PERFORMANCE OF PREFABRICATED FERROCEMENT SHEET TO RETROFIT RC TIED COLUMNS

Submitted By

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Dedication

This work is lovingly dedicated to my beloved family, whose unwavering support, sacrifices, and belief in me made this journey possible. Achieving my M.Engg. degree has been a path filled with challenges, but it is through their constant presence and encouragement that I found the strength to persevere.

My educational journey began humbly at Kastogari Dakhil Madrasha, progressed through Bogura Polytechnic Institute, and later continued at Southern University Bangladesh, and then at Chittagong University of Engineering Technology. At every stage, I was guided and nurtured by remarkable teachers who treated me with genuine care like a son. Their wisdom and kindness helped lay the foundation for everything I would later achieve.

While pursuing my degree, I also stepped into the professional world through my first job at the BSRM Group of Companies. Balancing this role with my academic responsibilities was no easy task. Weekly travel across long distances to attend classes, coupled with the demands of private work and thesis commitments, often tested the limits of my endurance. Yet, it was in these moments of fatigue and doubt that my family stood strongest—offering me not just their time and patience, but emotional and mental strength that never wavered.

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This achievement is far more than an individual success. It is a shared triumph—a testament to the love of a family, the kindness of mentors, and the resilience built through struggle.

In the end, to my dearest family: this degree is as much yours as it is mine.

Approval/Declaration by the Supervisor

This is to certify that Md. Anisur Rahman 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 they are 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.



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Abstract

The durability and performance of reinforced concrete (RC) structures are often compromised due to aging, environmental exposure, poor construction quality, and extreme loading conditions such as earthquakes or cyclones. In developing countries like Bangladesh, where a significant portion of the built environment is vulnerable and maintenance resources are limited, a cost-effective and structurally efficient retrofitting technique is urgently required. In this regard, this research explores the feasibility and effectiveness of a retrofitting method using prefabricated ferrocement sheets (PFSs) to strengthen partially damaged tied RC columns.

In this study, an experimental investigation was conducted to assess the structural performance of eighteen one-third-scale column specimens representing three concrete strength levels (20 MPa, 24 MPa, and 28 MPa), divided into control, damaged, and retrofitted groups. The retrofitting involved bonding prefabricated ferrocement sheets, comprising single or double-layer wire mesh, onto the damaged columns using epoxy adhesives and mechanical anchors. All specimens were tested under axial displacement-controlled loading, and key performance indicators such as ultimate load capacity, initial stiffness, energy absorption, ductility index, and failure patterns were determined and evaluated.

The results obtained from the investigation indicate that the retrofitted columns outperformed both the control and damaged specimens across all measured parameters. Notably, columns retrofitted with double-layer ferrocement jacketing exhibited up to 164% of axial strength, an improvement of initial structural stiffness of 54% and energy absorption increased by 152% over partial damage specimens for column concrete strength with 28 MPa. Subsequently, the respective values for the PFSs retrofitted column with a single layer are: 123%,

40% and 105%. The ductility index also improved substantially for both retrofitting scenarios, while failure modes shifted from brittle longitudinal splitting to ductile diagonal crack propagation with a delayed collapse. These similar scenarios are equally true for column specimens with lower concrete strength. Apart from that, the methodological approach of this study demonstrates prefabricated ferrocement sheet wrapping as a structurally sound, less labour-intensive, time-efficient and economically scalable retrofitting technique for deteriorated RC columns, especially for a developing country like Bangladesh.

সারসংক্ষেপ

রিইনফোর্সড কংক্রিট (আর.সি.) কাঠামো সমূহ সময় পরিক্রমায় পরিবেশগত অনুঘটক, নির্মাণকালীন ত্রুটি-বিচ্যুতি এবং ভূমিকম্প ও ঘূর্ণিঝড়ের মতো প্রকৃতিক বিপর্যয়ের কারণে কাঠামোর স্থায়িত্ব ও দৃঢ়তা ক্রমশ হারাতে থাকে। বাংলাদেশের মতো উন্নয়নশীল দেশগুলো, যেখানে বিদ্যমান অবকাঠামোর একটি উল্লেখযোগ্য অংশ বর্তমানে ঝুঁকিপূর্ণ অবস্থায় আছে এবং সেসবের রক্ষণাবেক্ষণের জন্য প্রয়োজনীয় সম্পদের পরিমান সীমিত, সেখানে একটি অর্থিকভাবে লাভজনক ও কাঠামোগতভাবে কার্যকর রেট্রোফিটিং সমাধান অত্যন্ত প্রয়োজনীয়তা বহন করে। এরই প্রেক্ষিতে, এই গবেষণা কার্যক্রমটি প্রিফেব্রিকেটেড ফেরোসিমেন্ট শিট (পি.এফ.এস.) এর কার্যকারিতা ও সম্ভাব্যতা যাচাইয়ের জন্য একটি পরিক্ষামূলক উদ্যোগ নিয়েছে।

উক্ত গবেষণায় আংশিকভাবে ক্ষতিগ্রস্ত আর.সি. কলামগুলোর কাঠামোগত শক্তি বৃদ্ধির জন্য প্রিফ্যাব্রিকেটেড ফেরোসিমেন্ট শিট (পি.এফ.এস.) ব্যবহার করে এই রেট্রোফিটিং কৌশলের কার্যকারিতা ও ব্যবহারিক সম্ভাবনা যাচাই করা হয়। গবেষণায় তিন ভাগের একভাগ-স্কেলের মোট আঠারোটি কলাম প্রস্তুত করা হয়, যেগুলোয় তিনটি ভিন্ন ভিন্ন শক্তির কংক্রিট (২০, ২৪ এবং ২৮ মেগাপেস্কেল) ব্যবহার করা হয় এবং সাধারণ কলাম, ক্ষতিগ্রস্ত কলাম এবং রেট্রোফিটেড কলাম, এই তিনটি গ্রুপে ভাগ করা হয়। সকল পরীক্ষনীয় কলাম সমূহে কলাম গুলোর নিজস্ব অক্ষ বরাবর চাপ প্রয়োগ করে ডিসপ্লেসমেন্ট কন্ট্রোল কর্মপদ্ধতি অনুসারে এদের চূড়ান্ত ভার বহন ক্ষমতা, কাঠামোগত দৃঢতা, শক্তি শোষন ক্ষমতা, নমনীয়তা সূচক এবং কলাম ক্ষতিগ্রস্ত হওয়ার ধরণ যাচাই করা হয়।

চূড়ান্ত ফলাফলে দেখা যায়, রেট্রোফিট করা কলামগুলো স্বাভাবিক ও ক্ষতিগ্রস্ত নমুনার তুলনায় উপরি উক্ত সকল সূচকে উল্লেখযোগ্যভাবে উন্নত কর্মক্ষমতা প্রদর্শন করে। বিশেষ করে, ২৮ মেগাপেস্কেল শক্তির কলামগুলোর যেগুলোয় দুই স্তরের লোহার তারজালি যুক্ত ফেরোসিমেন্ট এর স্থর প্রয়োগ করা হয় সেইসকল কলামগুলো যথাক্রমে ১৬৪% এক্সিয়াল চাপ বহন ক্ষমতা, ৫৪% দৃঢ়তা ১৫২% শক্তি শোষণ ক্ষমতার প্রদর্শন করে। অপরদিকে, একক স্তর লোহার তারজালি বিশিষ্ট ফেরোসিমেন্ট এর স্থর যেসকল কলামে প্রয়োগ করা হয়, তাদের ক্ষেত্রে এই উন্নতির পরিমাণ যথাক্রমে ১২৩%, ৪০% ও

১০৫%। উল্লেখ্য যে, উভয় ধরনের রেট্রোফিটিং পদ্ধতির ক্ষেত্রে নমনীয়তা সূচকেও যথেষ্ট উন্নতি পরিলক্ষিত হয়েছে এবং কলামগুলোর ক্ষতিগ্রস্ত হওয়ার ধরণে যথেষ্ট পরিবর্তিত লক্ষণীয়। পূর্বে যেখানে ভঙ্গুর ধরণের লম্বালম্বি ফাটল দেখা যেত, সেখানে এখন ধীর গতীর তীর্যক ভাবে ফাটল সৃষ্ঠি হওয়া পরিলক্ষিত হয়। এইরূপ ফলাফল অন্য দুই অপেক্ষাকৃত কম শক্তির কংক্রিট কলামগুলোর ক্ষেত্রেও সত্য। এছাড়াও, এই গবেষণার পদ্ধতিগত ধরণ এটিও প্রমাণ করে যে, প্রিফ্যাব্রিকেটেড ফেরোসিমেন্ট একটি কাঠামোগতভাবে নির্ভরযোগ্য, তুলনামূলকভাবে কম শ্রমনির্ভর, সময়-সাশ্রয়ী এবং অর্থনৈতিকভাবে লভজনক একটি বাস্তবায়নযোগ্য রেট্রোফিটিং কৌশল, যা বাংলাদেশ ন্যায় পশ্চাৎপদ দেশের জন্য অত্যন্ত গুরুত্ববহ।

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Nomenclature

Symbols, Acronyms and Abbreviations

ACI	:	American Concrete Institute
ASCE	:	American Society of Civil Engineers
BNBC	:	Bangladesh National Building Code
CFRP	:	Carbon Fibre Reinforced Polymer
DI	:	Ductility Index
FRP	:	Fibre Reinforced Polymer
GFRP	:	Glass Fibre Reinforced Polymer
MS	:	Mild Steel
OPC	:	Ordinary Portland Cement
PFS	:	Prefabricated Ferrocement Sheet
RC	:	Reinforced Concrete
UTM	:	Universal Testing Machine
CC1	:	Control Column Specimen - 01
CC2	:	Control Column Specimen - 02
CC3	:	Control Column Specimen - 03
PDC1	:	Partial Damage Column Specimen - 01
PDC2	:	Partial Damage Column Specimen - 02
PDC3	:	Partial Damage Column Specimen - 03
RCSL1	:	Retrofitted Column Prefabricated Ferrocement Sheet with a Single Layer Mesh Specimen - 01

RCSL2 : Retrofitted Column Prefabricated Ferrocement Sheet with a Single Layer Mesh Specimen - 02

RCSL3 : Retrofitted Column Prefabricated Ferrocement Sheet with a Single Layer Mesh Specimen - 03

RCDL1 : Retrofitted Column Prefabricated Ferrocement Sheet with a Double Layer Mesh Specimen - 01

RCDL2 : Retrofitted Column Prefabricated Ferrocement Sheet with a Double Layer Mesh Specimen - 02

RCDL3 : Retrofitted Column Prefabricated Ferrocement Sheet with a Double Layer Mesh Specimen - 03

Chapter 1 : INTRODUCTION

1.1 GENERAL

Columns are fundamental and perhaps the most important structural components in a building's structural system, designed to withstand axial and lateral loads. Preferably, these are made of reinforced concrete (RC), whose excellent mechanical properties, economy and formability make it one of the widely used construction materials [1]. The mechanical harmony between the concrete with excellent compressive strength and added superior tensile capacity from reinforcement makes reinforced concrete (RC) a versatile construction material to withstand a wide range of load conditions [2]. An RC column essentially carries the gravity loads transferred from the overlying slabs, beams and columns to safely carry the same to the foundation. Apart from that, it plays an important role in providing lateral resistance against dynamic loads like earthquakes and cyclonic winds. Hence, RC columns are given high importance as their failure can lead to immediate catastrophe. As a result, the design and rehabilitation of RC columns are a critical focus in both the practical field and academia [3].

All structural element shows their characteristic structural failure when the service load exceeds the capacity of the column and RC columns are no exception [4]. This failure can occur under two primary circumstances. The most likely one that first comes to mind is when a structurally sound column experiences extreme loading conditions, such as excessive gravity load, seismic load, strong wind, heavy snowfall, etc., that push the element beyond its capacity. Another one is related to aging, where material degradation [5–8] and corrosion of reinforcements are the cause [9–14]. Besides these, there are a few scenarios, but not to be ignored are poor construction practice, material and constructional imperfection, inefficient seismic detailing in a seismically active region [15–18],

chemical attack [18–24], biological degradation [25–27], etc. Concrete structures are designed for a defined service life, after which their structural integrity declines significantly [28–30]. This challenge is especially pressing in developing countries like Bangladesh, where adherence to design provisions and standard construction practice is often inconsistent. As a result, there is a definite global need for efficient, cost-effective and easy-to-construct retrofitting methods to repair damaged or partially damaged structural components, with the main focus on RC columns.

The term retrofitting refers to the engineering techniques adopted to restore or enhance an existing structural element, since the component lacks adequate load-bearing capacity due to incurred damage, overstress, or substantial changes in design requirements. While the demolition and reconstruction might seem like the immediate course of action, such an approach is not always feasible, particularly when factors such as building occupancy, economic constraints, logistic challenges, or cultural and historical significance are taken into account. Several studies have emphasized that retrofitting offers a more sustainable and practical alternative compared to complete replacement [31, 32]. Therefore, retrofitting has become a preferred strategy for strengthening damaged RC columns. Various retrofitting methods are available in current engineering practice. The selection of a particular method depends on the nature and severity of the structural damage, capacity requirement, environmental considerations, etc [33–35]. Among the most common retrofitting techniques are concrete jacketing and steel jacketing. In addition, some of the innovative techniques include fibre reinforced polymer (FRP) and carbon fibre reinforced polymer (CFRP) jacketing, glass fibre reinforced polymer (GFRP), shape memory alloy, etc [36–42]. Currently, one of the most promising and increasingly popular alternatives for structural retrofitting is the use of ferrocement.

Ferrocement is a composite matrix of cementitious material reinforced with one or more uniformly distributed layers of wire mesh throughout its cross-section, which is the primary reason behind the excellent performance of ferrocement against crack and impact loads [43]. Thin profile and flexibility of the mesh reinforcement, ferrocement provides a wide range of workability and adaptability. Whereas the traditional approach is often costly and at times impractical. When applied to the retrofitting of RC elements, ferrocement has demonstrated commendable performance. It also showed a notable improvement in the ductility and load-carrying capacity of RC columns [44–46]. The advantage of ease of application, cost-effectiveness and scalability makes it an increasingly prominent solution in the field of infrastructural rehabilitation. On top of that, prefabricated ferrocement components facilitate automation and mechanization in the construction process, significantly reducing the construction time compared to traditional in-situ construction.

When prefabrication is integrated with ferrocement technology, it presents a promising and efficient development, especially for the retrofitting works of RC structures. Furthermore, this will enhance the performance of the RC columns under various loading conditions, including seismic events and show greater resistance to crack formation. Therefore, the idea of retrofitting partially cracked RC columns using PFS is a relatively novel concept, yet it holds substantial potential for advancing structural resilience.

From a practical standpoint, the development of prefabricated ferrocement sheets (PFSs) holds particular significance for developing countries like Bangladesh. In these regions, construction lacks quality control, lacks skilled labour and has limited access to advanced technology. Additionally, post-disaster recovery considerations after a seismic event are frequently overlooked during the planning and design phases of construction. This oversight is especially critical for aging buildings and infrastructure located in moderately

prone earthquake zones, like where Bangladesh is located. In such contexts, the availability of a rapid and reliable retrofitting solution becomes vital for enhancing disaster resilience, ultimately safeguarding both lives and property. Thus, prefabricated ferrocement sheets (PFSs) not only serve as a method for structural rehabilitation but also contribute significantly to the social and economic stability of the vulnerable communities. This hybrid innovation combines the advantages of modern engineering performance with low-tech, locally accessible construction materials and comparatively less technical retrofitting methods, paving the way for sustainable and inclusive retrofitting practices for RC structures, particularly columns.

1.2 PROBLEM OF STATEMENT

At present, several retrofitting techniques are used to strengthen RC columns. However, conventional retrofitting techniques pose many challenges and limitations. For instance, concrete jacketing increases both the cross-sectional dimensions and the weight of the column, thereby reducing the usable space and imposing additional stress on the foundation. Furthermore, this technique takes a considerable amount of time to complete the overall retrofitting task, thereby not only exacerbating the overall cost of the work but also affecting the structural resilience. Meanwhile, other advanced solutions, such as fibre-reinforced polymer (FRP) wrapping, while being lightweight and relatively quick to install, are sensitive to temperature and very costly, and demand skilled labour for implementation.

In the current period, ferrocement has shown promise as a retrofitting material. As a locally available material, it is cost-effective and at the same time less technical to be applied without requiring any skilled labor. However, its in-situ applications again draw the limitation of time and delayed rehabilitation work, which in turn also increases the overall cost. Apart from that, there have been a number of ways of applying the ferrocement in the retrofitting of structural

members, especially columns. Many of them showed effectiveness in retrofitting and some are yet to be explored. Despite these, there is no standard technique for its effective application to retrofitting.

To address the challenges associated with repair time, high cost, limited practicality and the need for enhanced structural performance and durability, pre-fabricated ferrocement sheets (PFSs) provide a compelling alternative. Their lightweight nature, corrosion-resistance and ease of installation make them especially suitable for retrofitting applications.

This study experimentally investigates the performance of PFS for retrofitting partially damaged RC tied columns of three different concrete grades (20, 24, and 28 MPa) using two mesh configurations (single and double-layer mesh), tested under axial compression mode.

1.3 OBJECTIVES

This study aims to evaluate the effectiveness of PFSs 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 ultimate load capacity, load-displacement behaviour, stiffness, and energy absorption of control, damaged, and PFS-retrofitted columns.

II. To investigate the failure and cracking patterns of control, damaged, and PFS-retrofitted columns.

III. To evaluate the influence of mesh layering (single vs. double) on the performance of PFS retrofitting.

IV. To assess the effect of concrete strength (20, 24, and 28 MPa) on the retrofitting performance.

V. To provide practical recommendations for implementing PFS retrofitting in real construction projects.

1.4 SCOPE

The scope of the current study is required to clarify the boundaries of the research, which are noted below-

I. This research studies scaled-down RC square columns for control columns, damaged columns and retrofitted columns.

II. The study introduced partial damage RC columns via introducing controlled cavity (03 nos. at only three faces of the column), inserting 75 mm deep and 75 mm wide MS Sheet Spike during casting and removing after hardening of concrete

III. This study adopted the wrapping of damaged RC columns with pre-fabricated ferrocement sheets (PFSs) for retrofitting purposes.

IV. This study concentrates on the load-controlled axial loading only for laboratory testing, which is the primary load for column elements and observed failure and cracking patterns and other parameters such as load-displacement behaviour, stiffness, energy absorption and ductility.

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 prefabricated ferrocement sheets (PFSs) as a retrofitting material. Subsequently, it outlines the objectives and the scope of this study.

Chapter 02 presents a comprehensive review of past studies 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 PFSs for RC column retrofitting.

Chapter 03 describes the methodological approach to the experimental study, starting with the specimen details and ending with the final test setup for the compressive test.

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

Reinforced concrete (RC) has long stood as the cornerstone of modern infrastructure for its excellent structural reliability and economic efficiency. Since its widespread adoption in the early 20th century, RC has enabled the rapid expansion of urban landscapes and the construction of increasingly complex civil structures. Yet, like all engineered systems, RC structures are not immune to the passage of time. Factors such as material degradation, harsh environmental exposure, design flaws, construction inaccuracies, upgrading building code and unexpected loads ranging from a wide variety of manmade and natural loading conditions can compromise their integrity and performance [47]. In such a case, the wholesale demolition and replacement of such structures is neither financially viable nor environmentally responsible. Consequently, the demand for effective and sustainable retrofitting strategies has grown significantly, particularly in the case of RC columns, which serve as fundamental load-bearing members for almost every structure we can see around. The failure of these elements means an inevitable collapse of the entire structure, making their maintenance vital to ensuring overall structural safety and resilience [3].

To address this challenge, engineers and researchers have developed an array of retrofitting techniques over the decades. The subsequent sections systematically illustrate a comprehensive review of the range of traditional retrofitting techniques and interventions to draw out the current state of knowledge on both conventional and innovative retrofitting methods, critically examining their mechanisms, performance outcomes, limitations, and the prevailing gaps in research. Through this comprehensive examination, the review underscores the

pressing need for continued investigation into novel retrofitting strategies, particularly prefabricated ferrocement, to retrofit the damaged RC columns.

2.2 PRESENT STATE OF THE PROBLEM

Among all structural elements, columns are both highly critical and particularly susceptible to failure. The failure of a single column can trigger a redistribution of loads to neighbouring members, potentially initiating a progressive collapse if those elements are unable to carry the additional stresses. Furthermore, such localized damage can induce unbalanced moments, heightening the risk of bending and shear failures in vulnerable regions. Therefore, timely retrofitting and strengthening of partially damaged columns is essential to restore structural integrity and preserve the continued functionality of the structure.

Current retrofitting techniques, including concrete jacketing, steel jacketing, and fibre-reinforced polymer (FRP) wrapping, etc., have demonstrated their effectiveness. However, they are often constrained by factors such as high initial cost, labour-intensive, extended curing periods, and the requirement for skilled personnel. These limitations become particularly significant in emergency situations or in locations with limited accessibility. Currently, there have been a number of extensive studies on the performance of ferrocement as a retrofitting option. Despite these efforts, the application of prefabricated ferrocement sheets in retrofitting, particularly for partially damaged RC tied columns, remains underexplored. A key challenge is the lack of comprehensive performance assessments that address critical parameters such as ultimate load capacity, deformation characteristics, ductility, and failure mechanisms. Furthermore, essential variables, including the number and of layers of mesh, type of bonding agent, and concrete grade, etc., have not been sufficiently investigated. This study seeks to address these gaps by exploring the viability of prefabricated ferrocement sheets as an effective and practical retrofitting solution for damaged

RC columns, with a focus on its intended structural capacity as well as eliminating the burden of cost, technical skill and most importantly the rehabilitation time.

2.3 COMMON RETROFITTING TECHNIQUES

2.3.1 RC Jacketing

Among all retrofitting techniques, RC jacketing is one of the most commonly employed techniques. This method involves encasing the old RC element with a new layer of reinforced concrete, as shown in Figure 2.1. The mechanical interlocking between the new and old RC material is achieved through the use of shear connectors to ensure the composite action. The first thing to be noticed is that the added outer concrete layer enlarges the column cross-section, resulting in increased stiffness and greater confinement of the core concrete, which in turn enhances its capacity to resist service load. From several past studies, it is also proven that reinforced concrete (RC) jacketing notably improves the load-bearing capacity of RC columns [48, 49].

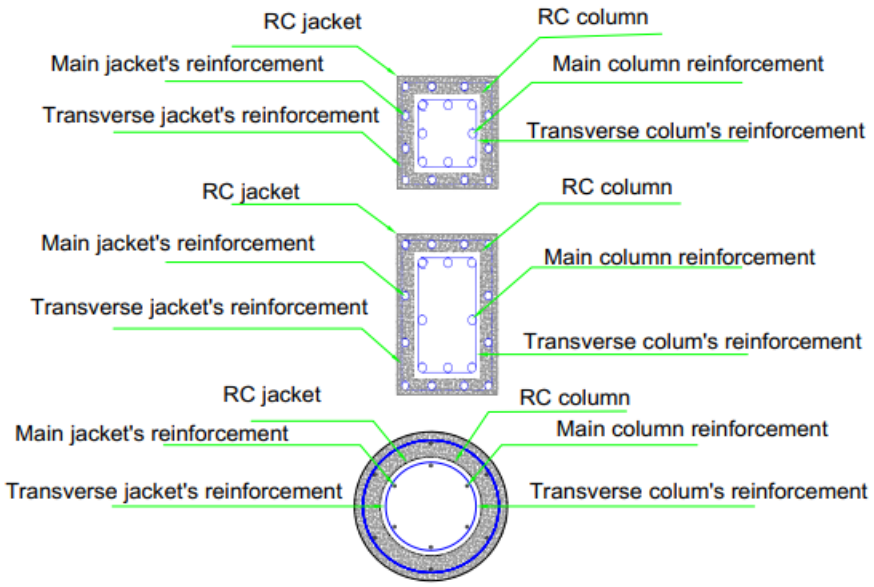


Figure 2.1: RC jacketing of square, rectangular and circular RC columns

Moreover, it enhances the lateral stability of the column during seismic activity by limiting the lateral displacements and increasing ductility, thereby improving the structure's ability to dissipate energy during an earthquake [48–50]. Apart from its ability to significantly enhance structural performance, its design procedure is very straightforward and cost-effective [51].

Despite all these benefits, RC jacketing comes with some drawbacks. An effective application requires thorough surface preparation, installation of shear studs, application of chemical bonding agents, etc., to ensure proper adhesion with the existing concrete. Additionally, the added concrete jacket increases the structure's dead load and reduces the total usable area.

2.3.2 Steel Jacketing

Stainless steel jacketing is one other currently popular structural rehabilitation technique where slick strips of metal plates or an entire steel sheet or even steel angles, etc. are made into a cage-like structure around the retrofitted elements, just as shown in Figure 2.2. The gaps between the steel and the concrete are then filled with grout or epoxy to ensure proper bonding and provide confinement. In some cases, they are further reinforced with stiffeners to improve their structural efficiency. Through this technique, load-bearing capacity, ductility and resistance to shear of the column can be significantly upgraded [52].



Figure 2.2: Partial and full encasement of RC column using steel jacketing

The full or partial confinement provided by the steel jacketing are particularly effective in preventing brittle shear failure at beam-column joints, improving the lateral performance of RC columns, contributing to a more stable load-displacement response, such as higher drift capacity [53]. Experimental research demonstrates that latticed steel jackets are effective in rehabilitating shear-dominated columns by enhancing stiffness, strength, and energy dissipation capacity [54]. Furthermore, steel jacketing has proven beneficial for eccentrically loaded RC columns under monotonic loading conditions [55].

Steel jacketing technique gained its versatile use due to its ability to effectively confine core concrete, prevent spalling or cracking of the cover concrete, and its ease of implementation, quick installation and economic viability. However, the relatively high initial cost of steel materials may sometimes pose a constraint. Additionally, its most significant limitation is that steel is vulnerable to corrosion, especially in humid or coastal environments, which can severely restrict its long-term applicability. Also, it is worth noting that steel is very susceptible to temperature; as a result, its structural capacity drastically degrades when there is a fire outbreak.

2.3.3 Concrete Encasement

Concrete encasement is a retrofitting method in which a structural element is enveloped by a new layer of concrete, resulting in a composite section. Unlike reinforced concrete (RC) jacketing, this technique does not necessarily require additional reinforcement or wire mesh as shown in Figure 2.3. For RC elements, the surface is first prepared before high-strength concrete is cast into formwork and then compacted properly. Adequate curing is essential to achieve the desired mechanical strength of the newly applied layer.

This method is favoured for its simplicity and rapid execution, as it typically involves plain or lightly reinforced concrete. Concrete encasement enhances

ductility by confining the core element, thereby increasing its overall strength. [56]

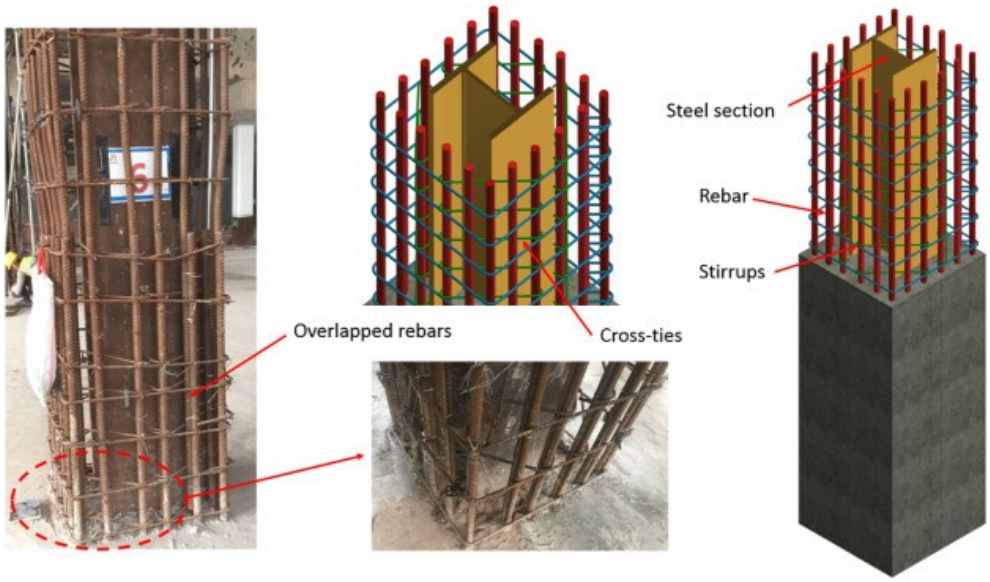


Figure 2.3: Concrete encased column

Previous literature reviews indicate that the use of special detailing in concrete-encased steel columns leads to remarkable improvements in ductility, as evident through increased inelastic displacement, ductility index and larger plastic hinge rotations [56]. Additionally, studies on the fire performance of concrete-encased concrete-filled steel tubes (CFST) demonstrate excellent fire resistance, as well as strength enhancement and substantial retention of post-fire residual strength [57]. Concrete encasement also contributes to better corrosion resistance as well as enhanced fire protection in steel columns, addressing some of the key limitations of steel structures addressed in the previous section.

However, the technique has its limitations. The strength gains achieved through plain concrete encasement are generally modest compared to those attained through RC jacketing, where reinforced detailing plays a critical role. There's also a potential risk of relative slip between the new encasement and the original column, which can compromise structural performance. In summary, concrete

encasement may be regarded as a simplified form of RC jacketing, best suited for low-intensity retrofitting applications.

2.3.4 External Binding

External binding refers to the retrofitting technique used primarily to strengthen RC elements such as columns by wrapping them externally using various materials such as fibre-reinforced polymer (FRP), including glass fibre-reinforced polymer (GFRP) and carbon fibre-reinforced polymer (CFRP). FRP wrapping has proven particularly effective in enhancing the shear strength, ductility, and overall load-bearing capacity of reinforced concrete (RC) columns. The shape of the column significantly influences the effectiveness of this technique. Circular columns tend to benefit the most from FRP wrapping due to the uniform confinement pressure that can be applied around their perimeter. In contrast, rectangular columns exhibit reduced efficiency, as confinement pressure is less uniformly distributed. Efforts to improve confinement in rectangular sections using additional post-wrapping measures are often considered aesthetically unappealing by stakeholders. Figure 2.4 illustrates different fiber-reinforced polymer (FRP) techniques.



a) **b)**

Figure 2.4: a) CFRP wrapping b) GFRP wrapping

Despite its structural advantages, FRP wrapping is associated with high material and labor costs and demands skilled workmanship for successful implementation. Moreover, FRP materials are sensitive to moisture during installation, which can affect bonding and long-term durability. Tensioned CFRP, in particular, has demonstrated unsatisfactory performance in some applications [59]. However, studies indicate that CFRP wrapping, especially on rectangular columns with generously rounded corners, can delay rupture and significantly increase ultimate load capacity [60]. Finite element analyses of GFRP-wrapped RC columns have shown improvements in both load-carrying capacity and ductility.

2.3.5 Shotcrete Jacketing

Shotcrete, commonly referred to as sprayed concrete, is a specialized form of concrete jacketing wherein concrete is pneumatically projected at high velocity onto a desired surface. This technique enables application over irregular geometries and hard-to-access areas without the need for conventional formwork. Owing to its rapid placement capabilities, shotcrete is particularly well-suited for fast-track construction projects and emergency structural repairs following disasters.



Figure 2.5: Shotcrete jacketing

However, this method is not without limitations. It is prone to issues such as inadequate bonding, the formation of internal voids, and surface cracking that are especially prevalent in humid or poorly ventilated environments.

2.4 FERROCEMENT AS RETROFITTING MATERIAL

Apart from conventional retrofitting methods, ferrocement has shown a promising potential for being adopted as an alternative in the field of structural strengthening, which is also the backbone of this current study. Sought for its efficiency, affordability, and ease of application, ferrocement offers a viable solution for the repair and retrofitting of reinforced concrete (RC) structures. Ferrocement is typically composed of:

I. A mixture of cement-sand mortar with a mix ratio ranging from 1:2 to 1:2.5 by weight, and a water–cement ratio of 0.4 to 0.6 [61].

II. Variable sizes of wire mesh, which are commonly woven steel wire, expanded metal, or welded wire fabric, as shown in Figure 2.6.

III. Admixtures, as needed, to enhance performance.

The key difference between the ferrocement and regular reinforced concrete mix is that it excludes coarse aggregates and deformed bars. Instead, the entire strength characteristics depend on the strength of the mortar and the steel mesh. Despite its thin section, typically 10–25 mm, it demonstrates impressive mechanical properties, including high tensile strength (30~50 MPa), enhanced crack resistance, significant energy absorption, and ductile behavior, even when applied to complex geometries [62].

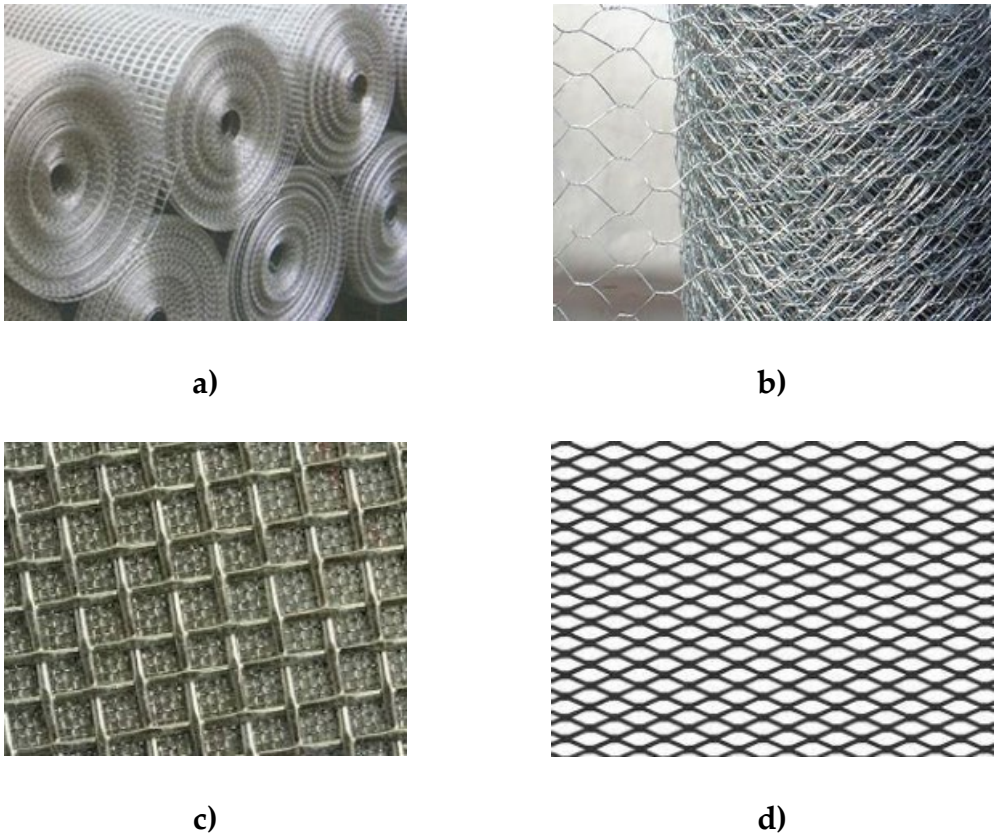


Figure 2.6: Types of wire mesh used in ferrocement applications: a) welded wire mesh; b) hexagonal wire mesh; c) woven wire mesh; d) expanded metal

Rigorous research has been conducted to evaluate the effectiveness of ferrocement in retrofitting applications. For instance, Al-Rawe et al. [63] investigated six scaled RC columns under biaxial loads and reported a 38.8% improvement in load capacity after ferrocement jacketing. Similarly, Islam and Kabir [64] tested 150 mm × 150 mm × 1500 mm RC columns under axial loading, finding a 58% increase in strength and a 78% increase in ductility when two layers of wire mesh were used versus one. Abdullah and Takiguchi [65] experimented with different ferrocement configurations, circular and square and observed substantial gains in ductility and confinement for all retrofitted specimens. Bari et al. [66] assessed fire-damaged RC columns and found that ferrocement jacketing helped recover lost strength. After a 46% reduction due to fire exposure, load capacity was restored by 23% with one layer of wire mesh and by 49% with two layers. Kaish et al. [67] explored three retrofitting strategies: square jacketing

with single-layer wire mesh and rounded corners, jacketing with shear keys at the center of each face, and jacketing with two additional layers of mesh at each corner. All three configurations effectively mitigated stress concentrations common in square columns, where the third technique performed best under concentric loading and the first option excelled under eccentric conditions. Figure 2.7 below shows different ferrocement retrofitting configurations.

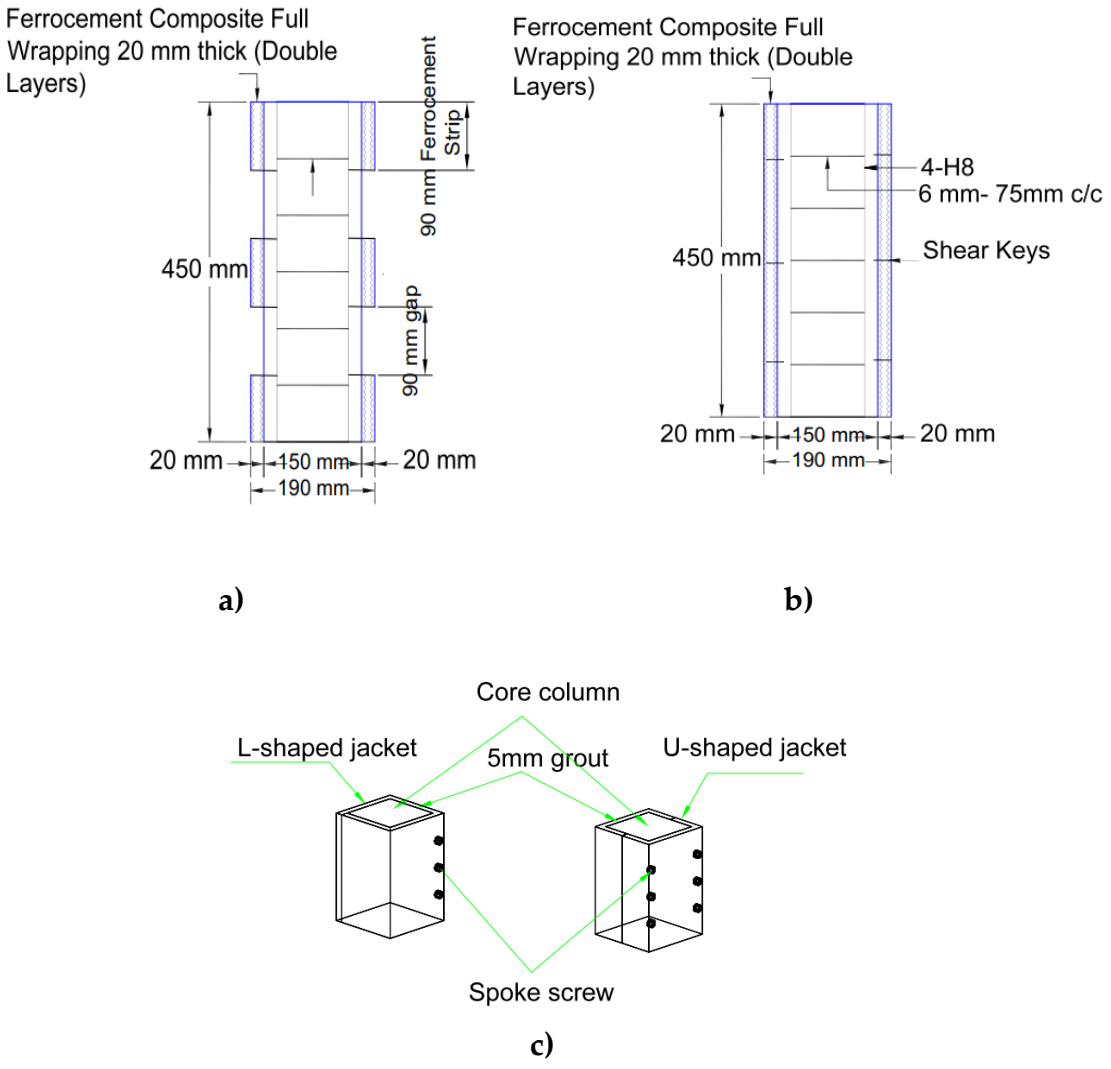


Figure 2.7: Different configurations of ferrocement retrofitting for RC columns: a) strip wrapping; b) full wrapping; c) L & U-shaped wrapping

Besides the retrofitting of RC columns, the use of ferrocement for improving the strength of RC beams has revealed some other interesting facts. For example, Dhanoa et al. [68] observed a 45% increase in the load-carrying capacity of RC

beams retrofitted with ferrocement, along with improved stiffness, as indicated by moment–rotation curves. Makki [69] introduced bolted connections between ferrocement layers and RC beams to prevent slippage, reporting an impressive increase of 69.8% to 175% in ultimate load capacity. Additionally, he noted that increasing the wire mesh diameter contributed positively to structural performance. Muhit et al. [70] tested 20 RC beams (203 mm × 203 mm × 1000 mm), using different layer configurations of mesh. Their results showed a 46% gain in ultimate shear capacity when a three-layer mesh was used. Notably, the retrofitted beams failed in flexure despite their original shear deficiency, demonstrating enhanced ductility, reduced crack widths, and greater ductility compared to un-retrofitted beams [71].

Additionally, Amala et al. [72] evaluated high-performance mortar mixes (1:1.5 ratio) for ferrocement jacketing of square columns, achieving an 8.85% increase in load capacity compared to control specimens. R et al. [73] compared full and strip wrapping methods, finding that full wrapping significantly outperformed the strip technique in both strength and deflection control. A notable innovation in this domain is the integration of prefabricated ferrocement jacketing systems. Kaish et al. [74] introduced a semi-automated retrofitting approach using prefabricated "L"- and "C"-shaped jackets. Their study highlighted the feasibility and advantages of prefabricated solutions, with the "C"-shaped jackets exhibiting superior load-carrying capacity. Additionally, "U"-shaped jackets were found particularly effective for retrofitting square columns.

2.5 RESEARCH GAPS AND OPPORTUNITIES

Although conventional retrofitting techniques, such as reinforced concrete and steel jacketing, FRP wrapping, and in-situ ferrocement applications, are widely recognized and extensively utilized, they often fall short in addressing the demands for economic feasibility, simplified construction procedures, and reduced execution time. In contrast, ferrocement jacketing can be a compelling

alternative, offering modularity, ease of installation, and the potential for rapid structural rehabilitation. However, in-situ fabrication of ferrocement sheet again draws attention towards the increased time as well as cost associated with it. In this regard, prefabrication or off-site fabrication ensures superior quality control, while its relatively low cost, minimal technical complexity, and enhanced structural performance, particularly in terms of axial load resistance, confinement strength, crack control, and ductility, make it a particularly attractive solution for retrofitting, especially in large-scale or post-disaster contexts.

Nonetheless, the broader implementation of prefabricated ferrocement systems is constrained by several critical research gaps. In the previous studies, most of the retrofitting technique performance was conducted on the undamaged column, which doesn't truly simulate the actual pre- and post-retrofitting condition. Although several approaches like horizontal strip, complete wrapping, L and U-shaped wrapping, etc., were explored along with axial capacity, ductility and failure mode as performance indices. But several other parameters, like stiffness and energy absorption of the column specimen, are important to evaluate the structure's resistance towards deformation and failure. Besides these, this relatively innovative retrofitting technique lacks the proper standard for effective retrofitting applications. Hence, the current technique of retrofitting with prefabricated ferrocement sheets (PFSs) lacks comprehensive comparisons with conventional methods, particularly regarding structural capacity, energy dissipation, and failure behaviour, etc. In this regard, the present study aims to address these gaps through experimental investigation with a suite of different concrete strengths and meshing configurations, thereby laying the foundation for adopting this technique as a cost-effective, time-efficient, and less technical retrofitting strategy, which is valuable for resource-constrained settings such as those in developing countries like Bangladesh.

2.6 SUMMARY OF LITERATURE REVIEW

After this comprehensive review of the existing retrofitting techniques, it is evident that ferrocement can be a significant potential for retrofitting applications. With inherent properties such as high tensile strength, crack resistance and its versatile use, ferrocement holds high hope for structural rehabilitation at the same time offering a faster, efficient and more adaptable solution. As highlighted in the literature review, the use of prefabricated ferrocement components in retrofitting remains a relatively underexplored area, indicating a clear need for further research. Additionally, prefabricated ferrocement sheets to retrofit and strengthen pre-cracked square RC columns is also a new aspect in this domain. This innovative research also examines the influence of the concrete compressive strength of the existing columns to evaluate the comparative effects of using single-layer versus double-layer wire mesh reinforcement within the prefabricated ferrocement elements.

Chapter 3 : METHODOLOGY

3.1 GENERAL

This chapter presents the methodology and experimental setup that have been implemented to investigate the retrofitting performance of the prefabricated ferrocement sheets (PFSs) on partially damaged reinforced concrete (RC) tied columns and compare it with un-retrofitted RC columns and partially damaged RC columns. A quantitative experimental approach was adopted, focusing on the structural behaviour of the retrofitted columns under axial loadings. The methodological flowchart of the entire study has been represented in the flowchart shown in Figure 3.1.

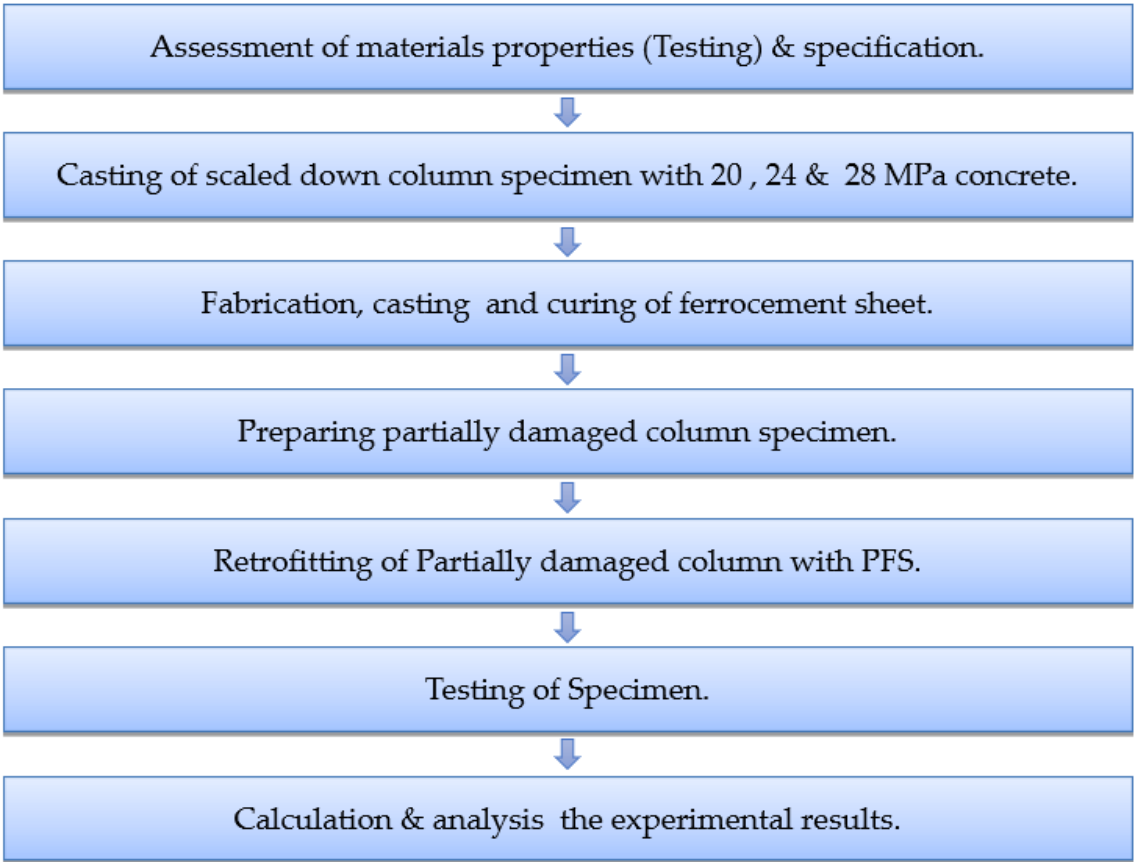


Figure 3.1 Schematic diagram of experimental details

3.2 EXPERIMENTAL PROGRAM

The experimental program includes investigating the properties of the materials used, like cement, fine aggregate, coarse aggregate, and the reinforcements, which are all determined through the ASTM standard test procedure.

3.2.1 Material properties

Table 3.1 below presents the material properties of the fine aggregate, coarse aggregate, cement reinforcement and water used in the concrete mix proportion. Subsequently, Table 3.2 illustrates the concrete mix design used for 20 MPa, 24 MPa and 28 MPa concrete.

Table 3.1: Material properties

Materials	Description	Properties	Test Standards
Fine Aggregate	Sylhet Sand	F.M. = 2.48	ASTM C33
Coarse Aggregate	Crushed Granite	ρ = 2.6–2.9 g/cm³	ASTM C33
Cement	OPC	$f_{c,\,avg}$ = 41 MPa	ASTM C109-16a
Reinforcement	Deformed MS 400W	f_y = 500 MPa	-
Concrete (28 days)	Mix design 1	f'_c = 20 MPa	ASTM C39
	Mix design 2	f'_c = 24 MPa	
	Mix design 3	f'_c = 28 MPa	
		E_c = 25 GPa	ASTM C469

Table 3.2: Weighted mix design for 20 MPa, 24 MPa and 28 MPa concrete

Material	Material Quantity (Kg)		
	Mix-1 (20 MPa)	**Mix-2 (24 MPa)**	**Mix-3 (28 MPa)**
Cement	350	390	420
Water	165	160	160
Fine Aggregate (Sand)	750	720	690
Coarse Aggregate	1130	1110	1120
Water / Cement Ratio	0.47	0.41	0.38

3.2.2 Test specimen

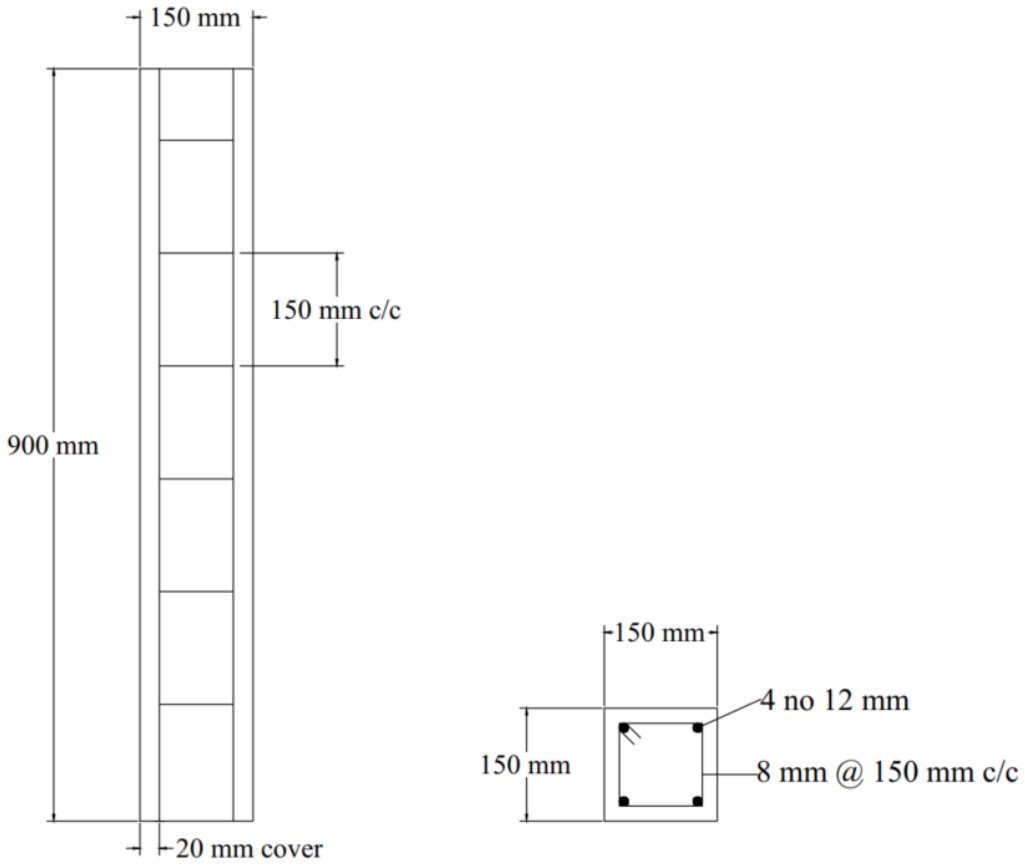
In this experiment, the test specimens are categorised into four groups: control reinforced concrete (RC) columns, partially damaged and retrofitted columns with single and double-layer mesh. The size of the column specimen groups is 150 × 150 × 900 mm. All the column groups have been prepared using three different concrete strengths of 20, 24 and 28 MPa, 4 no. 12 mm diameter longitudinal rebar with 8 mm diameter confinement bars at an equal interval of 150 mm c/c. Table 3.3 shows the column description.

Table 3.3: Description of column specimen

Group	Specimen	Column Description
Group 1-Control Column	CC1, CC2, CC3	Control column with 20, 24 and 28 MPa concrete at virgin condition (03)
Group 2-Partially Damaged Column	PDC1, PDC2, PDC3	Partially damaged column with 20, 24 and 28 MPa concrete (03)
Group 3-Single Layer Retrofitted Column	RCSL1(1,2), RCSL2(1,2), RCSL3(1,2)	20, 24 and 28 MPa RC column retrofitted with a prefabricated ferrocement sheet with a single-layer mesh. There are two specimens for each concrete strength group (06)
Group 4-Double Layer Retrofitted Column	RCDL1(1,2), RCDL2(1,2), RCDL3(1,2)	20, 24 and 28 MPa RC column retrofitted with a prefabricated ferrocement sheet with a double-layer mesh. There are two specimens for each concrete strength group (06)

3.2.2.1 RC control columns

Three columns with three different concrete strengths of 20, 24 and 28 MPa have been cast and designed as control columns in their pristine condition. The reinforcement details, casting arrangement and the casted RC tied columns are shown in Figures 3.1 and 3.2, respectively.



a) **b)**

Figure 3.2: Reinforcement details of RC tied column: a) longitudinal section; b) cross-section



a) **b)**

Figure 3.3: RC tied column: a) casting mould; b) specimen

3.2.2.2 Partially damaged columns

Partially damaged RC columns, three specimens with three different concrete strengths were cast. The pre-damage state of this specimen group was made by three 75 mm long and 75 mm deep holes on three faces of the column. These holes were created by inserting MS sheet spikes in the casting arrangement before casting and thereafter removing them when the concrete has gained a minimum strength. The arrangement of the partially damaged column is shown below in Figure 3.3.



a) **b)**

Figure 3.4: Partially damaged RC column: a) casting mould; b) specimen

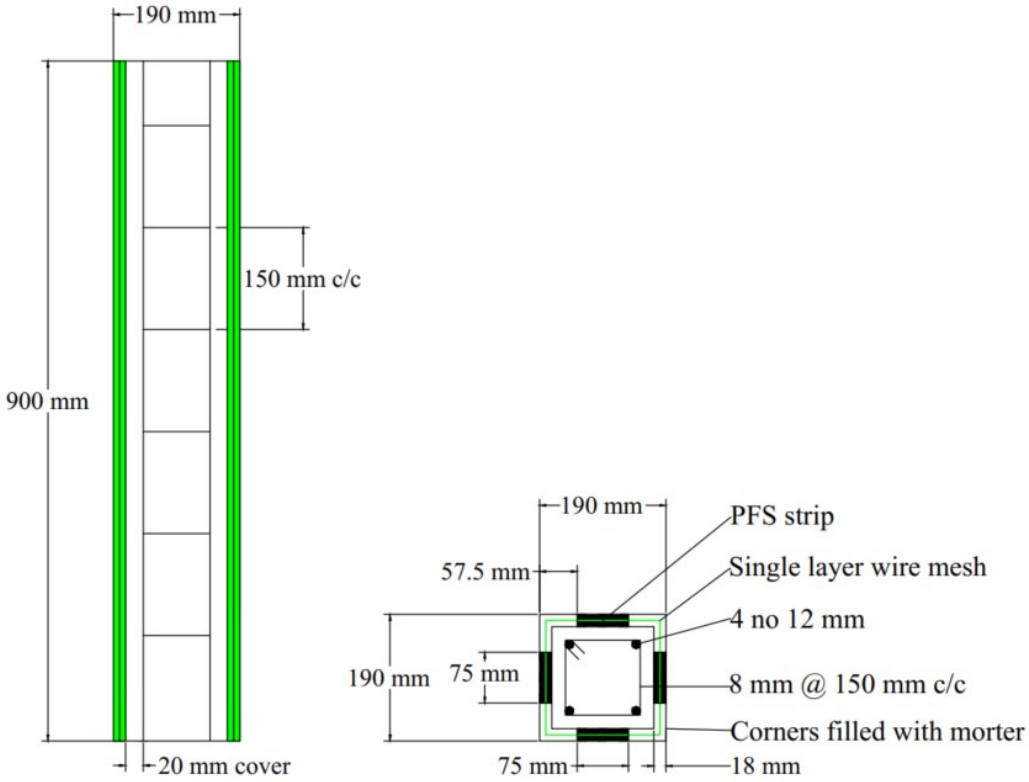
3.2.2.3 Retrofitted columns

The retrofitted columns are categorized into two groups based on the prefabricated ferrocement sheets (PFSs) with single-layer and double-layer wire mesh. These sheets consist of four 18 x 75 × 900 mm ferrocement strips.

Before wrapping the PFSs around the partially damaged column, the column surface was prepared for a smooth contact surface. The prefabricated ferrocement sheets were then wrapped around the partially damaged RC columns using high-strength epoxy adhesive on the contact surfaces of the PFSs and the column. Supplemental wire weaving techniques were introduced to attach the closing end of the ferrocement sheet in a tight manner at the corner of

the column. The wrapping techniques of PFSs around the partially damaged column are shown in detail in Figures 3.4 to 3.6. Finally, the gap between the ferrocement sheet in the PFS was filled with standard mortar mix.

a)



b)

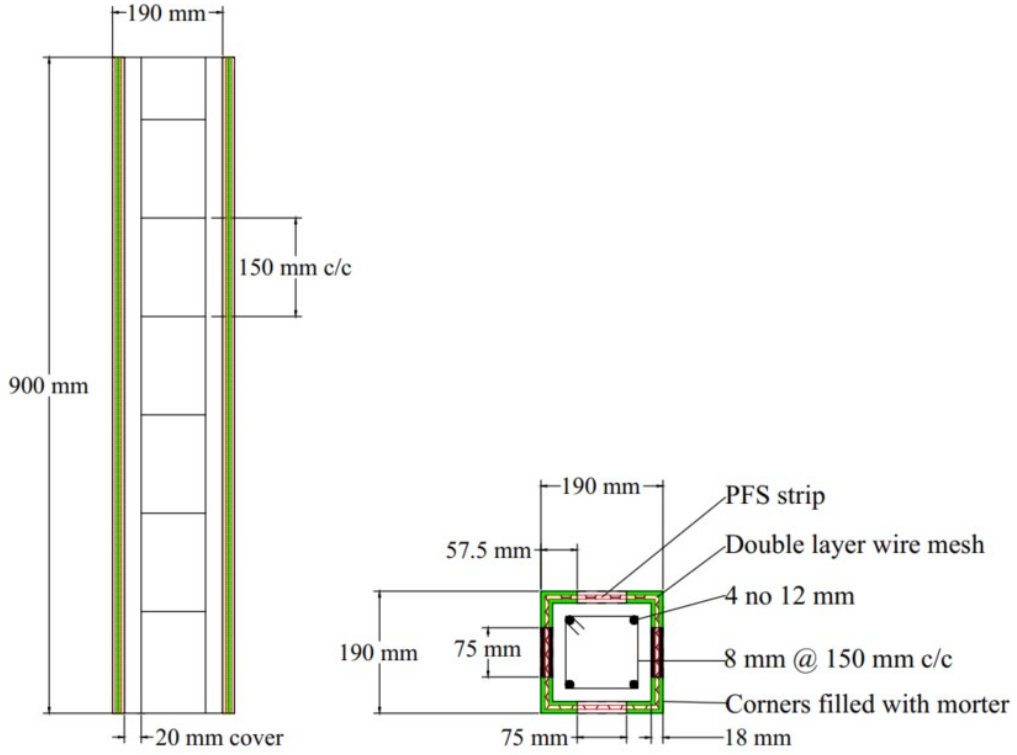


Figure 3.5: Details of prefabricated ferrocement sheet retrofitting techniques with: a) single-layer wire mesh; b) double-layer wire mesh

a)



b)



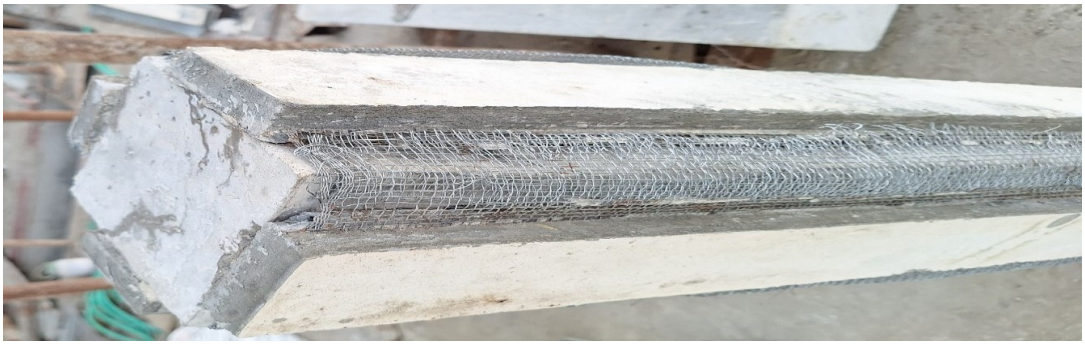
c)



Figure 3.6: Fabrication of ferrocement sheet: a) casting arrangement of PFS; b) during casting; c) after casting



a) b)



c)

Figure 3.7: Retrofitting arrangement of the partially damaged columns: a) cross-sectional view; b) casting arrangement; c) end joint of PFSs

3.3 TESTING PROGRAM

3.3.1 Experimental setup

This study involves experimental testing of reinforced concrete (RC) tied columns retrofitted with prefabricated ferrocement sheets (PFSs). All test specimens were scaled down to dimensions of 150 × 150 × 900 mm and reinforced with four 12 mm diameter 400 MPa longitudinal rebars and 8 mm diameter stirrups spaced at 150 mm centre to centre. For each specimen group, three concrete grades were used: 20 MPa, 24 MPa, and 28 MPa.

For the retrofitted column groups, prefabricated ferrocement sheets having two different meshing configurations: a single layer and a double layer and 22-gauge

galvanized wire mesh (mesh opening size: 4 mm × 4 mm) embedded in 18 mm thick cement mortar were applied. Prior to the retrofitting, the surface of each damaged column was thoroughly cleaned and roughened to improve the bonding between the column specimen and the PFS surface. Retrofitting was carried out using a high-strength epoxy adhesive, along with mechanical anchorage to ensure proper attachment and load transfer.

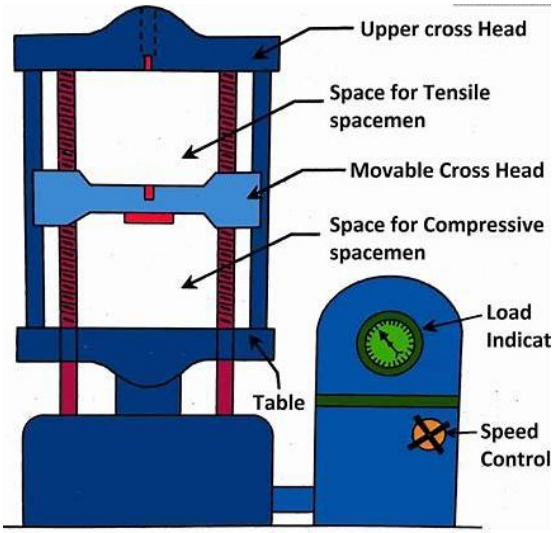


Figure 3.8: Diagrammatic representation of 1000 KN UTM



a) **b)**

Figure 3.9: Experimental setup of: a) column specimen; b) strain gauge

All the specimens have been cured for 28 days under water. Before the testing programme, the specimens are air-dried. The dimensions of the specimen were again measured to ensure that the specimen's dimensions had not changed after the casting and curing process. The machine used for testing the specimens is a Universal Testing Machine (UTM) with 1000 KN capacity, which is manually controlled as shown in Figure 3.5. At the very beginning, the top and bottom plate of the UTM is cleaned, and their verticality is checked to get good load concentration without obstacles. Then the specimen was installed on the UTM platform, with a rubber pad with an MS plate used to evenly distribute the applied load. A number of strain gauges were installed to record vertical and lateral displacements, as shown in Figure 3.9. Also, digital cameras were used to document deformation and failure patterns during the tests. The test was started after ensuring the position of the column and the proper arrangements of the system setup.

3.3.2 Load application

In this experimental study, a displacement-controlled loading method is applied for axial compression to the column specimens. Under mechanical testing, two main loading approaches can be used: load control and the displacement control method. However, load control is often unsuitable for situations where displacement may change significantly without a corresponding increase in load, particularly in post-peak or softening regions of the load-slip curve. Throughout the test, a load increment of 20 KN has been applied in the nonlinear/post-peak region until failure occurred. Each test typically lasted around 5 to 10 minutes.

3.3.3 Data recording

During the axial load testing of the scaled RC column specimens, all load data were recorded directly from the dial attached to the Universal Testing Machine (UTM). Whereas the vertical and lateral deformations of the specimen corresponding to the applied vertical loading were recorded from the dial gauges installed. All data were recorded manually during the experiment.

3.4 CALCULATION METHOD

3.4.1 Axial load

The ultimate axial capacity of the column can be obtained from the experimental result corresponding to the height record of axial load. The theoretical axial load capacity of the tied reinforced concrete (RC) column is given by,

$$P_n = 0.85 \times f'_c \times A_c + A_s \times f_y \quad (1)$$

$$\varphi P_n = 0.65 \times P_n \quad (2)$$

where,

P_n = Nominal axial load capacity

φP_n = Factored axial load capacity

f'_c = 28-day compressive strength of concrete

A_c = Area of concrete area = Gross area (A_g) – Area of steel (A_s)

f_y = Yield strength of steel

A_s = Area of Steel

3.4.2 Load and deformation

The force displacement curve, specifically axial load vs vertical deformation, can be plotted using the experimentally recorded data of applied load for the UTM and deformation for the vertical strain gauge. A load displacement curve can show ultimate load carrying capacity and associated displacement at different stress points: yield point, ultimate and fracture point of each RC column. Apart from that, the literal buckling strain can be obtained from the literal strain gauge installed during the experiments. Furthermore, the initial stiffness of the sample can be easily obtained from the tangent at the elastic portion of the load vs. displacement curve.

3.4.3 Stiffness

Stiffness is defined as the load required per unit displacement. It reflects the ability of a structural system to resist deformation both before and after the yielding of the material. In this study, only the initial stiffness of the RC column groups has been considered.

The initial stiffness represents the slope of the initial linear portion before the elastic limit forms the load vs deformation curve. It is a critical parameter in evaluating the elastic behaviour of the structural elements. Higher initial stiffness indicates a stronger resistance to displacement, which is particularly beneficial in minimizing immediate structural deformations during loading. Retrofitting techniques, especially those involving ferrocement layers, are effective in enhancing the initial stiffness of damaged or weak structural elements. The theoretical axial elastic stiffness of the concrete can be calculated using the simplified equation (3) shown below.

$$K = \frac{AE}{L} \tag{3}$$

where,

K = Stiffness

A = Gross cross-sectional area

E = Modulus of elasticity of concrete (or composite)

L = Member length

However, the effective stiffness of a reinforced member, such as an RC tied column or a prefabricated ferrocement sheet retrofitted column, depends on all the constituent materials: concrete, reinforcement and ferrocement. In such a case, the elastic stiffness of the RC column and retrofitted columns can be calculated using equation (4).

$$K = \frac{F_2 - F_1}{\Delta_2 - \Delta_1} \quad (4)$$

where,

F_1, F_2 = 10% and 20% of the ultimate axial load

Δ_2, Δ_1 = Displacement at 10% and 20% of the ultimate axial load

These values can be obtained from the load-deformation curve obtained from the experimental study.

3.4.4 Energy absorption

Energy absorption capacity of structural elements is a key indicator of their overall performance under applied loading. This parameter is determined from the area under the load-displacement curve, which encompasses both elastic and plastic deformation phases. The elastic energy represents the recoverable portion stored in the structure, whereas the plastic energy is dissipated permanently through inelastic deformation.

In this study, the strain energy of the experimental column specimens was calculated by integrating the area under the load-displacement curve using MATLAB (2018a) software. The area under the initial linear portion of the curve

was considered as the elastic energy, while the remaining area up to failure was taken as the plastic energy.

The significance of energy absorption lies in its ability to reflect the ductility, toughness, and resilience of structural members. A higher energy absorption capacity indicates that the column can sustain larger inelastic deformations before collapse, which is particularly important for post-yield performance. For damaged or retrofitted columns, an increase in energy absorption capacity demonstrates the effectiveness of the retrofitting technique in restoring and enhancing structural resilience. In this context, the prefabricated ferrocement sheet (PFS) retrofitting system contributes to improved energy dissipation, thereby enhancing both the strength and ductility of reinforced concrete (RC) columns under extreme loading conditions such as earthquakes or cyclic loads.

3.4.5 Ductility

The ductility of the reinforced column can be evaluated through the ductility index, which is a dimensionless parameter used to indicate the capacity of the structure to undergo elastic deformation without sudden failure. It is a critical parameter for the dynamic performance of the structural component. The ductility index is given by the equation (5) as follows.

$$DI = \frac{\Delta u}{\Delta y} \tag{5}$$

where,

DI = Ductility index

Δu = Displacement at peak load

Δy = Displacement at yield point

Ductility is a vital performance parameter for evaluating the resistance of RC columns against failure. Structures with higher ductility can absorb and dissipate greater amounts of energy with more pronounced deformation capacity, thereby

delaying failure and enhancing overall safety. Low ductility in a member generally indicates a premature brittle failure. However, as the ductility value improves, the member failure gradually shifts towards flexural failure. Thus, ductility evaluation provides a direct measure of the retrofitted column's resilience under extreme loading conditions.

3.4.6 Facture mode

The failure pattern of the reinforced concrete column, as well as the damaged and retrofitted column of different concrete strengths, is observed and compared from the experimental observation of the failure mode of all four column specimen groups to understand and interpret the failure criteria with the other parameters such as stiffness, ductility, etc., for control, partially damaged and retrofitted partially damaged column.

3.5 SUMMARY

The experimental study explores the effectiveness of prefabricated ferrocement sheets as a retrofitting solution for damaged reinforced (RC) columns. As a result, an eighteen (18) number of scaled-down column specimens, including four column groups: control column (CC), partially damaged column (PDC) and retrofitted column with prefabricated ferrocement sheet with single mesh and a double-layer mesh (RCSL & RCDL), have been tested. Also, three different concrete strengths of 20, 24, 28 MPa have been used for fabricating the columns in each specimen group. The experimental program involves a standardized test procedure for constituent materials of columns, fabrication of the column specimen and test under axial loading using a universal testing machine (UTM) with a capacity of 1000 KN in a manual test setting. For each specimen, five key parameters have been assessed: Ultimate axial load capacity, axial loading vs displacement, stiffness, ductility index and failure pattern.

Chapter 4 : RESULTS & DISCUSSIONS

4.1 GENERAL

In the subsequent sections, the obtained results from the experimental investigation on the performance of the prefabricated ferrocement sheet (PFS) to retrofit the RC column have been discussed thoroughly.

4.2 EXPERIMENTAL TEST RESULT

4.2.1 Load-displacement curve

After carrying out the test, the load displacement curve of Figures 4.1 to 4.3 illustrates that the axial load carrying capacity of all retrofitted column specimens has significantly improved in compared with the control and partially damaged column. On the other hand, the partially damaged column showed a lower load-carrying capacity than the control column, which is expected. The yield point of each of the control specimen groups is found to be in the range of 300~340 KN for concrete, all strength groups: 20, 24 and 28 MPa.

For the retrofitted column, the ultimate axial load capacity increased beyond the capacity of the control column with a similar increase in member deformation in both the elastic and inelastic range. For instance, the ultimate load-carrying capacity in the control column and retrofitted column with single-layer PFS from the 20 MPa strength group are 440 KN and 500 KN, respectively, while the corresponding plastic displacements are 5.1 mm and 7.85. This trend kept dominating as the column's concrete strength increased. Apart from that, among the retrofitting specimen groups, the prefabricated ferrocement sheet (PFS) with a double-layer wire mesh progressively performed better than the PFS with a single-layer mesh as the concrete strength is increased from 20 to 28 MPa.

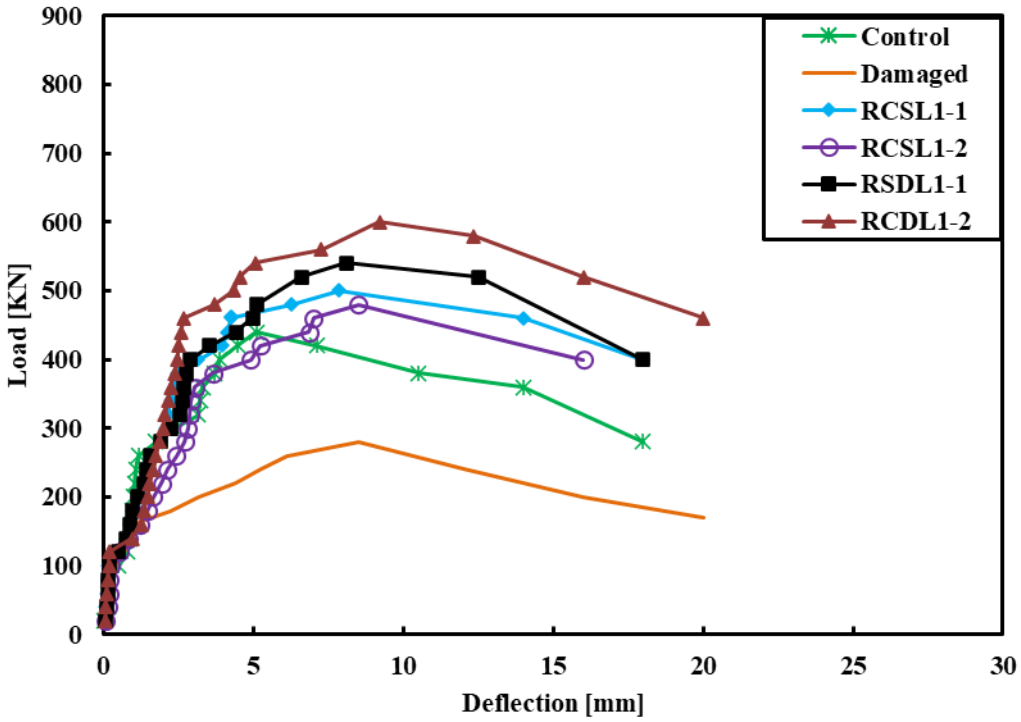


Figure 4.1: Axial load vs. average deflection (concrete 20 MPa

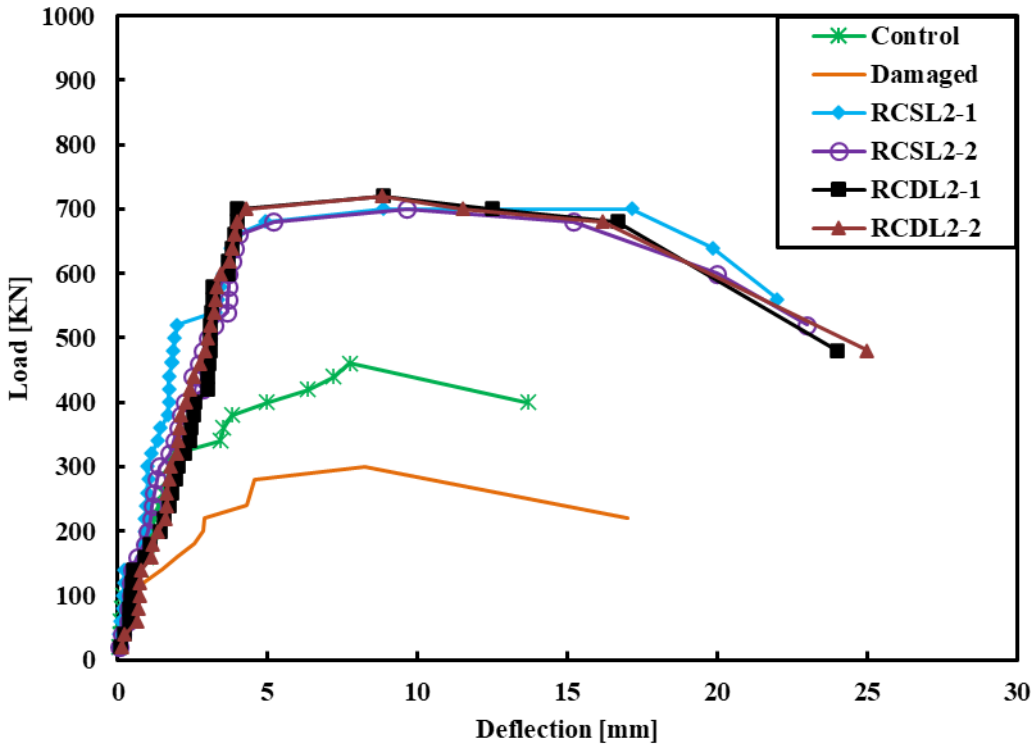


Figure 4.2: Axial load vs. average deflection (concrete 24 MPa)

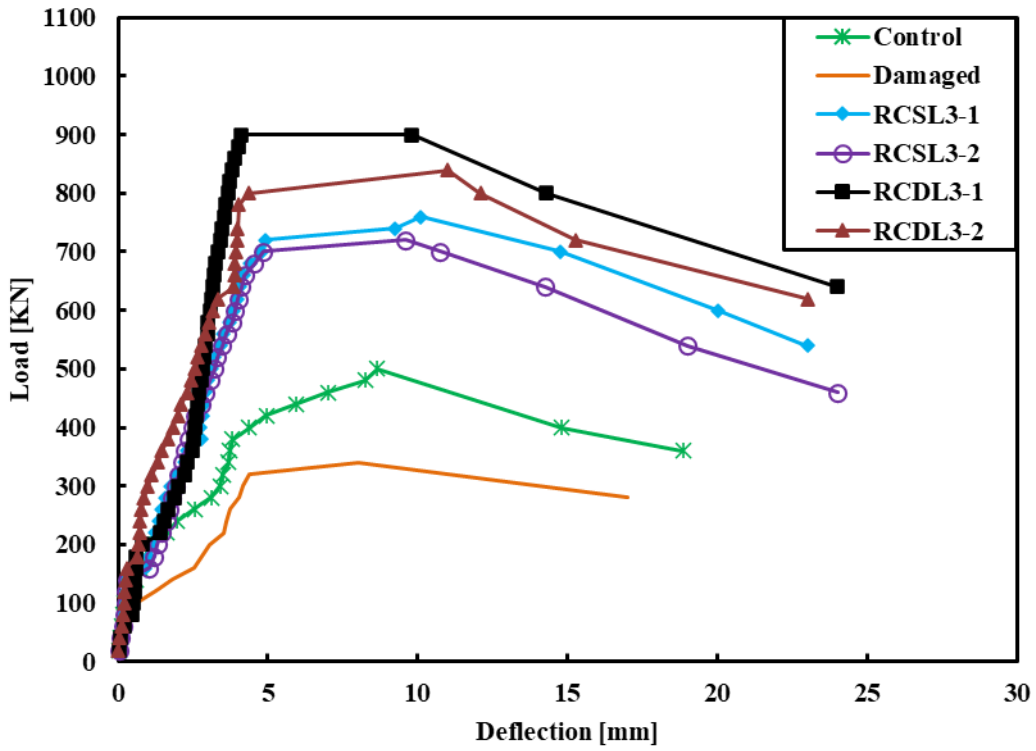


Figure 4.3: Axial load vs. average deflection (concrete 28 MPa)

4.2.2 Ultimate axial load capacity

The ultimate load capacity of each column specimen was measured through axial compression testing. The control specimen exhibited a load capacity of 440, 460 and 500 KN, respectively, for concrete with 20, 24 and 28 MPa strength, while the damaged specimen showed a significant average of 34% strength reduction for introducing a hole-like crack into each face of the damaged column group.

A significant improvement in axial load-carrying capacity can be observed for the current retrofitting techniques as the column's concrete strength increases. For example, PFS retrofitting with a double-layer mesh showed a remarkable improvement of up to 164% compared to the damaged RC column with concrete strength of 28 MPa, while the values are 140% and 114%, respectively, for column concrete strength of 24 and 20 MPa. This statement is equally true for PFS with single-layer mesh, as can be seen from Tables 4.1 to 4.3. The specimen with single-

layer ferrocement sheet jacketing reached a maximum of 500, 700 and 760 KN, while the double-layer retrofitted column achieved the highest capacity of 600, 720 and 900 KN, respectively, for concrete strength groups: 20, 24, 28 MPa. This indicates the effectiveness of prefabricated ferrocement sheets in restoring and enhancing the load-carrying performance of RC tied columns.

Table 4.1: Ultimate axial load capacity (concrete 20 MPa)

Specimen Group	**Ultimate Axial Capacity (KN)**	**% Capacity Improved over Damaged Column**
CC1	440	-
PDC1	280	-
RCSL1-1	500	78%
RCSL1-2	480	71%
RCDL1-1	540	93%
RCDL1-2	600	114%

Table 4.2: Ultimate axial load capacity (concrete 24 MPa)

Specimen Group	Ultimate Axial Capacity (KN)	% Capacity Improved over Damaged Column
CC2	460	-
PDC2	300	-
RCSL2-1	700	133%
RCSL2-2	700	133%
RCDL2-1	720	140%
RCDL2-2	720	140%

Table 4.3: Ultimate axial load capacity (concrete 28 MPa)

Specimen Group	Ultimate Axial Capacity (KN)	% Capacity Improved over Damaged Column
CC3	500	-
PDC3	340	-
RCSL3-1	760	123%
RCSL3-2	720	112%
RCDL3-1	900	164%
RCDL3-2	840	147%

4.2.2.1 Stress Effect in Concrete Specimens

The stress in the column specimens was obtained by dividing the ultimate axial load capacity by the corresponding cross-sectional area of the column. Since all specimens had a uniform cross-section of 150 × 150 mm (22,500 mm^2), the variation in stress directly reflects the strength enhancement due to concrete grade and retrofitting configuration. For 20 MPa concrete, the average ultimate stress values were close to the design compressive strength, confirming the adequacy of the mix design. However, partially damaged columns exhibited a significant reduction in stress capacity (12.44 MPa), while retrofitted specimens with prefabricated ferrocement sheets (PFS) restored up to 11% and 34% respectively, as shown in Table 4.4.

In the case of 24 MPa concrete, stress values increased proportionally, showing improved load-carrying capacity as shown in Table 4.5. Retrofitted specimens demonstrated much higher stress capacities compared to both control and damaged specimens, indicating the positive effect of confinement and strengthening provided by PFS.

For 28 MPa concrete, the highest stress values were achieved. Retrofitted columns, particularly those with double-layer ferrocement jacketing, developed stresses well above the design strength, which shows an improvement of up to 39% and 65% compared to partially damaged specimens. Table 4.6 shows the ultimate stress capacity of the column specimen with 28 MPa concrete. This highlights that the effectiveness of the retrofitting system becomes more pronounced with higher concrete grades, allowing the column to not only recover from damage but also to sustain greater axial loads.

The stress analysis across different concrete grades it is evident that the introduction of cracks in a partially damaged column significantly reduced the effective stress of the damaged specimen. When the PFS retrofitting was applied on these partially damaged columns, it showed a notable improvement in

restoring the capacity of these damaged columns through their enhanced stress, especially in the case of PFS with double-layer wire mesh. Furthermore, the use of a higher concrete grade contributes to the capacity enhancement of the retrofitting techniques. This demonstrates that stress evaluation is a critical measure of the efficiency of retrofitting in RC columns.

Table 4.4: Ultimate stress capacity (concrete 20 MPa)

Specimen Group	Ultimate Axial Capacity (KN)	Area of Specimen (mm^2)	Stress (MPa)	% Capacity Improved over Damaged Column
CC1	440	22500	19.56	-
PDC1	280	22500	12.44	-
RCSL1-1	500	36100	13.85	11%
RCSL1-2	480	36100	13.30	7%
RCDL1-1	540	36100	14.96	20%
RCDL1-2	600	36100	16.62	34%

Table 4.5: Ultimate stress capacity (concrete 24 MPa)

Specimen Group	Ultimate Axial Capacity (KN)	Area of Specimen (mm^2)	Stress (MPa)	% Capacity Improved over Damaged Column
CC2	460	22500	20.44	-
PDC2	300	22500	13.33	-
RCSL2-1	700	36100	19.39	45%
RCSL2-2	700	36100	19.39	45%
RCDL2-1	720	36100	19.94	50%
RCDL2-2	720	36100	19.94	50%

Table 4.6: Ultimate stress capacity (concrete 28 MPa)

Specimen Group	Ultimate Axial Capacity (KN)	Area of Specimen (mm2)	Stress (MPa)	% Capacity Improved over Damaged Column
CC3	500	22500	22.22	-
PDC3	340	22500	15.11	-
RCSL3-1	760	36100	21.05	39%
RCSL3-2	720	36100	19.94	32%
RCDL3-1	900	36100	24.93	65%
RCDL3-2	840	36100	23.27	54%

4.2.3 Stiffness of column

The stiffness of the retrofitted columns across different concrete strengths reveals a consistent enhancement over both the control column (CC) and partially damaged column (PDC). The initial stiffness of each column group with three different concrete strengths is shown in Tables 4.7~4.9. For 20 MPa concrete, the control column had a stiffness of 488.88 KN/mm, slightly below the theoretical value (554.83 KN/mm), while the PDC1 specimen dropped to 333.33 KN/mm. After the retrofitting, the damaged columns recovered their stiffness, with RCSL1 columns achieving up to 638.89 KN/mm, which indicates an improvement of 76~91%. Similarly, for RCDL1, this improvement was found to be about 77~80%. This confirms that both single and double-layer prefabricated ferrocement sheet wrapping effectively counteract stiffness degradation due to partial damage, bringing performance even above the theoretical baseline.

A similar trend is observed for 24 MPa columns. While the CC2 specimen exhibited a stiffness of 621.62 KN/mm, just above the theoretical 600 KN/mm, the PDC2 specimen showed a notable reduction to 461.54 KN/mm. On the contrary,

retrofitted columns, especially RCDL2-2, reached a stiffness as high as 660.55 KN/mm, which indicates up to 43% improvement over the damaged column. Interestingly, even single-layer retrofitting in this group restored or exceeded the theoretical stiffness, highlighting the robustness of the technique even in medium-strength concrete columns.

In the case of concrete strength of 28 MPa, the control specimen (CC3) exhibited a stiffness of 625 KN/mm, whereas the PDC3 declined to 507.46 KN/mm. Retrofitted columns again outperformed the control, with RCSL3 and RCDL3 specimens reaching values up to 633.33~712.87 KN/mm with an increase of 25~40% and simultaneously 705.00~782.61 KN/mm, representing an improvement of 39~54% respectively, indicating that even single-layer retrofitting can match or exceed the performance of double-layer solutions when applied for higher concrete strength. These results collectively demonstrate that prefabricated ferrocement jacketing not only restores strength but also significantly enhances the initial stiffness, leading to higher resistance towards cracking and structural stability.

Table 4.7: Initial stiffness of specimen groups (concrete 20 MPa)

Specimen Group	**P_{max} (KN)**	**10% P_{max}, F1 (KN)**	**20% P_{max}, F2 (KN)**	**10% δ_{max}, Δ1 (mm)**	**20% δ_{max}, Δ2 (mm)**	**Stiffness, K (KN/mm)**	**% Improved**
CC1	440	44	88	0.1300	0.2200	488.88	-
PDC1	280	28	56	0.0590	0.143	333.33	-
RCSL1-1	500	50	100	0.0800	0.1650	588.24	76%
RCSL1-2	480	48	92	0.1460	0.2180	638.89	91%
RCDL1-1	540	54	108	0.1295	0.221	590.16	77%
RCDL1-2	600	60	120	0.0850	0.2000	600.00	80%

Table 4.8: Initial stiffness of specimen groups (concrete 24 MPa)

Specimen Group	P_{max} (KN)	10% P_{max}, F1 (KN)	20% P_{max}, F2 (KN)	10% δ_{max}, Δ1 (mm)	20% δ_{max}, Δ2 (mm)	Stiffness, K (KN/mm)	% Improved
CC2	460	46	92	0.086	0.16	621.62	-
PDC2	300	30	60	0.13	0.195	461.54	-
RCSL2-1	700	70	140	0.125	0.235	636.36	38%
RCSL2-2	700	70	140	0.365	0.475	636.36	38%
RCDL2-1	720	72	144	0.403	0.515	642.86	39%
RCDL2-2	720	72	144	0.682	0.791	660.55	43%

Table 4.9: Initial stiffness of specimen groups (concrete 28 MPa)

Specimen Group	P_{max} (KN)	10% P_{max}, F1 (KN)	20% P_{max}, F2 (KN)	10% δ_{max}, Δ1 (mm)	20% δ_{max}, Δ2 (mm)	Stiffness, K (KN/mm)	% Improved
CC3	500	50	100	0.115	0.195	625.00	-
PDC3	340	34	68	0.186	0.253	507.46	-
RCSL3-1	760	76	152	0.173	0.293	633.33	25%
RCSL3-2	720	72	144	0.198	0.299	712.87	40%
RCDL3-1	900	90	180	0.500	0.615	782.61	54%
RCDL3-2	840	84	168	0.178	0.297	705.88	39%

4.2.4 Energy absorption

The experimental results across three different concrete strengths (20 MPa, 24 MPa, and 28 MPa) for columns demonstrate a significant improvement in the structural performance of retrofitted columns compared to control and partially damaged specimens, as illustrated in Tables 4.10-4.12. For the 20 MPa column specimen, although the control column (CC1) showed an energy absorption of 6295.5 KN/mm, the retrofitted specimens displayed a remarkable improvement. Particularly, the double-layer retrofitted columns (RCDL1-1 and RCDL1-2) reached a total energy absorption of over 8010.4 KN/mm and 9923.5 KN/mm, representing an 85~129% increase in energy absorption. The single-layer retrofitted columns also showed noticeable enhancement, with an energy absorption increase of around 76% compared to the PDC1 specimen. This indicates that PRF retrofitting not only restores strength but also significantly boosts the ductile performance of deteriorated columns.

For columns with higher concrete strengths, the effectiveness of the retrofitting system becomes even more evident. For the 24 MPa concrete, a similar trend of increased energy absorption was observed, with values of 146% and 166% for single-layer and double-layer wire mesh, respectively. The trend continues in the 28 MPa group, where the RCDL3-1 specimen achieved the highest energy absorption (17537 KN/mm), a 152% increase compared to the pre-damaged column. This suggests that the prefabricated ferrocement jacketing system, especially in its double-layer configuration, is highly effective in enhancing both the strength and ductility of RC columns. Also, as concrete strength increases, the retrofitting system exhibits a compounding effect, indicating its suitability for high-strength applications where both load resistance and energy dissipation are critical.

Overall, from the perspective of elastic and plastic energy absorbed, the resulting value from the retrofitted column compared to the partially damaged column

indicates enhanced capacity and resistance against failure through a demonstration of significantly higher energy absorption in the elastic range as well as in the plastic range.

Table 4.10: Stain energy of specimen groups (concrete 20 MPa)

Specimen Group	Elastic Energy (KN/mm)	Plastic Energy (KN/mm)	Total Energy Absorbed, E (KN/mm)	% Increase
CC1	476.00	5819.50	6295.50	-
PDC1	746.25	3586.05	4332.30	-
RCSL1-1	784.95	6855.05	7640.00	76%
RCSL1-2	804.40	5391.80	6196.20	43%
RCDL1-1	910.00	7100.40	8010.40	85%
RCDL1-2	1058.10	8865.40	9923.50	129%

Table 4.11: Stain energy of specimen groups (concrete 24 MPa)

Specimen Group	Elastic Energy (KN/mm)	Plastic Energy (KN/mm)	Total Energy Absorbed, E (KN/mm)	% Increase
CC2	841.05	6061.35	6902.40	-
PDC2	705.60	4932.40	5638.00	-
RCSL2-1	1203.10	12677.90	13881.00	146%
RCSL2-2	936.80	12904.20	13841.00	145%
RCDL2-1	764.00	13678.00	14442.00	156%
RCDL2-2	863.50	14123.50	14987.00	166%

Table 4.12: Stain energy of specimen groups (concrete 28 MPa)

Specimen Group	Elastic Energy (KN/mm)	Plastic Energy (KN/mm)	Total Energy Absorbed, E (KN/mm)	% Increase
CC3	807.00	6495.00	7302.60	-
PDC3	529.00	6422.40	6951.40	-
RCSL3-1	982.70	13275.30	14258.00	105%
RCSL3-2	1074.80	12624.20	13699.00	97%
RCDL3-1	972.95	16564.05	17537.00	152%
RCDL3-2	1557.90	14321.10	15879.00	128%

4.2.5 Ductility

The ductility index (DI), defined as the ratio of ultimate displacement to yield displacement, is a critical parameter in assessing the deformation capacity and energy dissipation characteristics of reinforced concrete columns. In this experimental study, the DI values across the three concrete strength levels: 20, 24 and 28 MPa, have revealed some important insights into the behaviour of control column (CC), partially damaged concrete (PDC), and retrofitted specimens using single-layer (RCSL) and double-layer (RCDL) prefabricated ferrocement sheet retrofitting technique.

For 20 MPa concrete, the control column (CC1) has exhibited a DI of 2.15, which has dropped to 1.93 in the partially damaged column (PDC1), reflecting the adverse impact of damage on ductility. The current retrofitting technique has significantly improved the ductility, with RCSL1 specimens reaching DI values of up to 2.49, and RCDL1 specimens achieving a DI of 2.50, indicating a clear enhancement in deformation capacity due to ferrocement confinement.

Additionally, these consistent trends were observed with a slightly enhanced response for the higher concrete group: 24 and 28 MPa. Likely before, partially damaged specimens showed the lowest ductility, regardless of concrete strength. Among the retrofitting column groups, single-layer ferrocement retrofitting

(RCSL) led to moderate increases in ductility, while double-layer ferrocement retrofitting (RCDL) consistently yielded the highest ductility indices compared to the un-retrofitted group, demonstrating an enhanced energy dissipation and deformation capacity under axial loading. Overall, a higher ductility value for the retrofitted column indicates that PFS retrofitting can absorb and dissipate greater amounts of energy with more pronounced deformation capacity, thereby delaying failure and enhancing overall safety.

Table 4.13: Ductility index of specimen groups (concrete 20 MPa)

Specimen Group	**Ultimate Load, P_{max} (KN)**	**Ultimate Displacement, Δu (mm)**	**Yield Displacement, Δy (mm)**	**Ductility Index (DI) = Δu/Δy**
CC1	440	5.10	2.37	2.15
PDC1	280	8.50	4.40	1.93
RCSL1-1	500	7.85	3.15	2.49
RCSL1-2	480	8.50	3.65	2.33
RCDL1-1	540	8.10	3.53	2.30
RCDL1-2	600	9.20	3.68	2.50

Table 4.14: Ductility index of specimen groups (concrete 24 MPa)

Specimen Group	Ultimate Load, P_{max} (KN)	Ultimate Displacement, Δu (mm)	Yield Displacement, Δy (mm)	Ductility Index (DI) = Δu/Δy
CC2	460	7.75	3.42	2.27
PDC2	300	8.25	4.30	1.92
RCSL2-1	700	8.85	3.28	2.70
RCSL2-2	700	9.65	3.21	3.01
RCDL2-1	720	8.85	3.16	2.80
RCDL2-2	720	8.83	3.26	2.71

Table 4.15: Ductility index of specimen groups (concrete 28 MPa)

Specimen Group	Ultimate Load, P_{max} (KN)	Ultimate Displacement, Δu (mm)	Yield Displacement, Δy (mm)	Ductility Index (DI) = Δu/Δy
CC3	500	8.65	3.68	2.35
PDC3	340	8.00	3.73	2.14
RCSL3-1	760	10.1	3.43	2.94
RCSL3-2	720	9.58	3.63	2.64
RCDL3-1	900	9.80	3.27	3.00
RCDL3-2	840	11.00	3.85	2.86

4.2.6 Failure pattern

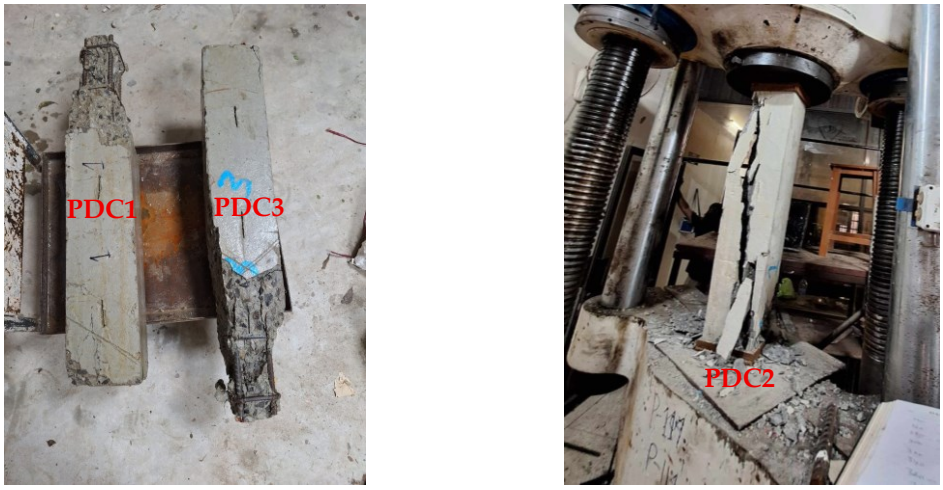
This study investigated the effectiveness of prefabricated ferrocement sheets for retrofitting of partially damaged reinforced concrete (RC) tied columns. Failure patterns of the different specimens are examined carefully during the experiment, as shown in Figure 4.4.

As can be seen from Figures 4.4(a) to (c), the control specimen exhibited a brittle failure mode characterized by crushing of cover concrete with shear failure at the end of the column for each concrete strength of 20 MPa, 24 MPa and 28 MPa. Concrete cover got crushed during this failure. The collapse occurred abruptly with minimal warning, underscoring the vulnerability of columns to catastrophic brittle failure under axial load. In contrast, the partially damaged column showed an even more brittle response due to pre-existing cracks. It developed a similar shear failure mode for the partially damaged column with 20 MPa and 28 MPa concrete, just like the control column at a relatively early stage with larger cracks, as shown in Figure 4.5(a). However, the specimen with 24 MPa concrete ended up showing a sudden vertical splitting crack, demonstrating the significant reduction in load-carrying capacity and ductility when columns are partially damaged. This is shown in Figure 4.5(b).



a) **b)** **c)**

Figure 4.4: Failure mode of Control specimen with different concrete strength



a) **b)**

Figure 4.5: Failure mode of the partially damaged column

For the retrofitting column groups, a noticeable transformation in failure behaviour is observed. The application of prefabricated ferrocement sheet wrapping changed the failure mode from brittle to semi-ductile or ductile failure, depending on the number of wire meshes applied. In the case of the ferrocement sheet with a single-layer mesh, it provided effective lateral confinement. Specimens in this category developed finer, more evenly distributed cracks in both vertical and diagonal directions. The single-layer PFS retrofitting delayed the onset of critical cracking and enabled a more controlled failure. As a result, failure of the column shifted from longitudinal splitting to diagonal failure of the ferrocement strip in the case of RCSL with 20 MPa, 24 MPa and 28 MPa, as shown in Figures 4.6(a) to (e), respectively. Furthermore, tearing of the wire mesh with debonding of PFS happened in the case of the retrofitted column, as shown in Figure 4.6 (f)

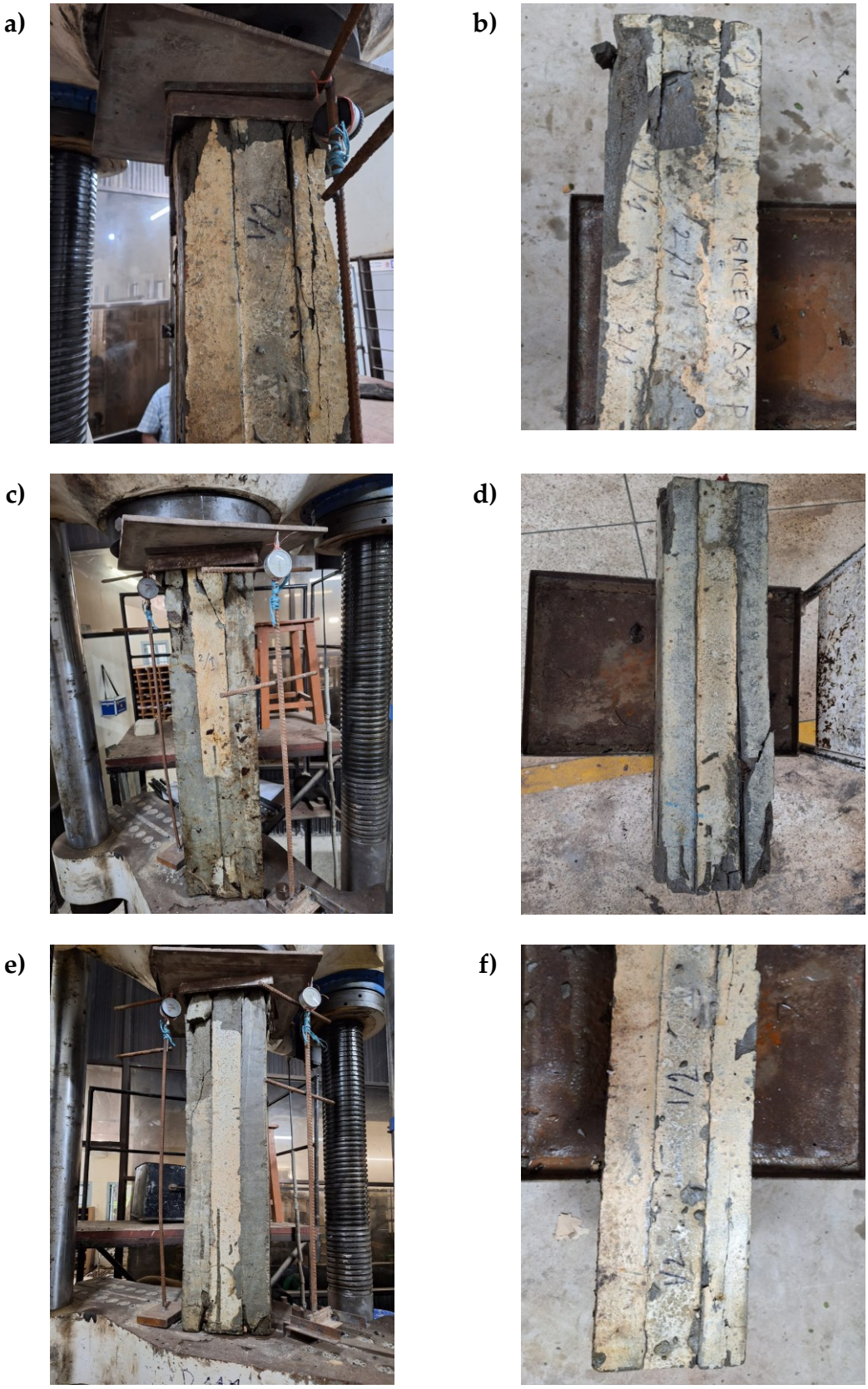


Figure 4.6: Failure mode of RCSL for different concrete strengths

However, compared to the single-layer mesh, the double-layer PFS demonstrated the most favourable structural response. These specimens exhibited a fully ductile failure mode, characterized by gradual stiffness degradation and the development of widespread, narrow diagonal cracks. Due to the confinement effect of the double-layer mesh within the ferrocement sheet, they have withstood significantly higher axial loads and have accommodated larger deformations before failure. From Figure 4.7(a, b, c and d), it is seen that the failure mode is concentrated toward the corners of the column, leading to the tensile failure of the cover concrete for each specimen. Crushing & debonding failure is also seen to occur at the top end of the PFS in RCDL3 (e, f). Furthermore, joint failure and followed by crushing of the concrete cover is notable in RCDL, indicating that the mesh of PFS has provided confinement strength to the cover concrete before it fails just after the failure of PFS joints.

a)



b)



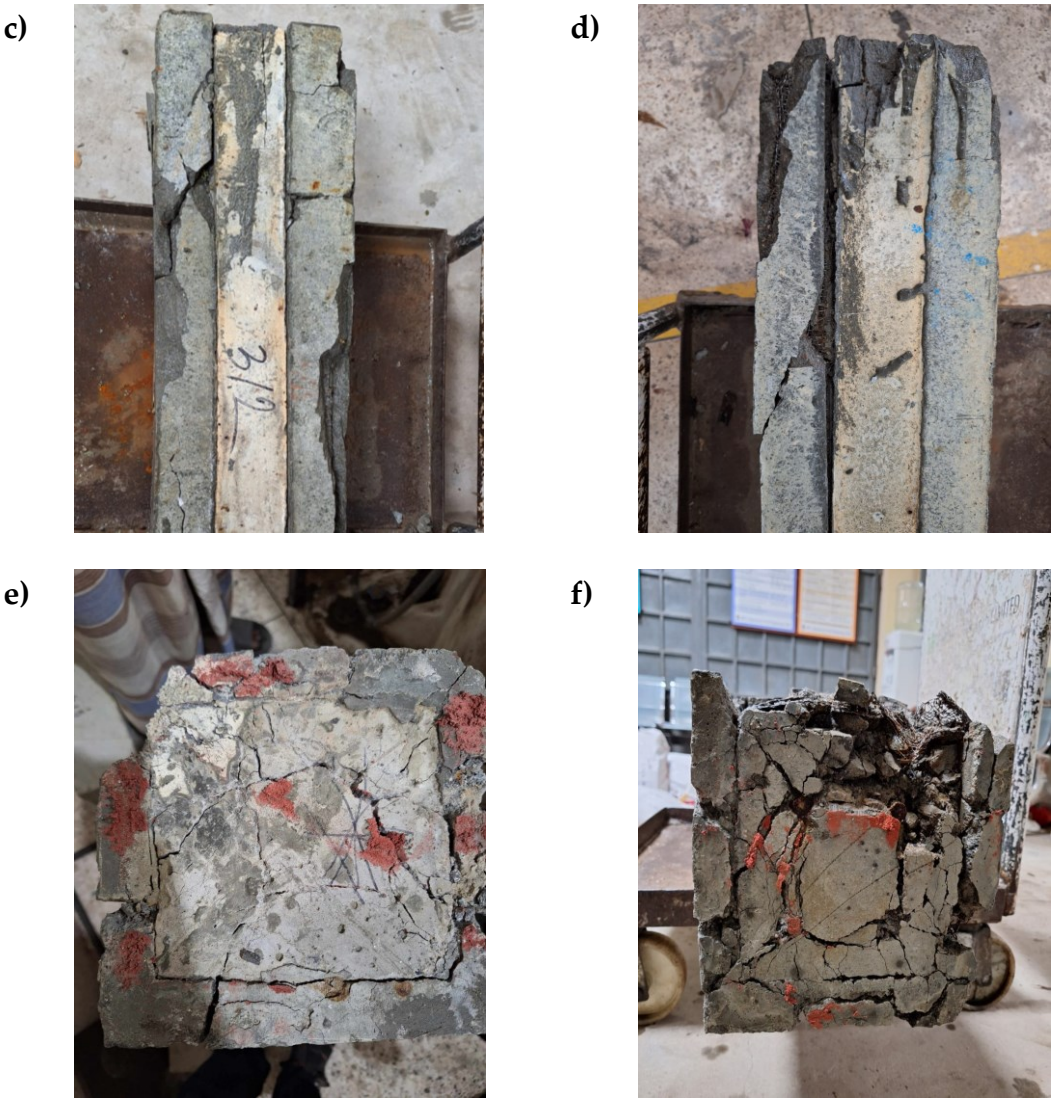


Figure 4.7: Failure mode of retrofitted columns with prefabricated ferrocement sheet with double-layer mesh for different concrete grades

4.2.7 Comparative Statement

Compared to earlier studies, the prefabricated ferrocement sheet retrofitting proposed in this research achieved substantially greater improvements across all performance parameters. Specifically, the axial capacity increase of 164% far surpasses the strip and full retrofitting in study-1 (31.4%) and L and U-shaped retrofitting in study-2 (23%). Besides, the ductility of the retrofitted column in the current study is comparable with that in the previous study. Additionally, this study uniquely quantified initial stiffness recovery and

energy absorption, demonstrating the holistic effectiveness of PFS retrofitting in restoring and enhancing the performance of partially damaged RC tied columns. A summarized result of the current study and studies made by other researchers is presented in Table 4.16.

Table 4.16: Comparative performance summary of PFS

Parameter	**Current Study**	**Study 1** [73]	**Study 2** [75]
Column Size (mm)	150 × 150 × 900	150 × 150 × 450	150 × 150 × 300
Concrete Grade (MPa)	20, 24 and 28	30	Low-strength concrete
Retrofitting Method	Prefabricated ferrocement sheet (Single- & Double-layer mesh)	In-situ ferrocement horizontal strip and complete wrapping (Single, Double, Triple layer)	Prefabricated "L" & "U" jackets
Max. Axial Capacity (KN)	RCSL1: 480~500 RCSL2: 700 RCSL3: 720~760 RCDL1: 540~600 RCDL2: 720 RCDL3: 840~900	Horizontal Strip: 485~574 Full wrapping : 520~738	L-shape: 400 U-shape: 420
Max. Axial Capacity Improvement	164% (Double-layer)123% (Single-layer)	31.4% (Double-layer)15.3% (Single-layer)	23% (U-jacket)
Ductility Index	RCSL1: 2.33~2.49 RCSL2: 2.70~3.01 RCSL3: 2.94~3.00 RCDL1: 2.30~2.50 RCDL2: 2.80~2.71 RCDL3: 3.00~2.86	Horizontal Strip: 2.5~3.1 Full wrapping : 2.2~2.4	L-shape: 3.5 U-shape: 4.6
Initial Stiffness Recovery	Up to 54%	Not reported	Not reported
Energy Absorption Improvement	Up to 152%	Not reported	Not reported
Failure Mode	Shifted from brittle splitting → ductile diagonal cracking	Crushing Failure	Corner joint failure

Chapter 5 : CONCLUSIONS

5.1 CONCLUSION

This study investigates a sustainable retrofitting solution for partially damaged reinforced concrete (RC) tied columns using prefabricated ferrocement sheets (PFSs). The objective stems from the urgent need for an efficient, reliable, low-cost, and high-performance retrofitting technique for deteriorated structural elements, especially in disaster-prone and economically constrained regions like Bangladesh, where construction quality, material degradation, and seismic vulnerability pose serious challenges to structural safety.

i. Single-layer PFS increased axial load capacity by 78%–133%, while double-layer PFS achieved up to 114%–164%, effectively restoring and enhancing column strength.

ii. Initial stiffness of Single-layer PFS improved by 25–91%, whereas double-layer PFS provided a recovery of 39–80%, surpassing even the control column values. This indicates that the retrofitting method not only repaired the damage but also enhanced the initial rigidity of the columns.

iii. Single-layer PFS boosted energy absorption by 146%, while double-layer PFS achieved up to 166%, significantly enhancing the resistance of columns to severe loading and demonstrating better resilience under extreme events.

iv. Ductility index increased from 2.14 (damaged) up to 2.94 (single-layer) and 3.00 (double-layer) for 28 MPa concrete, showing improved deformation and energy dissipation capacity & proving PFS wrapping delayed collapse and made the failure more ductile and safer.

v. Single-layer PFS retrofitted columns showed reduced brittle failure, while double-layer PFS provided superior confinement with delayed cracking and ductile, stable post-yield behaviour as visible from the inspection of the failure mode.

vi. Prefabricated modular jacketing systems save the time of assembly and curing process for ferrocement sheet, offering faster installation, improved quality control, and a cost-effective alternative to traditional in-situ ferrocement retrofitting.

vii. Conducted tests on realistically simulated damaged tied RC columns, providing practical insights into post-disaster rehabilitation and addressing a critical gap in existing research.

viii. Exploring the performance of PFS retrofitting with three commonly used concrete grades (20, 24 and 28 MPa) established a clear performance hierarchy between single-layer and double-layer PFS retrofitting, giving engineers practical design guidance based on required strength, stiffness, and ductility recovery.

Overall, the findings of this investigation highlight prefabricated ferrocement sheet wrapping as an effective retrofitting technique for RC columns. It offers structural recovery, enhanced ductility, and greater energy absorption without significantly increasing column size or cost. Besides introducing prefabrication, it greatly reduces the retrofitting period. The system's simplicity, light weight, and adaptability to different damage levels make it highly suitable for post-disaster rehabilitation, structural strengthening, and routine retrofitting of aging infrastructure, particularly in low-resource settings. Therefore, from both structural and implementation perspectives, prefabricated ferrocement sheet retrofitting, especially with double-layer mesh, emerges as a robust, practical, and sustainable alternative to conventional methods, bridging the gap between modern performance needs and real-world implementation constraints.

5.2 FUTURE RECOMMENDATION

While the present study focuses on axial compression loading, future research should consider:

i. The seismic performance of PFS-retrofitted columns under cyclic or lateral loading;

ii. Long-term durability under environmental exposure, including corrosion and moisture.

iii. Development of design guidelines and analytical models for standardizing the use of prefabricated ferrocement jacketing in retrofitting practices.

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