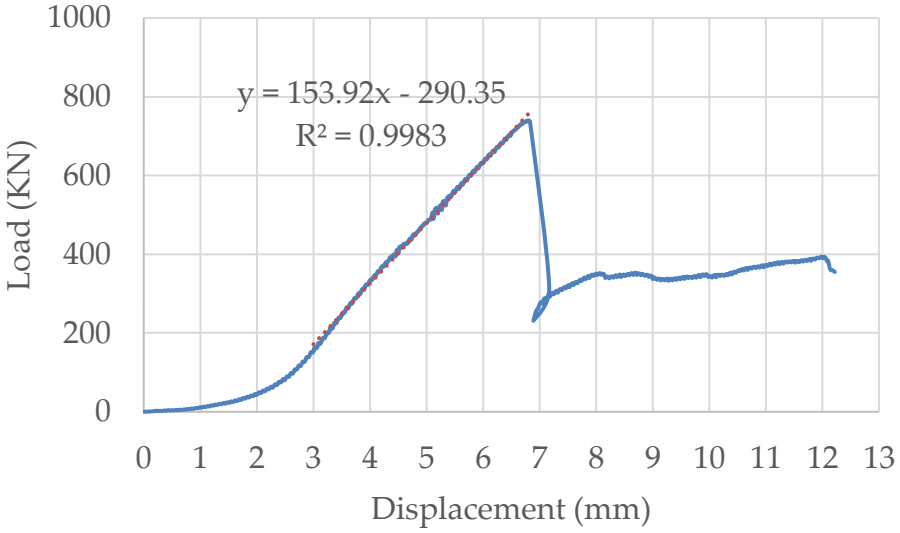


Figure 4. 12: Load-displacement curve of specimen B5

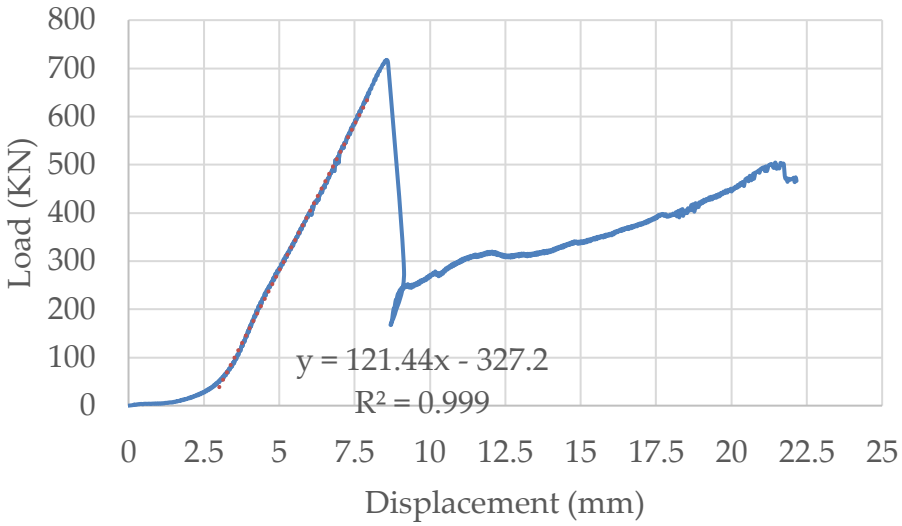


Figure 4. 13: Load-displacement curve of specimen B6

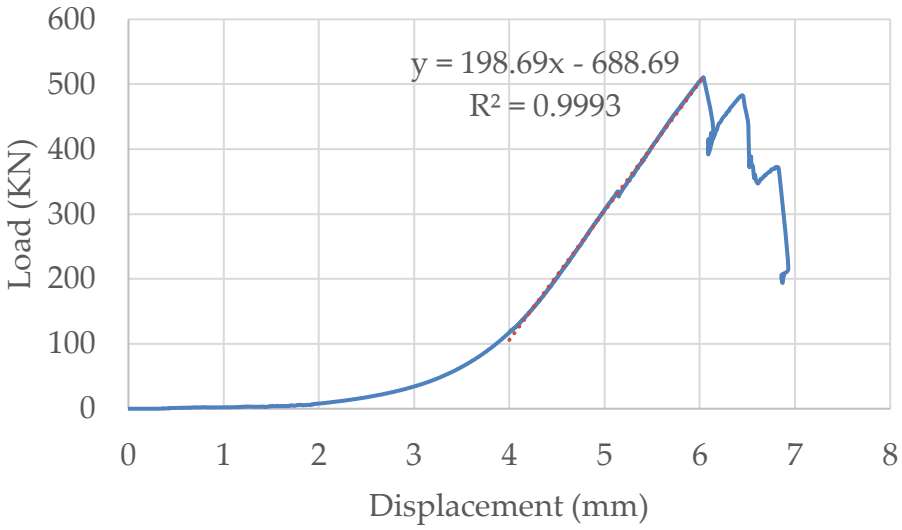


Figure 4. 14: Load-displacement curve of specimen C1

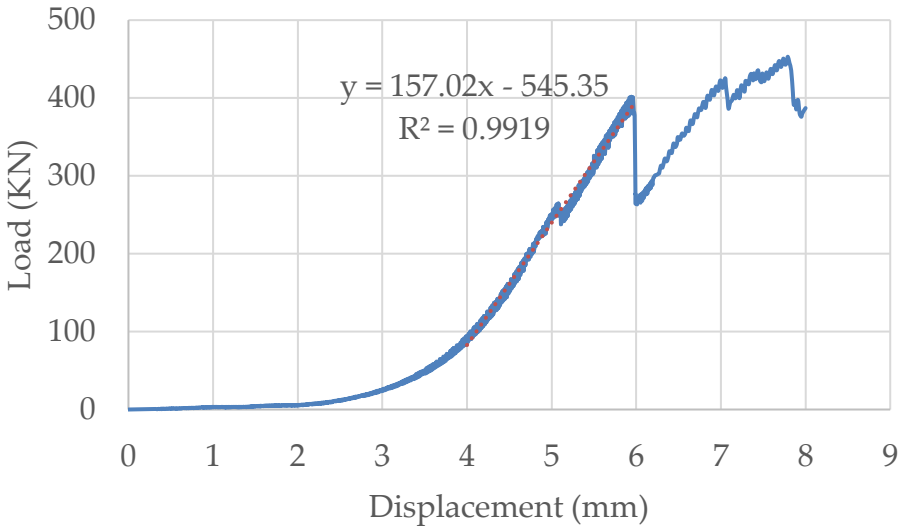


Figure 4. 15: Load-displacement curve of specimen C2

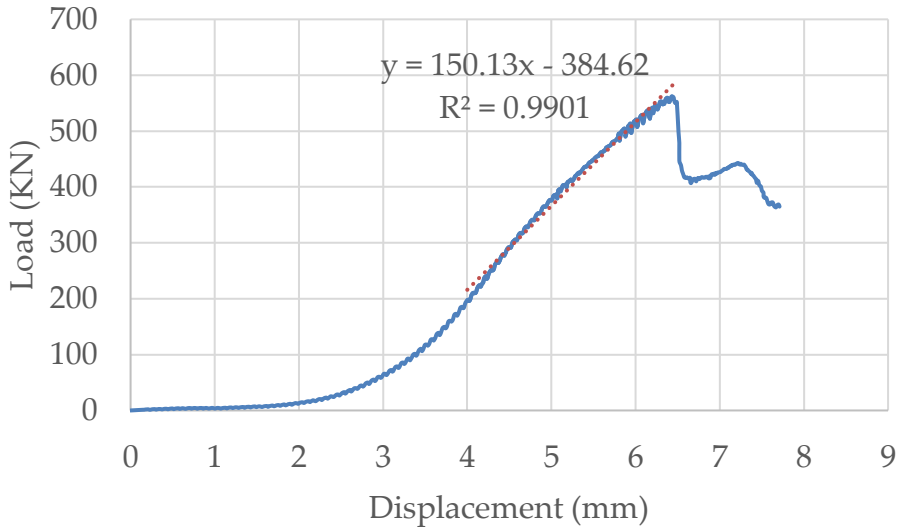


Figure 4. 16: Load-displacement curve of specimen C3

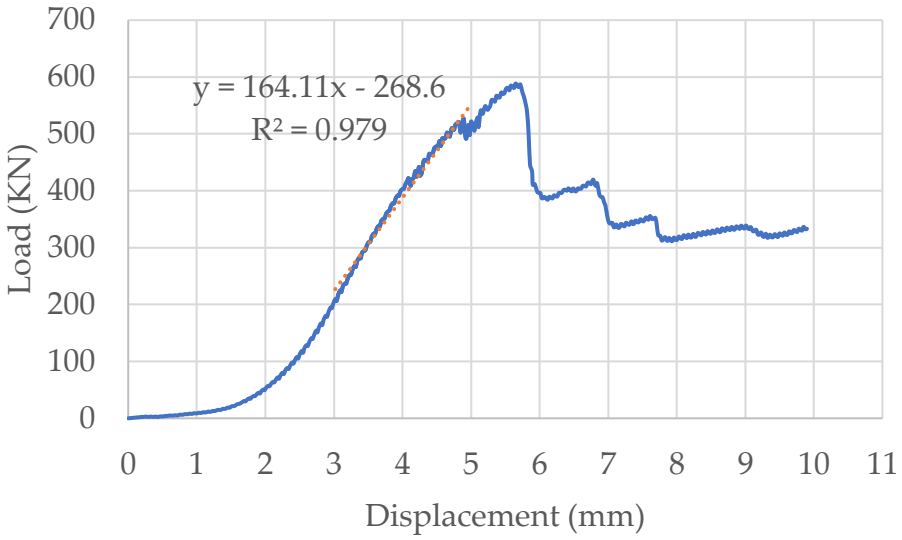


Figure 4. 17: Load-displacement curve of specimen C4

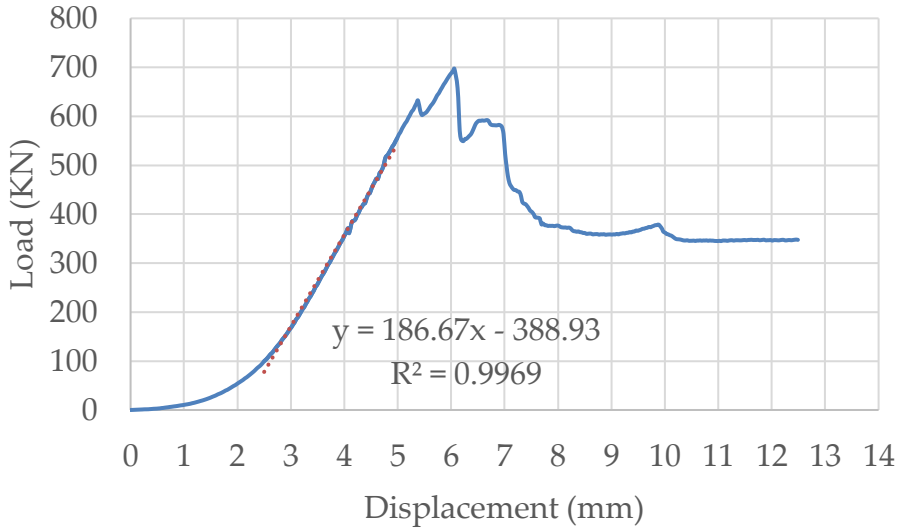


Figure 4. 18: Load-displacement curve of specimen C5

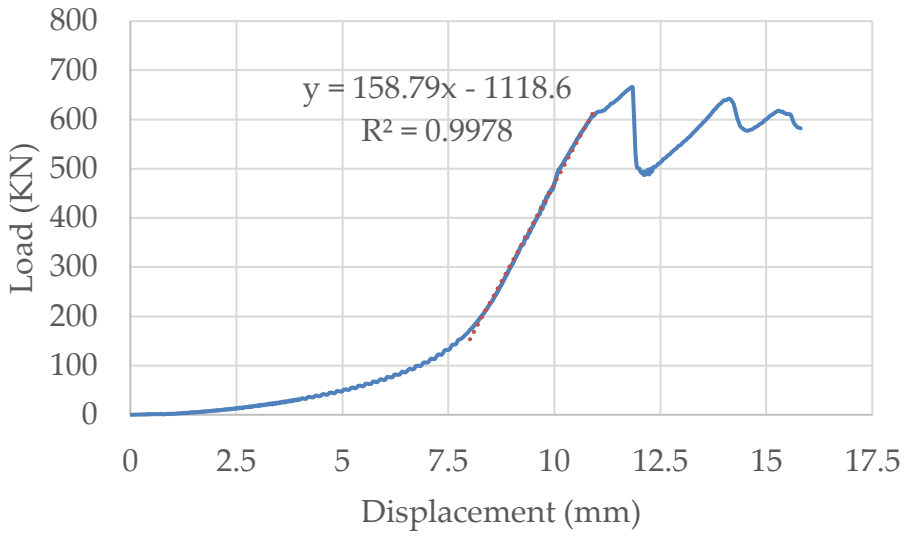


Figure 4. 19: Load-displacement curve of specimen C6

The ultimate load-carrying capacity and stiffness as obtained are shown in Table 4.4 and Figure 4.20. The average value is reported for the single-layer wire mesh and the double-layer wire mesh according to the three concrete groups used in this study.

Table 4. 4: Summary of ultimate load capacity and stiffness

Concrete Group	Sample Characteristic	Sample Name	Ultimate Load Capacity (KN)	Average Ultimate Load Capacity (KN)	Stiffness (KN/mm)	Average Stiffness (KN/mm)
M1	**Control**	A1	360	360	226.03	226.03
	Control-PC	A2	221.8	221.8	244.54	244.54
	Single Layer Wire Mesh	A3	800	772.5	138.43	135.235
		A4	745		132.04	
	Double Layer Wire Mesh	A5	851	855.16	140.11	141.885
		A6	859.32		143.66	
M2	**Control**	B1	547	547	164.56	164.56
	Control-PC	B2	492.1	492.1	134.47	134.47
	Single Layer Wire Mesh	B3	673.32	665.47	137	135.25
		B4	657.62		133.5	
	Double Layer Wire Mesh	B5	739.48	728.45	153.92	137.68
		B6	717.42		121.44	
M3	**Control**	C1	510.28	510.28	198.69	198.69
	Control-PC	C2	453.02	453.02	157.02	157.02
	Single Layer Wire Mesh	C3	560.2	573.5	150.13	157.121
		C4	586.8		164.11	
	Double Layer Wire Mesh	C5	697.12	681.23	186.67	172.73
		C6	665.34		158.79	

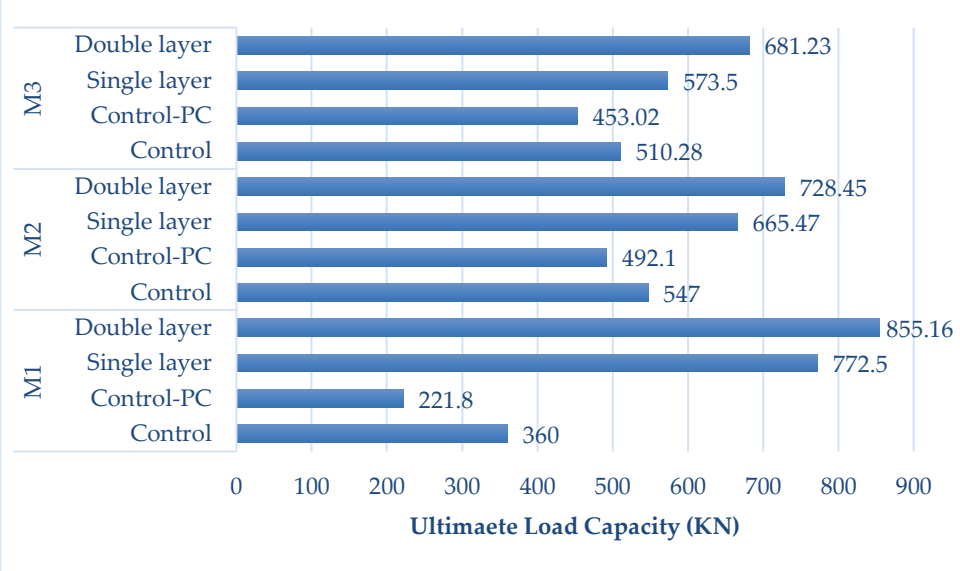


Figure 4. 20: Comparison of the ultimate load capacity of the specimens

From the results, it can be seen that the control specimens of group M1 showed a lower value of ultimate load despite the higher strength of the concrete. This may be due to faulty preparation of specimens, during which internal cracks were developed by poor workmanship. All specimens were tested with a loading rate of 0.6mm/s.

The use of retrofitting with PFAs seemed to increase the axial load capacity of the RC columns significantly. The highest value was found for the M1 group, where PFA retrofitting with a double-layer wire mesh showed a 10.70% increase in capacity compared to PFA with a single layer. A trend was seen that the increase in axial load capacity decreased with the reduction of the concrete strength of the RC columns.

For the M2 group, an increase of 35.23% and 48.03% were observed for the RC columns retrofitted with PFAs with a single layer and a double layer of wire mesh, respectively, compared to the capacity of the pre-cracked sample. For the M3 group, an increase of 26.6% and an increase of 50.4% were observed for the RC columns retrofitted with PFAs with a single layer and a double layer of wire mesh, respectively, compared to the capacity of the pre-cracked sample.

Therefore, it can be said that the increase in the axial load capacity after retrofitting with PFAs showed better performance for RC columns.

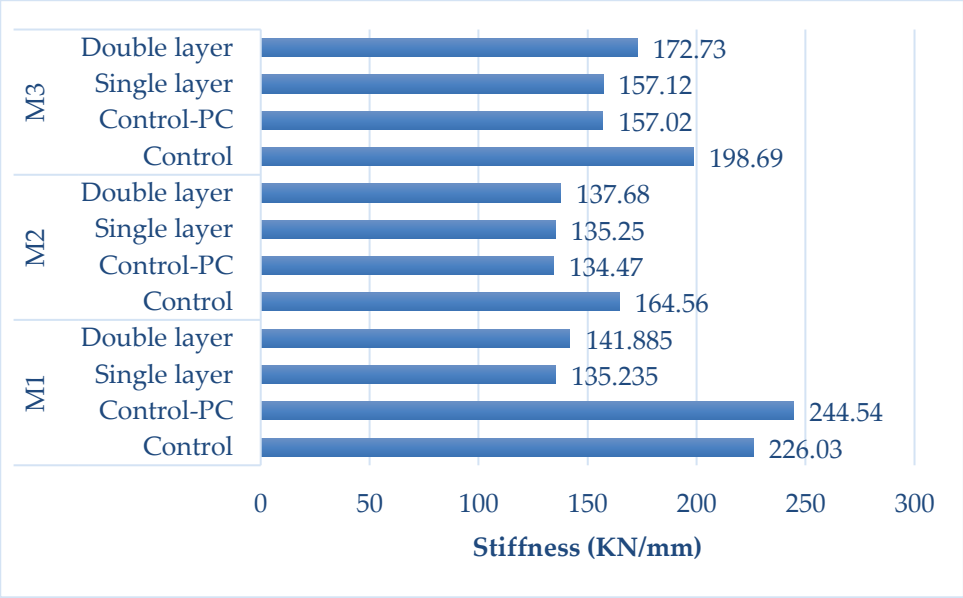


Figure 4. 21: Stiffness comparison of the specimens

For stiffness, the PFA jacketed columns showed a lower stiffness compared to the control un-retrofitted columns. Again, the stiffness values obtained for the control columns of the M1 group showed very high values, which may be associated with the higher concrete strength during the testing of the RC columns. For the results obtained from the M2 and the M3, it can be clearly stated that retrofitting of the pre-cracked samples with PFAs did not significantly increase their stiffness; rather maintained almost the same values of stiffness while carrying higher axial load. Also, the use of double wire mesh showed a little increase in stiffness compared to single wire mesh.

4.4.2 Energy Absorption and Ductility

The area under the load-displacement curve represents the total energy absorbed by the RC column. The elastic energy can be obtained by the area under the initial portion of the curve up to the point at which the curve stays linear. Subtracting elastic energy from total energy will give the plastic energy associated with an RC column and give an indication regarding the ductility of the column. The area under the load-displacement curve was found using MATLAB (2018a) employing the trapezoidal rule. The calculated energy of the tested specimen based on the load-displacement curve is presented in Table 4.5.

The samples A5 and A6 of the M1 concrete group, with a concrete compressive strength of 36.40 MPa, could not be completely crushed in the universal testing machine, as the machine has a capacity of 1000KN and for safety purposes, more than 850 KN could not be applied. For this reason, plastic energy could not be determined and values are not reported in Table 4.5.

Table 4. 5: Energy absorption of the tested specimens

Concrete Group	Sample Characteristics	Sample Name	Total energy (KN-mm)	Average Total Energy (KN-mm)	Elastic Energy (KN-mm)	Average Elastic Energy (KN-mm)	Plastic Energy (KN-mm)	Average Plastic Energy (KN-mm)
M1	**Control**	A1	683.98	683.98	98.56	98.56	585.42	585.42
	Control-PC	A2	116.83	116.83	19.42	19.42	97.41	97.41
	Single Layer	A3	3789.56	3766.38	2119.36	1813.97	1670.20	1952.41
		A4	3743.20		1508.58		2234.62	
	Double Layer	A5	-	-	2550.45	2517.16	-	-
		A6	-		2483.87		-	
M2	**Control**	B1	1925.12	1925.12	663.37	663.37	1261.75	1261.75
	Control-PC	B2	1360.61	1360.61	508.48	508.48	852.13	852.13
	Single Layer	B3	3550.60	3548.55	992.98	1094.64	2557.62	2453.91
		B4	3546.50		1196.3		2350.20	
	Double Layer	B5	4205.36	4253.28	1890.91	1949.71	2314.45	2303.58
		B6	4301.20		2008.5		2292.70	
M3	**Control**	C1	1073.48	1073.48	332.23	332.23	741.25	741.25
	Control-PC	C2	1307.01	1307.01	233.14	233.14	1073.87	1073.87
	Single Layer	C3	2780.36	2795.31	765.41	805.02	2014.95	1990.29
		C4	2810.25		844.63		1965.62	
	Double Layer	C5	3546.50	3614.14	1053.4	1289.55	2493.10	2324.59
		C6	3681.78		1525.7		2837.1	

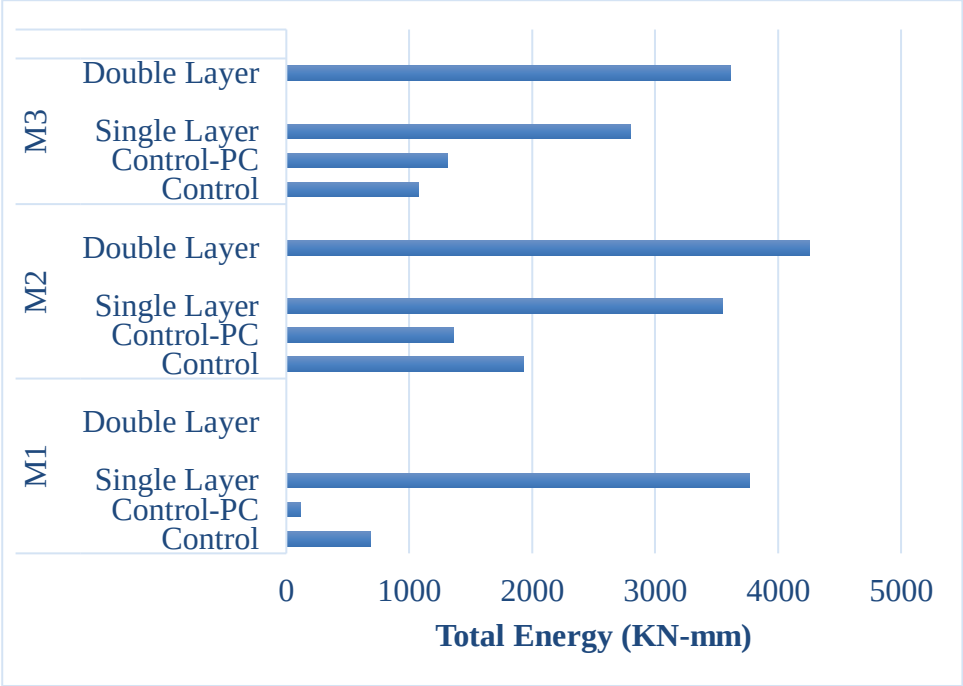


Figure 4. 22: Total energy absorption

The total energy is found to increase after the application of jacketing with PFAs. In the case of the M2 concrete group, double wire mesh showed more energy absorption compared to single-layer wire mesh. The increase in energy absorption is 160.80% for single wire mesh and 212.60% for a double layer of wire mesh compared to the control pre-crack RC column. For the M3 concrete group, a similar trend of increased energy absorption was observed, with values of 113.87% and 176.52% for single-layer and double-layer wire mesh, respectively. With the decrease in the concrete strength, the effect of an increased layer of wire mesh seems to be decreasing in the case of energy absorption. Also, the energy absorption capacity of the retrofitted samples seems to be decreasing with the decrease in the concrete compressive strength of the Rc columns.

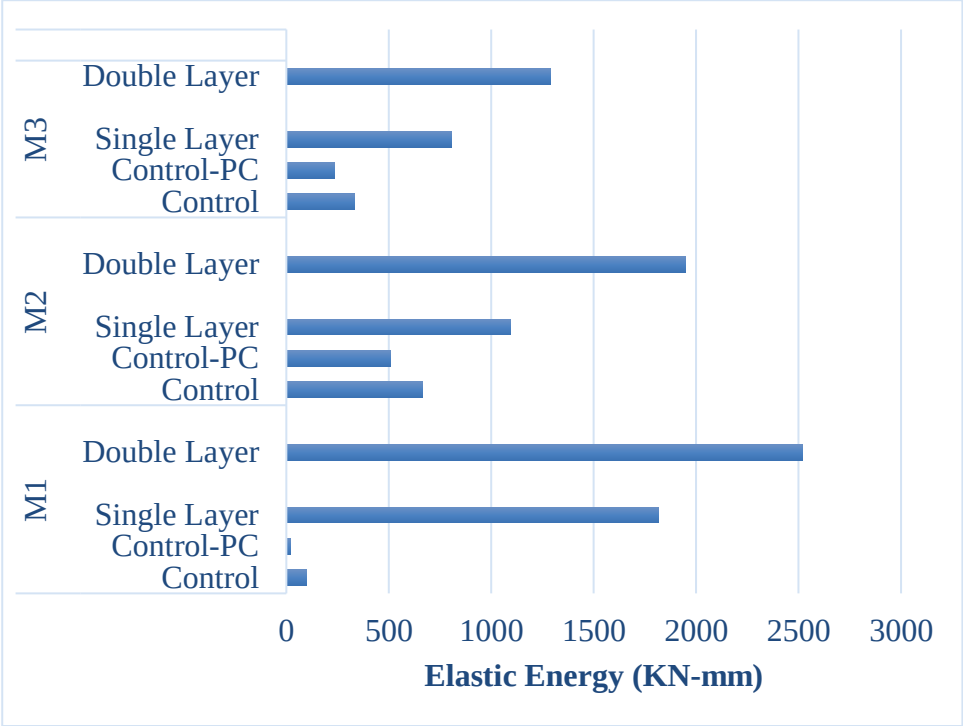


Figure 4. 23: Elastic energy absorption of the specimens

The elastic energy is depicted by the area under the load-displacement curve up to the yield point. A common trend depicted in the results is that the elastic energy absorption decreases with the decrease in the concrete strength of the RC columns. Also, the increase in the layer of wire mesh increases the elastic energy absorption of the RC columns jacketed with PFAs. However, the difference between the elastic energy absorption of the retrofitted specimens with single wire mesh and double wire mesh is found to decrease with the decrease in the concrete strength of the RC columns. Overall, retrofitting of the RC columns with PFAs significantly increased the elastic energy absorption of the RC columns.

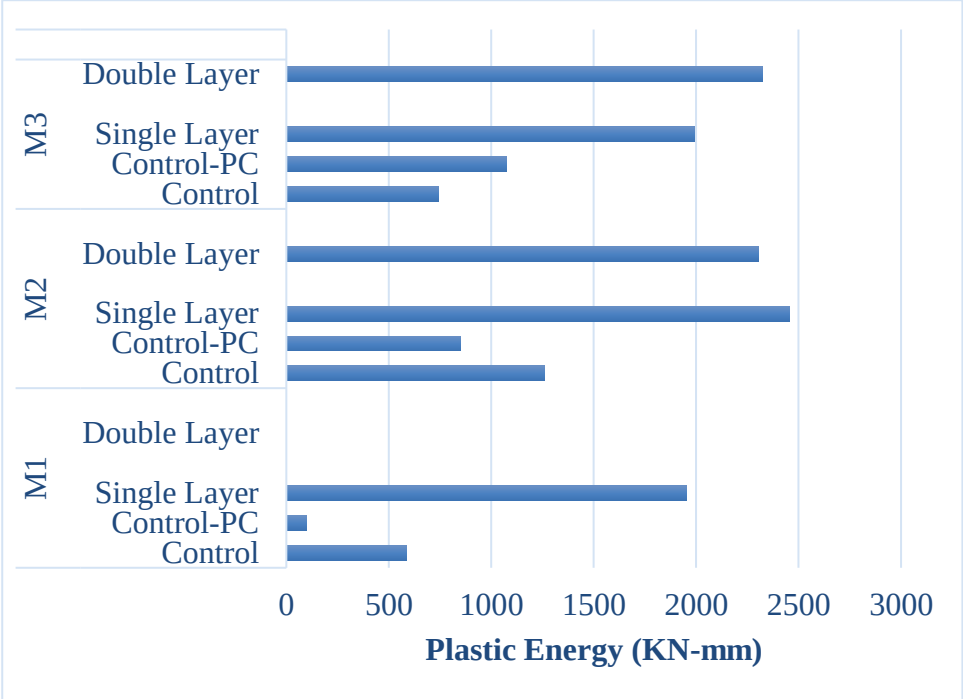


Figure 4. 24: Plastic energy absorption of the specimens

For the M1 concrete group, the plastic energy could not be compared due to the limitations of the testing machine. Comparing the plastic energy of the retrofitted RC columns of M2 and M3 groups, it can be said that retrofitting the RC columns with PFAs increased the plastic energy of the specimens. An increase in plastic energy represents an increase in the ductility of the specimens. Therefore, retrofitting RC columns with PFAs ensures more ductile behaviour of the RC columns than the control and control pre-cracked specimens.

4.5 FAILURE PATTERN

The failure modes of the specimens obtained during testing are shown in Figures 4.25-4.42



Figure 4. 25: Failure mode of specimen A1



Figure 4. 26: Failure mode of specimen A2



Figure 4. 27: Failure mode of specimen A3



Figure 4. 28: Failure mode of specimen A4



Figure 4. 29: Failure mode of specimen A5



Figure 4. 30: Failure mode of specimen A6

Control specimens A1 and A2 failed at the contact surface with the testing machine, indicating a crushing failure of concrete. The top surface of the columns

was destroyed in a scattered manner. For A3 and A4, split-line cracks were seen at the joint where the PFAs were connected. The debonding of the PFAs from the column surface was also seen. The cracks primarily initiate at the joints and propagate along the pre-cracks and are sometimes accompanied by the bending effects, which is evident by the diagonal propagation of these cracks after continuing straight for a while. A5 and A6 showed only concrete crushing at the top and bottom and the cracks continued to propagate longitudinally only. Debonding of the PFAs from the column surface was also observed without any tearing of the wire mesh.



Figure 4. 31: Failure mode of specimen B1



Figure 4. 32: Failure mode of specimen B2



Figure 4. 33: Failure mode of specimen B3



Figure 4. 34: Failure mode of specimen B4



Figure 4. 35: Failure mode of specimen B5



Figure 4. 36: Failure mode of specimen B6

The B1 and B2 control specimens failed at the contact surface with the testing machine. The concrete cover got spilled off and broken apart longitudinally. The B3, B4, B5 and B6 samples failed with crack initiation at the top or bottom along the joints of the PFAs, which also propagated diagonally. This was similar to M1 groups, indicating that the high-strength mortar used to fill the gaps between the PFAs after their assemblage needs further improvement. Also, the PFAs debonding from the column surface was observed without any wire mesh tearing, both for single-layer wire mesh and double-layer wire mesh.



Figure 4. 37: Failure mode of specimen C1



Figure 4. 38: Failure mode of specimen C2



Figure 4. 39: Failure mode of specimen C3



Figure 4. 40: Failure mode of specimen C4



Figure 4. 41: Failure mode of specimen C5



Figure 4. 42: Failure mode of specimen C6

C1 and C2 samples showed a crushing of concrete at the joint. Their concrete cover got crushed and the concrete cover spilled off the column surface. C3 and C4 showed the failure of the joint between the PFAs first and then propagated

longitudinally. A little debonding of the PFA from the column surface and the wire mesh tearing was observed on one side of the PFA. C5 and C6 showed the same failure pattern, but no wire mesh cracking was observed.

Overall, some RC columns failed in crushing mode as in shear failure, particularly the control specimens. The retrofitted specimens also showed debonding of PFAs from column surface and wire mesh tearing. These failures are shown in Figures 4.43 to 4.45.



Figure 4. 43: Crushing failure of concrete



Figure 4. 44: Tearing of wire mesh in specimen



Figure 4. 45: Debonding of PFA from RC column surface

4.6 LATERAL DEFLECTION

To determine lateral deflection, two dial gauges were fitted in the two orthogonal directions of the test specimens. The results are shown in Table 4.6 and the average values are reported in Figure 4.46 for ease of comparison.

Table 4. 6: Lateral deflection of the tested specimens

Concrete Group	Sample Characteristics	Sample Name	Maximum Lateral Deflection (mm)			
			X	X (Average)	Y	Y (Average)
M1	Control	A1	0.8	0.8	0.78	0.78
	Control-PC	A2	0.85	0.85	0.82	0.82
	Single Layer Wire Mesh	A3	1.73	1.715	1.69	1.71
		A4	1.7		1.73	
	Double Layer Wire Mesh	A5	1.95	1.945	1.88	1.9
		A6	1.94		1.92	
M2	Control	B1	0.69	0.69	0.62	0.62
	Control-PC	B2	0.65	0.65	0.64	0.64
	Single Layer Wire Mesh	B3	0.73	0.715	0.75	0.755
		B4	0.7		0.76	
	Double Layer Wire Mesh	B5	1.67	1.76	1.72	1.715
		B6	1.85		1.71	
M3	Control	C1	0.45	0.45	0.42	0.42
	Control-PC	C2	0.35	0.35	0.34	0.34
	Single Layer Wire Mesh	C3	0.57	0.545	0.55	0.54
		C4	0.52		0.53	
	Double Layer Wire Mesh	C5	1.17	1.15	1.11	1.095
		C6	1.13		1.08	

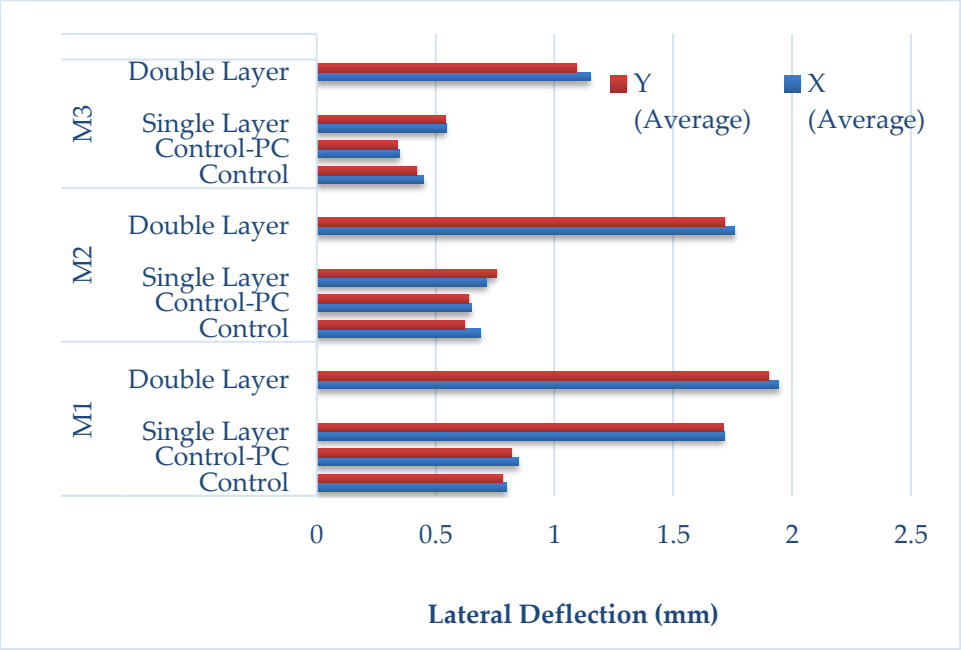


Figure 4. 46: Lateral deflection of different categories of specimens

The values obtained in both the orthogonal directions depict that the lateral deflection of the RC columns with high concrete compressive strength showed higher lateral deflection, which also complements their high energy absorption. With the decrease in the concrete compressive strength of the RC columns, the lateral deflection in both X and Y directions also decreased for the RC columns retrofitted with PFAs. The confinement effect due to the application of PFAs allows greater deflection.

4.7 COMPARISON WITH PREVIOUS RESEARCH

The obtained results are complemented by similar studies by other researchers. The experiment conducted by Kaish et al.[119] using a C-shaped jacket on an uncracked column sample with a concrete strength of 20 MPa showed a 68.3 % increase in ultimate stress. They used a sliding dovetail joint to connect the jackets and cement grout between the column face and jacket. The study by Mahmood et al.[120] using 25 MPa concrete showed an increase of 23% in axial load capacity for cracked columns retrofitted by U-shaped prefabricated jackets. They used spoke screws and cement grout to connect the jackets to the

column. surface. A summarized result of this study and studies by other researchers is presented in Table 4.7.

Table 4. 7: Summary of performance comparison

Parameter	**Current Study**	**Study 1**[119]	**Study 2**[120]
Column Size (mm)	150 × 150 × 900	150 × 150 × 300	150 × 150 × 300
Concrete Grade (MPa)	36.40, 34.20 and 31.40	20	Low-strength concrete
Retrofitting Method	Prefabricated ferrocement angle (Single- & Double-layer mesh)	Prefabricated "L" and "C" jackets	Prefabricated "L" & "U" jackets
Max. Axial Capacity (KN)	A3-A4: 772.50 A5-A6: 855.16 B3-B4: 665.47 B5-B6: 728.45 C3-C4: 573.50 C5-C6: 681.23	L-shape: 636.75 C-shape: 765	L-shape: 400 U-shape: 420
Max. Axial Capacity Improvement	50.40% (M3-Double-layer)35.23% (M2-Single-layer)	68.3% (C-shape)	23% (U-jacket)
Stiffness Recovery	M3 double layer: 86.9% M2 double layer: 83.67% M1 double layer: 63.77%	Not reported	Not reported
Energy Absorption Improvement	M2 single layer: 184% M2 double layer: 220% M3 single layer: 260% M3 double layer: 336%	Not reported	Not reported
Failure Mode	Shifted from brittle splitting → ductile diagonal cracking	Joint failure	Corner joint failure

Overall, it is clear that retrofitting of RC cracked columns with pre-fabricated ferrocement angles (PFA) significantly boosted their load carrying capacity, maintained their stiffness, improved energy absorption capacity, ductility and replaced the typical brittle failure mode with a ductile failure pattern.

Chapter 5 : CONCLUSION

5.1 GENERAL

This research work was carried out to investigate the effectiveness of pre-fabricated ferrocement angles (PFA) as a retrofitting method for partially damaged RC columns. The key parameters considered for this study include the load-displacement behaviour, stiffness, energy absorption, ductility, failure modes and lateral deflection. The experimental procedures involve testing a total of 18 RC column samples of 3 different types of concrete strength, M1, M2 and M3, each group containing 6 RC columns, that were a control column, a control pre-crack column, an RC column retrofitted with a single wire mesh PFAs and RC columns retrofitted with a double layer of PFAs. The major insights drawn from the experimental investigation are presented in this chapter.

5.2 KEY OUTCOMES

The following critical points were observed in the experimental result –

1. All RC columns retrofitted with PFAs displayed a significant increase in the axial load capacity compared to the control columns. The columns retrofitted with PFAs made with a double layer of wire mesh exhibited the highest enhancement, indicating a direct relation between the number of wire meshes in the PFAs and the gain in axial load capacity. The retrofitted RC columns of M2 concrete group showed an increase of 35.23% and 48.03% for single-layer wire mesh PFAs and double-layer wire mesh PFAs, respectively, compared to the control pre-cracked RC column. For the retrofitted RC columns of the M3 group, the corresponding values were 26.6% and 50.40%, respectively. It can be said that, PFA retrofitting method containing double wire mesh was able to achieve better results for RC columns made with lower concrete strength

2. The stiffness of the retrofitted RC columns seemed to remain the same as the control pre-cracked section. The confinement effect of the PFAs delayed the initiation of significant cracking and provided increased axial deformation resistance.

3. The improvement in the axial load-carrying capacity is found to depend on the actual concrete strength of the RC columns. With the decrease in the original concrete strength of the RC columns, the improvement in the axial load-carrying capacity also decreased.

4. The RC columns retrofitted with PFAs showed better energy absorption. The increase in the energy absorption capacity via the application of the PFA retrofitting method was more than 100% compared to the control pre-crack RC columns. However, with the decrease in the original concrete strength of the RC columns and the layer of wire mesh, this gain in energy absorption also showed a negative trend.

5. The PFA retrofitting increased the plastic energy of the RC columns compared to the control pre-crack column. This indicates an improvement in the ductility of the cracked RC columns through PFA jacketing.

6. Visual inspection during the testing procedure revealed that the control columns showed localized, wider cracks of a brittle nature, whereas the retrofitted RC columns showed finer, distributed cracks. This also complements the increase in the ductility of the RC columns with PFA jacketing. The increase in ductility will ensure plastic deformation without any sudden collapse. Also, the confinement provided by the PFAs maintained its post-peak integrity, complemented by low lateral deflection of the retrofitted RC columns.

The use of PFA is a lightweight and rapid retrofitting method that presents a robust alternative to the conventional retrofitting methods for improving the resilience of RC structures.

5.3 LIMITATIONS

1. The universal testing machine used in this study has a load capacity of 1000 KN only. Therefore, the A5 and A6 samples could not be completely crushed as they were made of high-strength concrete.
2. Initially, a high load rate of 1mm/sec was used in the testing machine. This may have influenced their irregular load-displacement curve.
3. As usual, the pre-crack mechanism in this study showed a reduction in column load capacity compared to the uncracked column. Still, the effectiveness of such an arrangement needs further study.

5.4 FUTURE RECOMMENDATION

The following studies can be done as the continuation of the present study-

1. Performance of the column PFA jacketing under cyclic/lateral loading.
2. Creep and fatigue analysis of PFA retrofitted columns.
3. Performance of PFA jacketed columns under twisting load.
4. Numerical validation and design guidelines development.

BIBLIOGRAPHY

1. Moussard M, Garibaldi P, Curbach M (2018) The Invention of Reinforced Concrete (1848 – 1906). In: High Tech Concrete: Where Technology and Engineering Meet. Springer International Publishing, Cham, pp 2785–2794
2. Neville AM, Brooks JJ (2010) Concrete Technology, second edition. Pearson Education Limited
3. Park R., Paulay T. (2010) Reinforced concrete structures. Wiley
4. Darwin D, Dolan CW Design of Concrete Structures, 6th edition
5. Kato M, Michikoshi S, Baba S, Sakata H (2017) Behavior of slender RC columns with initial deformation in fire: Study on fire resistance of slender RC columns part 2. Journal of Structural and Construction Engineering 82:959–968. https://doi.org/10.3130/AIJS.82.959
6. Alekseytsev AV, Kurchenko NS (2023) Safety of Reinforced Concrete Columns: Effect of Initial Imperfections and Material Deterioration under Emergency Actions. Buildings 2023, Vol 13, Page 1054 13:1054. https://doi.org/10.3390/BUILDINGS13041054
7. Zhao J, Wei J, Wang J (2021) Design Forces of Horizontal Braces Unlocated at Middle of Columns considering Random Initial Geometric Imperfections. Advances in Civil Engineering 2021:. https://doi.org/10.1155/2021/1264270
8. Ahmad H, Fahad M, Aslam M (2022) Nonlinear numerical analysis and proposed equation for axial loading capacity of concrete filled steel tube column with initial imperfection. Structural Monitoring and Maintenance 9:81–105. https://doi.org/10.12989/SMM.2022.9.1.081
9. Li D, Wei R, Xing F, Sui L, Zhou Y, Wang W (2018) Influence of Non-uniform corrosion of steel bars on the seismic behavior of reinforced concrete columns. Construction and Building Materials 167:20–32. https://doi.org/10.1016/j.conbuildmat.2018.01.149
10. Yang S-Y, Song X-B, Jia H-X, Chen X, Liu X-L (2016) Experimental research on hysteretic behaviors of corroded reinforced concrete columns with different maximum amounts of corrosion of rebar. Construction and Building Materials 121:319–327. https://doi.org/10.1016/j.conbuildmat.2016.06.002
11. Liu Y, Miao Z, Jiang C, Lu Y (2025) Effects of non-uniform rebar corrosion on the seismic behaviour of RC Columns. Engineering Structures 328:119748. https://doi.org/10.1016/j.engstruct.2025.119748
12. Meda A, Mostosi S, Rinaldi Z, Riva P (2014) Experimental evaluation of the corrosion influence on the cyclic behaviour of RC columns. Engineering Structures 76:112–123. https://doi.org/10.1016/j.engstruct.2014.06.043

13. Ma Y, Che Y, Gong J (2012) Behavior of corrosion damaged circular reinforced concrete columns under cyclic loading. Construction and Building Materials 29:548–556. https://doi.org/10.1016/j.conbuildmat.2011.11.002
14. Lee H-S, Kage T, Noguchi T, Tomosawa F (2003) An experimental study on the retrofitting effects of reinforced concrete columns damaged by rebar corrosion strengthened with carbon fiber sheets. Cement and Concrete Research 33:563–570. https://doi.org/10.1016/S0008-8846(02)01004-9
15. Wu D, Ding Y, Su J, Li Z-X, Zong L, Feng K (2021) Effects of tie detailing configurations on reinforcement buckling and seismic performance of high-strength RC columns. Soil Dynamics and Earthquake Engineering 147:106791. https://doi.org/10.1016/j.soildyn.2021.106791
16. Hidayat B, Hu H-T, Hsiao F-P, Han AL, Pita P, Haryanto Y (2020) Seismic performance of non-ductile detailing RC frames: an experimental investigation. Earthquake and Structures 19:485–498. https://doi.org/https://doi.org/10.12989/eas.2020.19.6.485
17. Pantelides CP, Hansen J, Ameli MJ, Reaveley LD (2017) Seismic performance of reinforced concrete building exterior joints with substandard details. Journal of Structural Integrity and Maintenance 2:1–11. https://doi.org/10.1080/24705314.2017.1280589
18. Lin K, Lu X, Li Y, Zhuo W, Guan H (2019) A novel structural detailing for the improvement of seismic and progressive collapse performances of RC frames. Earthquake Engineering & Structural Dynamics 48:1451–1470. https://doi.org/10.1002/eqe.3208
19. Liu T, Zou D, Teng J, Yan G (2012) The influence of sulfate attack on the dynamic properties of concrete column. Construction and Building Materials 28:201–207. https://doi.org/10.1016/j.conbuildmat.2011.08.036
20. Saetta A, Scotta R, Vitaliani R (1998) Mechanical Behavior of Concrete under Physical-Chemical Attacks. Journal of Engineering Mechanics 124:1100–1109. https://doi.org/10.1061/(ASCE)0733-9399(1998)124:10(1100)
21. Piasta W (2017) Analysis of carbonate and sulphate attack on concrete structures. Engineering Failure Analysis 79:606–614. https://doi.org/10.1016/j.engfailanal.2017.05.008
22. Muhammed N, Shihab L, Sakin S (2022) Ultimate Load of Different Types of Reinforced Self-Compacting Concrete Columns Attacked by Sulphate. Civil Engineering Journal 8:2069–2083. https://doi.org/10.28991/CEJ-2022-08-10-04
23. Li C, Wu M, Chen Q, Jiang Z (2018) Chemical and mineralogical alterations of concrete subjected to chemical attacks in complex underground tunnel environments during 20–36 years. Cement and Concrete Composites 86:139–159. https://doi.org/10.1016/j.cemconcomp.2017.11.007

24. Umale S, Joshi GV (2019) Study of effect of chemicals (acid) attack on strength and durability of hardened concrete. International Research Journal of Engineering and Technology (IRJET) 6:
25. Márquez JF, Sanchez-silva M, Husserl J (2013) Review of reinforced concrete biodeterioration mechanisms. In: 8th International Conference on Fracture Mechanics of Concrete and Concrete Structures. Ciudad Real, Spain
26. Abu-Yosef A, Stalin A-M, Randall P (2023) Field Assessment of Biogenic Acid Attack in Concrete Structures. ACI Materials Journal 120:. https://doi.org/10.14359/51739147
27. Saetta A, Scotta R, Vitaliani R (1998) Mechanical Behavior of Concrete under Physical-Chemical Attacks. Journal of Engineering Mechanics 124:1100–1109. https://doi.org/10.1061/(ASCE)0733-9399(1998)124:10(1100)
28. Yuan H (2013) Degradation modeling of concrete submitted to biogenic acid attack. Université Paris-Est
29. Liang MT, Wang KL, Liang CH (1999) Service life prediction of reinforced concrete structures. Cement and Concrete Research 29:1411–1418. https://doi.org/10.1016/S0008-8846(99)00109-X
30. Baroghel-Bouny V, Nguyen TQ, Dangla P (2009) Assessment and prediction of RC structure service life by means of durability indicators and physical/chemical models. Cement and Concrete Composites 31:522–534. https://doi.org/10.1016/j.cemconcomp.2009.01.009
31. Alexander M, Beushausen H (2019) Durability, service life prediction, and modelling for reinforced concrete structures – review and critique. Cement and Concrete Research 122:17–29. https://doi.org/10.1016/j.cemconres.2019.04.018
32. Raza S, Khan MKI, Menegon SJ, Tsang H-H, Wilson JL (2019) Strengthening and Repair of Reinforced Concrete Columns by Jacketing: State-of-the-Art Review. Sustainability 11:3208. https://doi.org/10.3390/su11113208
33. Ma Z, Cooper P, Daly D, Ledo L (2012) Existing building retrofits: Methodology and state-of-the-art. Energy and Buildings 55:889–902. https://doi.org/10.1016/j.enbuild.2012.08.018
34. Pour MT (2015) Prioritization of methods for seismic retrofitting of structures. Journal of Engineering Science and Technology 64–80
35. Haque ABMR, Alam MS (2012) Optimal Retrofitting Method Selection for RC Frame Structures: A Case Study. In: 3rd International Structural Speciality Conference. Edmonton, Alberta
36. Caterino N, Iervolino I, Manfredi G, Cosenza E (2009) Comparative analysis of multi-criteria decision-making methods for seismic structural retrofitting. Wiley Online Library 24:432–445. https://doi.org/10.1111/J.1467-8667.2009.00599.X

37. Triantafillou TC (2001) Seismic retrofitting of structures with fibre-reinforced polymers. Progress in Structural Engineering and Materials 3:57–65. https://doi.org/10.1002/PSE.61
38. Motavalli M, Czaderski C (2007) FRP composites for retrofitting of existing civil structures in Europe: State-of-the-art review. In: Composite & Polycon 2007. Tampa, USA
39. Ronagh HR, Eslami A (2013) Flexural retrofitting of RC buildings using GFRP/CFRP – A comparative study. Composites Part B: Engineering 46:188–196. https://doi.org/10.1016/j.compositesb.2012.09.072
40. Delzendeh Moghadam M, Fathi A, Chaallal O (2024) Retrofitting of Steel Structures with CFRP: Literature Review and Research Needs. Applied Sciences 14:5958. https://doi.org/10.3390/app14135958
41. Kobatake Y (1998) A seismic retrofitting method for existing reinforced concrete structures using CFRP. Advanced Composite Materials 7:1–22. https://doi.org/10.1163/156855198X00011
42. Karimipour A, Edalati M (2021) Retrofitting of the corroded reinforced concrete columns with CFRP and GFRP fabrics under different corrosion levels. Engineering Structures 228:111523. https://doi.org/10.1016/j.engstruct.2020.111523
43. Alam MS, Nehdi M, Youssef MA (2009) Seismic performance of concrete frame structures reinforced with superelastic shape memory alloys. Smart Structural System 5:565–585. https://doi.org/10.12989/SSS.2009.5.5.565
44. Park R, Paulay T (2009) Reinforced Concrete Structures. wiley
45. Marquis F, Kim JJ, Elwood KJ, Chang SE (2017) Understanding post-earthquake decisions on multi-storey concrete buildings in Christchurch, New Zealand. Bulletin of Earthquake Engineering 15:731–758. https://doi.org/10.1007/S10518-015-9772-8/METRICS
46. Saatcioglu M, Mitchell D, Tinawi R, Gardner NJ, Gillies AG, Ghobarah A, Anderson DL, Lau D (2001) The August 17, 1999, Kocaeli (Turkey) earthquake - Damage to structures. Canadian Journal of Civil Engineering 28:715–737. https://doi.org/10.1139/CJCE-28-4-715
47. Adhikari SR, Guragain R, Shrestha SN, Pradhan S (2015) Building damage assessment after 2015 Gorkha Earthquake "Case of Panauti Municipality." In: International Day for Disaster Reduction-Nepal, 2015
48. Mehta PK, Monteiro PJM Concrete: Microstructure, Properties, and Materials, Third Edition. McGraw-Hill Companies, Inc
49. Paulay T, Priestly MJN (2009) SEISMIC DESIGN OF REINFORCED CONCRETE AND MASONRY BUILDINGS. wiley
50. HBRI (2020) Bangladesh National Building Code, BNBC-2020. Housing and Building Research Institute, Dhaka
51. Feng D-C, Liu Z-T, Wang X-D, Jiang Z-M, Liang S-X (2020) Failure mode classification and bearing capacity prediction for reinforced concrete columns based on ensemble machine learning algorithm. Advanced

Engineering Informatics 45:101126. https://doi.org/10.1016/j.aei.2020.101126
52. Sotoud S, Aboutaha RS (2014) Performance of RC Bridge Columns Subjected to Lateral Loading. In: Istanbul Bridge Conference. Istanbul
53. Kim S, Hwang H, Oh K, Shin J (2024) A Machine-Learning-Based Failure Mode Classification Model for Reinforced Concrete Columns Using Simple Structural Information. Applied Sciences 2024, Vol 14, Page 1243 14:1243. https://doi.org/10.3390/APP14031243
54. Kato D, Nagahashi T (2011) Failure Mode of Columns of Existing R/C Building Damaged During the 2007 Niigata Chuetsu-Oki Earthquake. Procedia Engineering 14:204–211. https://doi.org/10.1016/j.proeng.2011.07.024
55. Kim Y-E, Park J, To QB, Lee K, Shin J (2023) Finite Element Analysis-Based Blast Performance Evaluation for Reinforced Concrete Columns with Shear and Flexure Failure Modes. Sustainability 15:14967. https://doi.org/10.3390/su152014967
56. Wu Y (2022) Shear failure of RC members. In: Analytical Approaches for Reinforced Concrete. Woodhead Publishing, pp 437–482
57. Zhang Q, Kang X-Q, Zhu J-C, Hu D-K, Zhao H-T, Gong J-X (2025) Study on hysteretic model of flexure-shear critical reinforced concrete columns including the non-linear degradation effects of cyclic loading. Structures 73:108350. https://doi.org/10.1016/j.istruc.2025.108350
58. Domenico M Di, Ricci P, Verderame GM (2021) Failure mode assessment of flexure- and shear-sensitive RC members. In: Italian Concrete Days 2020
59. Nojavan A, Schultz AE, Chao SH (2018) In-plane bar buckling in RC columns in extreme seismic events. In: 11th National Conference on Earthquake Engineering 2018. Earthquake Engineering Research Institute, pp 2839–2843
60. Habib A, Yildirim U, Eren O (2020) Column repair and strengthening using RC jacketing: a brief state-of-the-art review. Innovative Infrastructure Solutions 5:1–11. https://doi.org/10.1007/S41062-020-00329-4/METRICS
61. Patil RA, Guruprasad YK (2023) Restoration of Vertical and Lateral Stability of a Distressed RC Structure Adopting RC Jacketing and Composite Structural Members. In: Recent Advances in Materials, Mechanics and Structures. Lecture Notes in Civil Engineering, vol 269. . Springer, Singapore, pp 517–528
62. Minafò G (2015) A practical approach for the strength evaluation of RC columns reinforced with RC jackets. Engineering Structures 85:162–169. https://doi.org/10.1016/j.engstruct.2014.12.025
63. KRAINSKYI P, KHMIL R, BLIKHARSKIY Z (2015) The strength of reinforced concrete columns, strengthened by reinforced concrete jacketing under loading. Journal of Civil Engineering, Environment and Architecture XXXII:209–220. https://doi.org/10.7862/rb.2015.151

64. Erange YGP, Jenothan M, Jayasinghe JASC, Bandara CS, Dammika AJ (2023) Enhancement of the Lateral Performance of RC Columns Using Steel Jacketing: A Numerical Approach. Engineer: Journal of the Institution of Engineers, Sri Lanka 56:51–64. https://doi.org/10.4038/ENGINEER.V56I2.7576
65. Ma C-K, Apandi NM, Sofrie CSY, Ng JH, Lo WH, Awang AZ, Omar W (2017) Repair and rehabilitation of concrete structures using confinement: A review. Construction and Building Materials 133:502–515. https://doi.org/10.1016/j.conbuildmat.2016.12.100
66. Xiao Y, Wu H (2003) Retrofit of Reinforced Concrete Columns Using Partially Stiffened Steel Jackets. Journal of Structural Engineering 129:725–732. https://doi.org/10.1061/(ASCE)0733-9445(2003)129:6(725)
67. Kaplan H, Ylmaz S (2012) Seismic Strengthening of Reinforced Concrete Buildings. In: Earthquake-Resistant Structures - Design, Assessment and Rehabilitation. InTech
68. Alcaraz-Vázquez J, Andrade JE, Gomez-Diaz A, González VY, Palma S, Vargas-Altamirano CF, Gómez JJ, Contreras-Reyes O, Alcocer SM (2023) Experimental Study on Non-ductile Reinforced Concrete Columns Strengthened with Latticed Steel Jacketing. In: Building for the Future: Durable, Sustainable, Resilient. fib Symposium 2023. Lecture Notes in Civil Engineering, vol 349. . Springer, Cham, pp 1430–1439
69. Elsamny MK, Hussein AA, Nafie AM, Abd-Elhamed MK (2013) Experimental Study of Eccentrically Loaded Columns Strengthened Using a Steel Jacketing Technique. International Journal of Civil and Environmental Engineering 7:900–907. https://doi.org/10.5281/ZENODO.1335872
70. Lai B, Liew JYR, Xiong M (2019) Experimental study on high strength concrete encased steel composite short columns. Construction and Building Materials 228:116640. https://doi.org/10.1016/J.CONBUILDMAT.2019.08.021
71. Mishra S, Kumar SRS (2022) Confinement detailing of concrete encased steel concrete composite columns. In: ASPS Conference Proceedings. Alwaha Scientific Publishing Services SARL, pp 111–119
72. Zhou K, Han L-H (2018) Fire performance of concrete-encased CFST columns and beam-column joints. In: Proceedings 12th International Conference on Advances in Steel-Concrete Composite Structures - ASCCS 2018. Universitat Politècnica València, Valencia
73. Epoxy Concrete Injection Epoxy Wood Injection epoxy crack repair. https://www.epoxy.com/injection.aspx. Accessed 16 Jul 2025
74. SRS-3000 Crack Injection Epoxy | Reliable Structural Crack Repair. https://www.structuralrs.com/structural-strengthening-products/srs-3000-crack-injection-epoxy. Accessed 16 Jul 2025

75. ACI committee E706 (2003) ACI-RAP-1-Structural Crack Repair by Epoxy Injection FIELD GUIDE TO CONCRETE REPAIR APPLICATION PROCEDURES
76. Abdulqadir ZM, Karim FR (2022) Evaluating the Efficiency of Epoxy Injection Technique for Repairing Normal and High Strength Concrete Beams - A Critical Review. CONSTRUCTION 2:48–55. https://doi.org/10.15282/construction.v2i2.8522
77. ACI Committee 546 (2014) Guide to Concrete Repair (ACI 546-14)
78. Noroozieh E, Mansouri A (2019) Lateral strength and ductility of reinforced concrete columns strengthened with NSM FRP rebars and FRP jacket. International Journal of Advanced Structural Engineering 11:195–209. https://doi.org/10.1007/S40091-019-0225-5/FIGURES/14
79. Agante MAB, Júlio ENBS, Barros JAO, Santos JMC (2017) Active CFRP-based confinement strategies for RC columns with rectangular cross sections. In: Proceedings of the 5th International Specialty Conference on Fibre Reinforced Materials. CI-Premier Pte Ltd., pp 29–36
80. Hajarul Falahi Abdul Halim N, Alih SC, Vafaei M, Abdul Ameer Mahdi H, Husein Al-Dahlaki M, Abdul Hussain A, Gora uf M, Jaganathan J, Anwar MP, Johnson Alengaram U (2018) Finite element analysis of rectangular reinforced concrete columns wrapped with FRP composites. IOP Conference Series Materials Science and Engineering 431:072005. https://doi.org/10.1088/1757-899X/431/7/072005
81. Pham TM, Youssed J, Hadi MNS, Tran TM (2016) Effect of Different FRP Wrapping Arrangements on the Confinement Mechanism. Procedia Engineering 142:307–313. https://doi.org/10.1016/j.proeng.2016.02.051
82. American Concrete Institute (2018) ACI 549R-18: Report on Ferrocement
83. Anand KA What is Ferrocement, its Applications and Advantages in Construction? https://www.getpowerplay.in/resources/blogs/what-is-ferrocement-its-applications-and-advantages-in-construction/. Accessed 4 Jul 2025
84. Paramasivam P, ONG KCG, Lee SL (1988) FERROCEMENT STRUCTURES AND STRUCTURAL ELEMENTS. In: Steel-Concrete Composite Structures. CRC Press, pp 299–348
85. Lalaj O, Yardım Y, Yılmaz S (2015) Recent perspectives for ferrocement. Research on Engineering Structures and Materials 1:11–23. https://doi.org/10.17515/resm2015.04st0123
86. Batra A, Ghangas S, Kumar L, Saxena H (2017) A Review study of Application of Ferro-Cement. International Research Journal of Engineering and Technology 04:
87. Hago AW, Al-Jabri KS, Alnuaimi AS, Al-Moqbali H, Al-Kubaisy MA (2005) Ultimate and service behavior of ferrocement roof slab panels. Construction and Building Materials 19:31–37. https://doi.org/10.1016/j.conbuildmat.2004.04.034

88. Sridhar J, Shinde GB, Vivek D, Naseem K, Gaur P, Patil PP, Tesema MT (2022) Response Surface Methodology Approach to Predict the Flexural Moment of Ferrocement Composites with Weld Mesh and Steel Slag as Partial Replacement for Fine Aggregate. Advances in Materials Science and Engineering 2022. https://doi.org/10.1155/2022/9179480
89. Konety M (2025) A Comprehensive Guide to Ferrocement in Construction. https://www.bricknbolt.com/blogs-and-articles/construction-guide/ferrocement-construction#advantages-of-ferrocement. Accessed 4 Jul 2025
90. Kaish ABMA, Jamil M, Raman SN, Zain MFM, Nahar L (2018) Ferrocement composites for strengthening of concrete columns: A review. Construction and Building Materials 160:326–340. https://doi.org/10.1016/J.CONBUILDMAT.2017.11.054
91. Sirimontree S, Witchayangkoon B, Lertpocasombut K (2015) Strengthening of Reinforced Concrete Column via Ferrocement Jacketing. American Transactions on Engineering & Applied Sciences 4:
92. Mourad SM, Shannag MJ (2012) Repair and strengthening of reinforced concrete square columns using ferrocement jackets. Cement and Concrete Composites 34:288–294. https://doi.org/10.1016/J.CEMCONCOMP.2011.09.010
93. Balamuralikrishnan R, Al Madhani M, Al Madhani R (2019) Study on Retrofitting of RC Column Using Ferrocement Full and Strip Wrapping. Civil Engineering Journal 5:. https://doi.org/10.28991/cej-2019-03091425
94. Hameed SH, Jaafer AA (2023) Review of Literature on Strengthening and Retrofitting of Reinforced Concrete Beams by Ferrocement. AIP Conference Proceedings 2775:. https://doi.org/10.1063/5.0140889/2904255
95. Singh Dhanoa G, Singh J, Singh R (2016) Retrofitting of Reinforced Concrete Beam by Ferrocement Technique. Indian Journal of Science Technology 9:. https://doi.org/10.17485/ijst/2016/v9i15/88243
96. Makki RF (2014) Response of reinforced concrete beams retrofitted by ferrocement. International Journal of Scientific & Technology Research 3:
97. Van Hong Bui L, Saiwimarn S, Sirimontree S, Thongchom C, Keawsawasvong S, Nguyen PT, Nguyen YTH, Lawongkerd J, Ngamkhanong C, Nguyen TT (2022) Experimental analysis on reinforced concrete beams enlarged with ferrocement retrofit system. Innovative Infrastructure Solution 7:. https://doi.org/10.1007/S41062-022-00935-4
98. Muhit I Bin, Jitu NET, Alam MR (2021) Structural shear retrofitting of reinforced concrete beam: multilayer ferrocement technique. Asian Journal of Civil Engineering 22:191–203. https://doi.org/10.1007/S42107-020-00306-3
99. Van Hong Bui L, Saiwimarn S, Sirimontree S, Thongchom C, Keawsawasvong S, Nguyen PT, Nguyen YTH, Lawongkerd J, Ngamkhanong C, Nguyen TT (2022) Experimental analysis on reinforced

concrete beams enlarged with ferrocement retrofit system. Innovative Infrastructure Solutions 7:1–14. https://doi.org/10.1007/S41062-022-00935-4/METRICS
100. Dhanoa GS, Singh J, Singh R (2016) Retrofitting of Reinforced Concrete Beam by Ferrocement Technique. Indian Journal of Science and Technology 9:1–9. https://doi.org/10.17485/IJST/2016/V9I15/88243
101. Makki RF (2014) Response Of Reinforced Concrete Beams Retrofitted By Ferrocement. International Journal of Scientific & Technology Research 3:
102. Kumar MS D, S S, Mohammed Uzair A, S G, Vijaya Raj M Y (2018) RC Beams Retrofitted by Ferrocement Laminates with Addition of Alccofine. Journal of Material Science & Engineering 07:478. https://doi.org/10.4172/2169-0022.1000478
103. Al-Rawe HS, Ahmed SY, Ahmed SY, Abdullah SM (2024) Experimental and Analytical Investigations on Biaxially Loaded Reinforced Concrete Columns Retrofitted by Ferrocement Jacketing. Journal of University of Babylon for Engineering Sciences 32:69–83. https://doi.org/10.29196/HKMVP175
104. Islam MT, Kabir A (2023) Effect of Ferrocement Confinement on RC Columns Under Axial Compression And Improvement. In: International Conference on Planning, Architecture and Civil Engineering. Rajshahi, pp 1094–1099
105. Abdullah, Takiguchi K (2003) An investigation into the behavior and strength of reinforced concrete columns strengthened with ferrocement jackets. Cement Concrete Composites 25:233–242. https://doi.org/10.1016/S0958-9465(02)00005-7
106. Bari AKMF, Amin A, Riyad RH, Talukder MdLR (2021) STRENGTHENING OF FIRE DAMAGED REINFORCED CONCRETE COLUMNS USING FERROCEMENT. Malaysian Journal of Civil Engineering 33:. https://doi.org/10.11113/mjce.v33.17495
107. Kaish ABMA, Alam MR, Jamil M, Zain MFM, Wahed MA (2012) Improved ferrocement jacketing for restrengthening of square RC short column. Construction and Building Materials 36:228–237. https://doi.org/10.1016/j.conbuildmat.2012.04.083
108. Amala M, Dhal L, Gokul V, Christi S, Dhanasekar K (2021) Strengthening of compression member by ferrocement with high performance mortar – Jacketing technique. Materials Today: Proceedings 43:1810–1818. https://doi.org/10.1016/j.matpr.2020.10.495
109. R. B, Al Madhani M, Al Madhani R (2019) Study on Retrofitting of RC Column Using Ferrocement Full and Strip Wrapping. Civil Engineering Journal 5:2472–2485. https://doi.org/10.28991/cej-2019-03091425
110. Teodosio B, Kristombu Baduge KS, Mendis P, Heath DJ (2019) Prefabrication of substructures for single-detached dwellings on reactive soils: a review of existing systems and design challenges. Australian

Journal of Civil Engineering 17:120–133. https://doi.org/10.1080/14488353.2019.1657056;JOURNAL:JOURNAL:TCEN20;WGROUP:STRING:PUBLICATION

111. Wang Z, Hu H (2018) Dynamic response to demand variability for precast production rescheduling with multiple lines. International Journal of Production Research 56:5386–5401. https://doi.org/10.1080/00207543.2017.1414970;WGROUP:STRING:PUBLICATION
112. Off-Site Construction Can Cut Project Time 73% | BuildingGreen. https://www.buildinggreen.com/newsbrief/site-construction-can-cut-project-time-73. Accessed 4 Jul 2025
113. Vähä P, Heikkilä T, Kilpeläinen P, Järviluoma M, Gambao E (2013) Extending automation of building construction — Survey on potential sensor technologies and robotic applications. Automation in Construction 36:168–178. https://doi.org/10.1016/J.AUTCON.2013.08.002
114. K M, K S (2020) Sustainable Performance Criteria for Prefabrication Construction System. International Journal of Scientific and Research Publications (IJSRP) 10:p10052. https://doi.org/10.29322/IJSRP.10.04.2020.P10052
115. Jaillon L, Poon CS (2008) Sustainable construction aspects of using prefabrication in dense urban environment: A Hong Kong case study. Construction Management and Economics 26:953–966. https://doi.org/10.1080/01446190802259043
116. Etman EE, Khalil A-HA (2003) EFFECT OF CORNER RADIUS ON THE BEHAVIOR OF STRENGTHENED RC COLUMNS WITH DIFFERENT HEIGHTS. In: Fifth Alexandria International Conference on Structural and Geotechnical Engineering. Alexandria, Egypt
117. Mostofinejad D, Hajrasouliha M (2018) Shear Retrofitting of Corner 3D-Reinforced Concrete Beam-Column Joints Using Externally Bonded CFRP Reinforcement on Grooves. Journal of Composites for Construction 22:04018037. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000862
118. Beschi C, Riva P, Meda A (2012) Corner Beam-Column Joints Seismic Retrofitting With High Performance Fiber-Reinforced Concrete Jacketing. In: 15 world conference on earthquake engineering
119. A. B. M. A. Kaish, Lutfun Nahar, Azizah Jaafar, Yagoub Ahmed (2018) Prospects of using Prefabricated Ferrocement Jacket for Semi-Automated Strengthening of RC Column. Electronic Journal of Structural Engineering 18:52–57. https://doi.org/10.56748/ejse.182632
120. Mahmood A, Kaish A, Mohammed Ali T, Al Zand A, Jamil M, Hamid R (2023) Prefabricated Ferrocement Jacket for Repairing and Strengthening Axially Loaded Square Sub-Standard Concrete Stub Columns. Buildings 13:2484. https://doi.org/10.3390/buildings13102484

121. Nitobond EP | Fosroc. https://www.fosroc.com.au/product/nitobond-ep. Accessed 23 Jul 2025
122. Renderoc HSXtra - Fosroc. https://www.fosroc.com/product/show/renderoc-hsxtra. Accessed 23 Jul 2025
123. Concure WB - Fosroc. https://www.fosroc.com/product/show/concure-wb-. Accessed 8 Aug 2025