ENHANCING FLEXURAL STRENGTH OF PRE-CRACKED REINFORCED CONCRETE BEAMS THROUGH FERROCEMENT RETROFITTING

S. M. Masrur Sakib[1], Abu Zakir Morshed[2], Abhishek Sarkar*[3], Md Abdul Kader Nahid[4] and Md. Shamim Sharear[5]

[1] Graduate, Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh, e-mail:
smmasrursakib@gmail.com
[2] Professor, Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh, e-mail:
azmorshed@ce.kuet.ac.bd
[3] Postgraduate Student, Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh, e-mail:
sarkar1701019@gmail.com
[4] Graduate, Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh, e-mail:
nahidkst13@gmail.com
[5] Graduate, Khulna University of Engineering & Technology (KUET), Bangladesh, e-mail:
shareartusherkuetce17@gmail.com

***Corresponding Author**

ABSTRACT

Reinforced concrete structural components often show signs of distress before reaching their expected service life due to various factors. When structures become compromised, immediate attention and appropriate remedial actions are necessary to restore functionality. Retrofitting, a process aimed at enhancing and fortifying the performance of deficient structural elements within a building or the entire structure, becomes crucial. The primary objective of retrofitting is to prevent structural collapse and potential harm to occupants. Ferrocement emerges as a valuable retrofitting material due to its quick application on damaged surfaces without the need for specialized bonding agents. Ferrocement offers advantages over conventional reinforced concrete, including lower weight, ease of construction, thinner cross-sections, and higher tensile strength. The study explored the viability of using ferrocement as a retrofitting material to enhance the flexural strength of pre-cracked RC beams. The experiment involved casting seven beams at 100x150x1000 mm. A control beam underwent testing under third-point loading to determine its ultimate load-bearing capacity. The remaining six beams were preloaded to 50% of the ultimate load of the control beam. Among these, two were retrofitted solely on the bottom side, and two were retrofitted on three faces (wrapped in a U shape) using ferrocement laminate. The other two beams were retrofitted using epoxy resin for comparison. Following retrofitting, all beams underwent testing using the same procedure as the control beam. The control beam exhibited an ultimate load capacity of 52 kN. After retrofitting, the beams reinforced with epoxy resin demonstrated the most substantial improvement in ultimate load capacity, reaching 70 kN. The U-wrapped retrofitting also resulted in a noteworthy increase in ultimate load capacity, reaching approximately 61 kN. Moreover, the deflections of the beams were effectively controlled following the strengthening process. The findings underscore the successful adaptation of innovative retrofitting solutions to extend the service life of structures while prioritizing safety and functionality.

Keywords:*Retrofitting of Concrete Structures, Ferrocement Retrofitting, Flexural Strengthening of Beams, Pre-Cracked Reinforced Concrete Beams, Epoxy Resin Retrofitting.*

1. INTRODUCTION

Retrofitting, also known as structural enhancement, involves strengthening deficient structural elements within a building or the entire structure. This process aims to improve the performance of a building to a predefined standard, regardless of whether an earthquake has occurred. The goal of retrofitting is to elevate the seismic performance of a building beyond that of its original state (Cosgun et al., 2022).

Numerous residential buildings currently in use are not sufficiently engineered to withstand earthquakes, according to a survey conducted on them. Many parts of Bangladesh are now in higher seismic zones due to a recent revision to the country's earthquake code, which raises the possibility of damage (Sadat et al., 2010). Buildings built prior to the code revision might therefore not be able to comply with the updated requirements. It is advised that these already-existing buildings be retrofitted to improve their seismic performance and guard against harm to people or property(Tomar, 2006).

While the primary aim for new construction is to ensure compliance with current building codes, there are often situations where it becomes necessary to enhance the seismic resistance of existing buildings. It may be important to consider the timing of code changes in relation to a building's construction to anticipate potential retrofit requirements. If retrofitting is needed for renovation purposes, the building must be brought up to current code standards. However, if the upgrade is desired for its own merits, the specific needs can be determined by examining the construction and design methods used at the time the building was originally built.

For instance, when considering code requirements for wind and earthquakes, one can look at the example of the Uniform Building Code (UBC). This model code is periodically updated, typically every three years, with editions published in 1994, 1991, 1998, 1985, 1982, 1979, 1976, 1973, and 1971, and so on. If a building were constructed in 1972, it would likely have been built in accordance with the 1971 UBC if that was the prevailing code at the time. Therefore, in 1999, the building could not be expected to meet the standards of the code, which had undergone updates since 1971 (Tomar, 2006).

A composite material called ferrocement is made up of a cement mortar matrix reinforced with one or more layers of extremely thin wire mesh, occasionally with skeletal steel for support. "A type of thin-wall reinforced concrete, typically made of hydraulic cement mortar, reinforced with closely spaced layers of continuous and relatively small-diameter mesh," is how the American Concrete Institute Committee 549 defines ferrocement. This mesh can be composed of other appropriate materials or be made of metal. In comparison to conventional concrete construction, ferrocement demonstrates superior toughness, ductility, durability, strength, and crack resistance (Yuan et al., 2020b). These characteristics are attained in structures with a typical thickness of less than 25 mm, a measurement that is uncommon in other building techniques and signifies a notable advancement over traditional reinforced concrete (Makki, 2014).

Ferrocement exhibits composite behaviour, as the presence of ductile wire mesh reinforcement enhances the properties of its otherwise brittle mortar matrix. The closer distribution and subdivision of wire meshes within the rich cement-sand mortar impart ductility and a superior crack-arrest mechanism to the material (Teng et al., 2008). Additionally, due to its thin profile, ferrocement elements have a lower self-weight per unit area compared to reinforced concrete elements, with typical thickness ranging from 10mm to 40mm. In contrast, reinforced concrete elements generally require a minimum thickness of around 75mm for shell or plate elements. This combination of low self-weight and high tensile strength makes ferrocement an attractive material for fabrication. The widespread distribution of small-diameter wire mesh reinforcement across its surface results in excellent resistance to cracking and improves other properties such as toughness, fatigue resistance, and permeability (Makki, 2014).

Ferrocement has found extensive applications in housing, particularly in roofs, floors, slabs, and walls. Some research has explored the use of ferrocement in beams and columns as well. For instance, research by Kaushik et al. in 1987 investigated the behaviour of ferrocement cylindrical shell units as roofing elements, demonstrating their suitability for low-cost housing and compliance with Indian loading, deflection, and crack width requirements. Another study by Jagdish and Radhakrishna in 1977 examined the effectiveness of ferrocement hyperbolic paraboloid shell roofing units for short spans of 4 meters, recommending their use with two layers of chicken mesh.

In the current context, various laminates such as CFRP (Carbon Fiber Reinforced Polymer), GFRP (Glass Fiber Reinforced Polymer), and Ferrocement are used for retrofitting structures. Ferrocement is gaining popularity due to its inherent advantages, including lightweight, ease of construction, low self-weight, and thinner sections (Yuan et al., 2020a). While some researchers have employed ferrocement laminates to enhance either flexural or shear strength in beams, it is often necessary to strengthen beams in both shear and flexure(Tomar, 2006).

This study focuses on casting and subsequently loading flexural deficient beams to 50% of their ultimate load capacity, followed by retrofitting them with 20mm thick ferrocement laminates bonded using cement slurry and epoxy resin, with wire mesh oriented at a 45° angle to the beam's longitudinal axis.

For this research, seven full-size beams measuring 100 x 150 x 1000 mm were cast. One of these beams was tested as a control to determine its ultimate load-carrying capacity. In contrast, the remaining six beams were subjected to loading up to 50% of their ultimate load capacity before being retrofitted with 20mm thick ferrocement laminates.

The preceding analysis highlights the significant influence of various parameters on the flexural strength of ferrocement elements, including variations in plaster thickness and the contribution of different stress levels of safe load. The improvement in mechanical properties suggests that welded wire mesh in ferrocement elements offers substantial resistance to flexure due to its high modulus of elasticity. Given the limited information available on the flexural behaviour of ferrocement, further studies are needed. Therefore, the objective of this study is to conduct experimental research on the flexural behaviour of retrofitted RC beams with ferrocement laminates in cases of flexural deficiency.

2. METHODOLOGY

2.1 General

The testing program has been carefully designed to assess the material properties necessary for casting beams and to analyse the subsequent performance of retrofitted beams. This comprehensive program encompasses several key steps.

Firstly, it involves the detailed examination of the fundamental properties of constituent materials, such as cement, sand, coarse aggregates, and steel bars, in strict accordance with relevant ASTM specifications. Following this, the program includes the actual casting of seven full-sized beams, each measuring 100 x 150 x 1000 mm, utilizing M20 grade concrete. The concrete mix used is meticulously designed based on the properties derived from the evaluation of these materials.

Once the beams are cast, the program proceeds to calculate the ultimate failure load that these beams can withstand. Subsequently, the beams are subjected to a load equivalent to 50% of their ultimate capacity. It is at this stage that the innovative retrofitting process comes into play. The beams are retrofitted with 20 mm thick ferrocement laminates, which are affixed using a combination of cement slurry and epoxy resin. Furthermore, a mesh is strategically positioned at a 45-degree angle to the longitudinal axis of the beam, reinforcing its structural integrity and enhancing its performance.

2.2 Materials

Various materials are employed in the design and casting of beams, including cement, fine aggregates, coarse aggregates, reinforcing bars, and, for retrofitting, MS welded wire mesh, cement slurry, and epoxy resin. The specifications and properties of these materials are detailed below.
Cement: The study utilizes Portland pozzolana 43 grade cement from a single lot. The physical properties of this cement, as determined through various tests, are presented in Table 1. All tests are conducted in accordance with the procedures outlined in IS: 8112-1989.

Fine Aggregates: Local sand is used as the fine aggregate in the cement mortar and concrete mix. The physical properties of the sand are displayed in Table 1.

Coarse Aggregates: Throughout the experimental study, crushed stone aggregate (locally available) of 20 mm is employed. The physical properties of coarse aggregates are provided in Table 1.

Water: Fresh and clean water is employed for casting and curing the specimens. The water used is relatively free from organic matter, silt, oil, sugar, chloride, and acidic materials, in accordance with Indian standard requirements.

Reinforcing Steel: HYSD steel of grade Fe-415 with diameters of 10mm, 8mm, and 6mm is used as longitudinal steel. 10 mm diameter bars are employed as tension reinforcement and compression steel, while 6mm diameter bars serve as shear stirrups. The properties of steel bars are outlined in Table 1.

Table 1: Physical Properties of Cement, Fine Aggregates, Coarse Aggregates and Steel Bars

Material	Characteristics with Values Obtained Experimentally
Cement	• Standard Consistency: 34 • Fineness of Cement as Retained on 90 Micron Sieve: 0.5 • Initial Setting Time: 35 mins • Final Setting Time: 5 hours • Specific Gravity: 3.07 • Compressive Strength at 7 days: 33.5 N/mm^2 • Compressive Strength at 28 days: 43.5 N/mm^2
Fine Aggregates	• Specific Gravity: 2.56 • Bulk Density (Loose): 1.48 kg/L • Fineness Modulus: 2.51 • Water Absorption: 2.06% • Grading Zone: Zone III
Coarse Aggregates	• Type: Crushed • Specific Gravity: 2.62 • Water Absorption: 3.65% • Fineness Modulus: 7.57
Steel Bars	• Diameter of Bars/Mesh Wire: 10 mm for Steel Bar-1, 6 mm for Steel Bar-2 • Yield Strength: 450.5 N/mm^2 for Steel Bar-1, 442.5 N/mm^2 for Steel Bar-2 • Ultimate Strength: 510.2 N/mm^2 for Steel Bar-1, 612.7 N/mm^2 for Steel Bar-2 • Percentage Elongation: 15.5% for Steel Bar-1, 32.9 for Steel Bar-2

Steel Mesh: For the ferrocement jacket, MS welded steel wire mesh with a diameter of 1.0 mm and square grids measuring 25x25 mm are used.

Concrete Mix: The M20 grade concrete mix is designed following the standard procedure using the properties of materials discussed. The water-cement ratio in the design is 0.5, resulting in a mix proportion of 1:1.45:3.123 (cement: sand: aggregate). The compressive strength of materials after 7 days and 28 days is 21.5 MPa and 29 MPa, respectively.

Mortar Mix: The recommended mix proportions for common ferrocement applications typically range from 1:1.5 to 1:2.5 (cement: sand) by weight, with a water-cement ratio of 0.35 to 0.5. In this study, the cement-sand mortar proportion for the ferrocement sheets is set at 1:2 (cement: sand), with a water-cement ratio of 0.40.

Epoxy Resin: Epoxy resin is an excellent sealant for concrete surfaces due to its strong bonding capabilities. It possesses attributes such as high strength, rapid strength development, toughness, quick curing, and ease of construction. Additionally, it offers resistance to abrasion, water, chemical corrosion, and freezing. In this experiment, Nitobond S B R Latex, an epoxy resin, is used to bond new cementitious mortars and screeds to existing cementitious surfaces, both horizontally and on vertical surfaces supported by formwork.

2.3 RCC Beam Design

In this study, the RCC beam is meticulously designed using M20 grade concrete and Fe 415 steel. The design approach follows the limit state method, considering the beam to be an under-reinforced section. The beam's design incorporates two 10 mm diameter steel bars on the compression face and two bars of the same diameter on the tension face. Additionally, 6 mm diameter stirrups are strategically placed at 100 mm intervals to enhance the beam's shear strength. The dimensions of the beam are fixed at 100 x 150 mm overall. Both the longitudinal section and cross-section of the beam are depicted in Figure1.

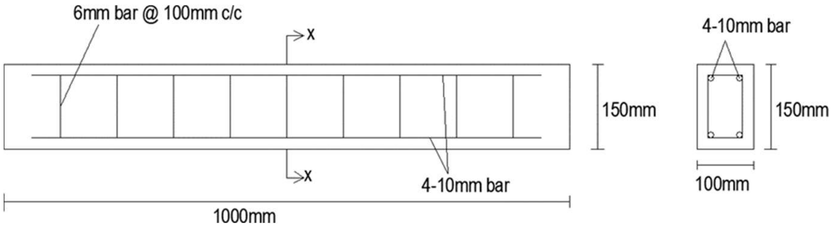

Figure 1: Longitudinal and Cross-Section of Control Beam

2.4 Casting Of Composite Beams

The casting of beams is a single-stage process. A mould with dimensions of 100 x 150 x 1000 mm is used for this purpose. Initially, the entire beam mould is coated with oil to facilitate the easy removal of the beam from the mould after the desired curing period. To ensure a uniform reinforcement cover, 20 mm spacers are employed. Once the steel bars are positioned as per the design, the concrete mix is poured into the mould, and a needle vibrator is used to provide vibrations. The vibration process continues until the mould is completely filled, leaving no gaps. After 48 hours, the beams are carefully removed from the mould, and they undergo a 28-day curing process in water, as shown in Figure 2.

Figure 2: Casting of Beams

2.5 Testing Arrangement

All seven beams are subjected to testing under simply supported end conditions. Third-point loading is adopted for the testing procedure, with the spacing between two concentrated loads being set at one-third of the beam's span to induce failure in flexure. The testing of beams is carried out with the assistance of a hydraulic-operated jack connected to a load cell. The load is applied to the beam using the hydraulic jack, and data is recorded through the data acquisition system, which is connected to the load cell. A dial gauge placed at the centre is used to measure deflection. Among the seven beams, one serves as the control beam and is tested after 60 days (following a 28-day curing period) to determine the ultimate load capacity. The remaining six beams are stressed up to 50% of their ultimate load capacity for the purposes of the experiment.

2.6 Retrofitting of Beams

After subjecting the beams to the specified stress level, they undergo a retrofitting process involving the application of steel wire mesh at a 45° orientation, as illustrated in Figure 7. Subsequently, the beams are covered with a 20 mm thick layer of cement mortar. This retrofitting process alters the final cross-section of the beams to dimensions of 140 x 170 x 1000 mm and 100 x 170 x 1000 mm. The impact of the 50% stress level on the strength of retrofitted beams with steel wire mesh is a key focus of the study. There are two approaches to placing the wire mesh: one involves covering only the bottom surface of the beam, while the other covers three sides of the beam. Out of the six stressed beams, four are retrofitted through in-situ casting, while the remaining two are retrofitted using epoxy resin, as shown in Figure 6.

The retrofitting process begins with the cleaning of the beam's surface. Once the surface is cleaned, a cement slurry is applied to create a strong bond between the ferrocement laminate and the beam. For four of the beams, the wire mesh is placed at a 45° angle, as shown in Figures 3, 4 and 5. Subsequently, a 20 mm plaster layer of 1:2 cement mortar (with a water-cement ratio of 0.45) is applied to the beam's surfaces. After this application, the beams are subjected to a curing period of 7 days. In the case of the other two beams, a ferrocement panel is created for the bottom surface and joined using epoxy resin. The testing procedure for all beams, including the control beam, involves applying a load using a third-point loading system to determine the ultimate load and corresponding deflections.

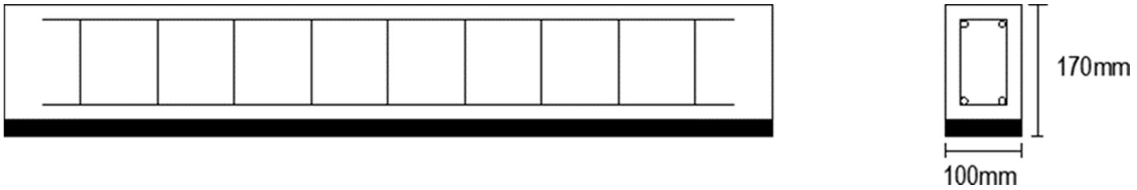

Figure 3: Longitudinal and Cross Section of Retrofitted Beam (Only Bottom)

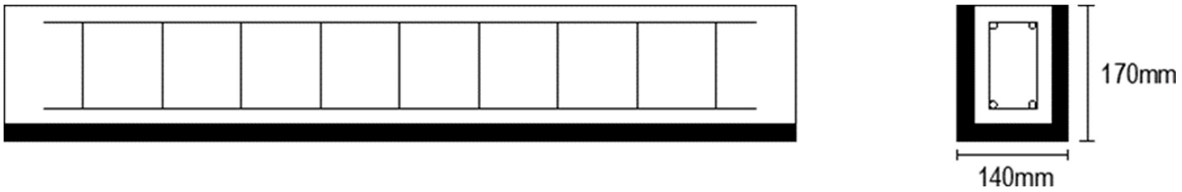

Figure 4: Longitudinal and Cross Section of Retrofitted Beam (U Rapped)

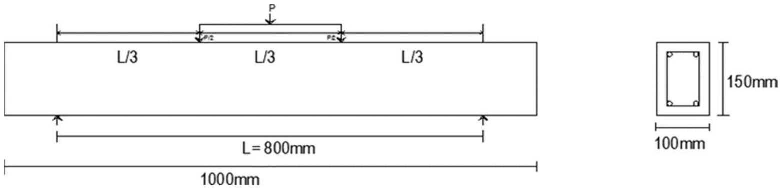

Figure 5: Loading System of Beam

Figure 6: Retrofitting Using Epoxy Resin

Figure 7: Orientation of Wire Mesh and Retrofitting Process

3. RESULTS

3.1 General

This study focuses on investigating the impact of stress levels on the strength of retrofitted beams with flexural deficiencies. The experimental approach involves initially subjecting the beams to a predetermined stress level of 50% of their ultimate load. Subsequently, the beams are retrofitted with 20 mm thick ferrocement laminates, incorporating a double-layer welded wire mesh positioned at a 45-degree angle to the longitudinal axis of the beams. A comparative analysis is conducted to evaluate the variations in strength between the retrofitted beams and the control beam under the same parameters, and the results are presented in the following section.

3.2 Testing Method

The testing methodology begins with the evaluation of the control beam, which is tested to failure, and data is recorded using a data acquisition system. Subsequently, the other six beams are each stressed to 50% of the ultimate load of the control beam. The ultimate load, determined through load testing, is found to be 52 kN, with the corresponding load at the 50% stress level being 26 kN. The retrofitting process involves the application of a 20 mm thick cement mortar with wire mesh bonded on the bottom side for two beams and on three sides for two beams. For the remaining two beams, a pre-casted ferrocement panel is joined with the beam using epoxy resin. After one week of curing, the beams are retested following the same procedure as the initial testing of the control beam. The results are recorded and presented in the subsequent sections.The designations of the beams used in this study are presented in Table 2.

Table 2: Specification of Beams

Specimen Name	Symbol and Characteristics
Control Specimen	Control beam (C1)
Retrofitted Beam 1	R1 (Bottom side, Cement mortar)
Retrofitted Beam 2	R2 (Bottom side, Cement mortar)
Retrofitted Beam 3	R3 (Three sides, Cement mortar)
Retrofitted Beam 4	R4 (Three sides, Cement mortar)
Retrofitted Beam 5	R5 (Bottom side, Epoxy resin)
Retrofitted Beam 6	R6 (Bottom side, Epoxy resin)

3.3 Control Beam

A single beam is subjected to testing as the control beam using a third-point concentrated loading system. Since this beam exhibits a deficiency in flexure, the distance between the two loads is deliberately chosen to be L/3 (where L is the span length). The two loads effectively divide the span into three equal parts. The load is incrementally increased in 5 kN intervals, and deflection is recorded at the centre of the span.

The results of the load and the corresponding deflection obtained during the testing are summarized in Figures 8 to 13. Initially, the deflection in the middle of the beam increases almost linearly with the increase in load. However, after a load of 30 kN, the deflection increases at a significantly higher rate until it reaches the ultimate load of 52 kN. The first crack in the beam is observed at a load of 24 kN, and subsequently, the number of cracks increases, spreading over the entire length of the beam. The pattern of cracks, as shown in Figure 16(a), is indicative of a flexural failure of the beam.

3.4 Comparative Analysis of Retrofitted and Control Beams

3.4.1 Effect of Ferrocement Laminate on Beams R1 & R2 Compared to Control Specimen

This section investigates the impact of retrofitting on flexurally deficient RC beams stressed to 50% of their ultimate load with bottom-side retrofitting (R1 & R2), as depicted in Figures8 and 9. Figures 16(b) and 16(c) illustrate the loading configuration and crack patterns in the retrofitted beams.

Upon analysis of the experimental data and corresponding graphs, it becomes evident that the retrofitting of Beam R1 results in an ultimate load capacity of approximately 53 kN, slightly exceeding the control beam's capacity of 52 kN. However, the deflection at the ultimate load for R1 is notably better at 2.76 mm compared to the control beam's 3.92 mm. Additionally, flexural cracks are observed in the R1 beam following the loading.

For the R2 specimen, an analogous trend is observed, with an ultimate load capacity close to that of R1 at around 51 kN. However, the deflection at the ultimate loading condition is approximately 2.70 mm, which represents improved deflection control compared to the control beam. R2 also exhibits flexural cracks.

3.4.2 Effect of Ferrocement Laminate on Beams R3 & R4 Compared to Control Specimen

This section explores the effect of retrofitting on shear-deficient RC beams, stressed to 50% of their ultimate load, with three-sided retrofitting (U-wrapped) (R3 & R4), as depicted in Figures10 and 11. Figures 16(d) and 16(e) illustrate the loading arrangement and crack patterns in the retrofitted beams.

Retrofitting beam R3 does not exhibit a significant improvement in ultimate load capacity, remaining at approximately 52 kN, equivalent to the control beam's capacity. However, R3 demonstrates better deflection control, with a deflection of 3.22 mm.

In contrast, the R4 beam delivers promising results, boasting an ultimate load capacity of about 61 kN, surpassing the control beam's capacity. Furthermore, the deflection in R4 is well-managed at 3.32 mm, lower than the control beam's deflection. The cracks formed in R4 suggest flexural failure and emphasize the effectiveness of this strengthening method.

3.4.3 Effect of Ferrocement Laminate on Beams R3 & R4 Compared to Control Specimen

This section examines the effect of retrofitting on flexurally deficient RC beams, stressed to 50% of their ultimate load, and retrofitted using epoxy resin (R5 & R6), as illustrated in Figures 12 and 13. Figures 16(f) and 17(g) depict the loading configuration and crack patterns in the retrofitted beams.

Analysis of the experimental data and corresponding graphs reveals that retrofitting results in an increase in the ultimate load-carrying capacity from 52 kN (Control Beam) to 70 kN (R5 Beam). The deflection at the ultimate load of 70 kN is 3.28 mm, compared to 3.92 mm for the control beam at 52 kN. For the R6 specimen, a similar trend is observed, with an increase in load from 52 kN (Control Beam) to 66 kN, accompanied by a deflection of approximately 3.4 mm. Consequently, for flexure-deficient beams stressed to 50% of their ultimate load, retrofitting using epoxy resin significantly increases the ultimate load.

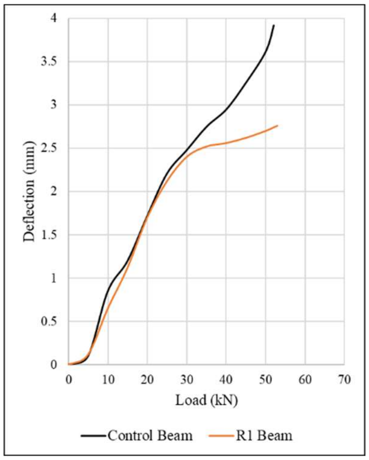

Figure8: Load Deflection Curve for R1 Beam

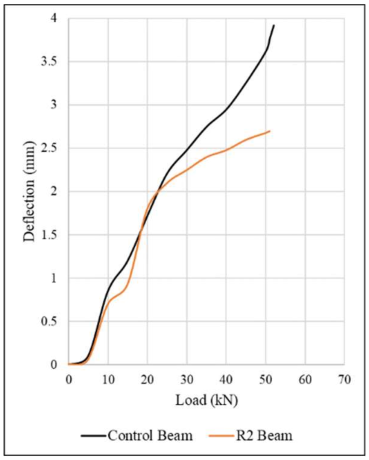

Figure9: Load Deflection Curve for R2 Beam

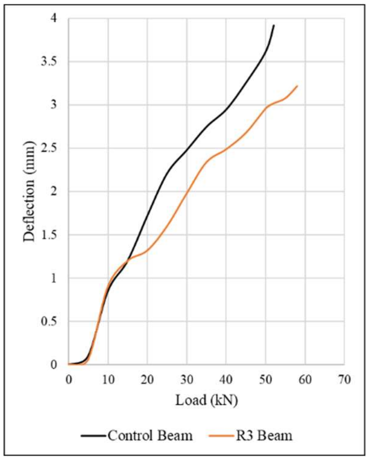

Figure 10: Load Deflection Curve for R3 Beam

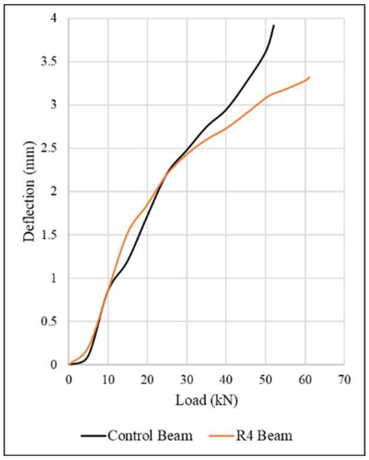

Figure 11: Load Deflection

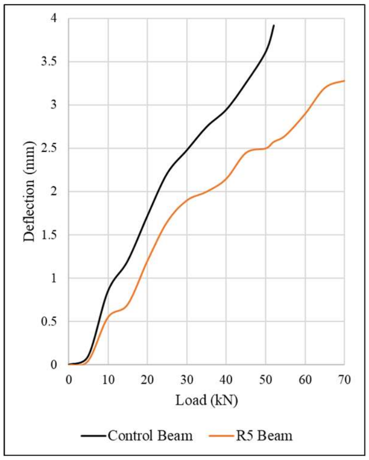

Figure 12: Load Deflection

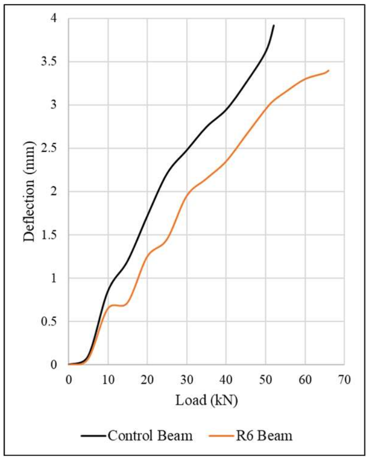

Figure 13: Load Deflection

Curve for R4 Beam Curve for R5 Beam Curve for R6 Beam

3.5 Comparative Analysis of Retrofitted And Control Beams

From a comparative perspective, Figures14 and 15 demonstrate that beams stressed to 50% of the ultimate load of the control beam and retrofitted using different methods exhibit varying behaviour. Beams retrofitted using epoxy resin show the most significant improvement in their ultimate load, increasing from 52 kN (Control Beam) to 70 kN, with only a minor increase in deflection. The results for bottom-side in-situ retrofitting closely resemble these findings, with the ultimate load increasing slightly to 53 kN while maintaining deflection control compared to the control beam. U-wrapped retrofitting also exhibits substantial improvement in the ultimate load, reaching 61 kN, while effectively controlling deflection to a maximum of 3.32 mm.

Table 3: Comparison of Experimental Ultimate Loads of Beams Tested in Flexure.

Beam Designation	Experimental Ultimate. Load (kN)	Gain in Ultimate Load on Strengthening		Predicted Failure Mode (Theoretical)	Actual Mode of Failure
		kN	%		
Control Beam	52	-	-	Flexure	Flexure
R1	53	1	1.92	Flexure	Flexure
R2	51	0	0	Flexure	Flexure
R3	58	6	11.54	Flexure	Flexure
R4	61	9	17.31	Flexure	Flexure
R5	70	18	34.62	Flexure	Flexure
R6	66	14	26.92	Flexure	Flexure

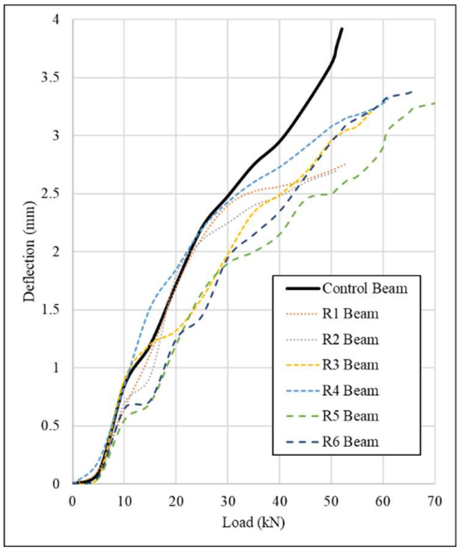

Figure 14: Load Deflection Curves for Comparison

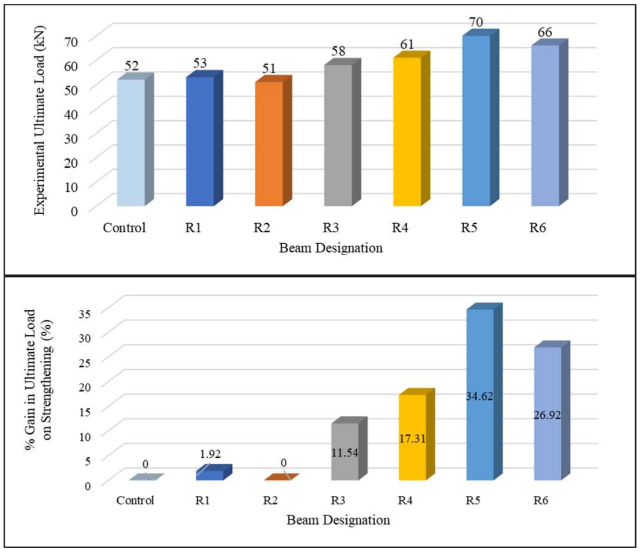

Figure 15: Ultimate Loads of Beams

3.6 Failure Pattern

The primary objective of this study is to observe the behaviour of beams failing in flexure, maintaining a distance of 266.7 mm between two-point loads. In the case of the control specimen, as shown in Figure 16(a), visible cracks in the middle of the beam confirm flexural failure, aligning with theoretical predictions. Following retrofitting with ferrocement laminates, the beams become more resistant to failure, as evidenced by the presence of flexural cracks in all retrofitted beams (R1, R2, R3, R4, R5, R6). Further investigations into the percentage improvement in flexural capacity are suggested for future work.

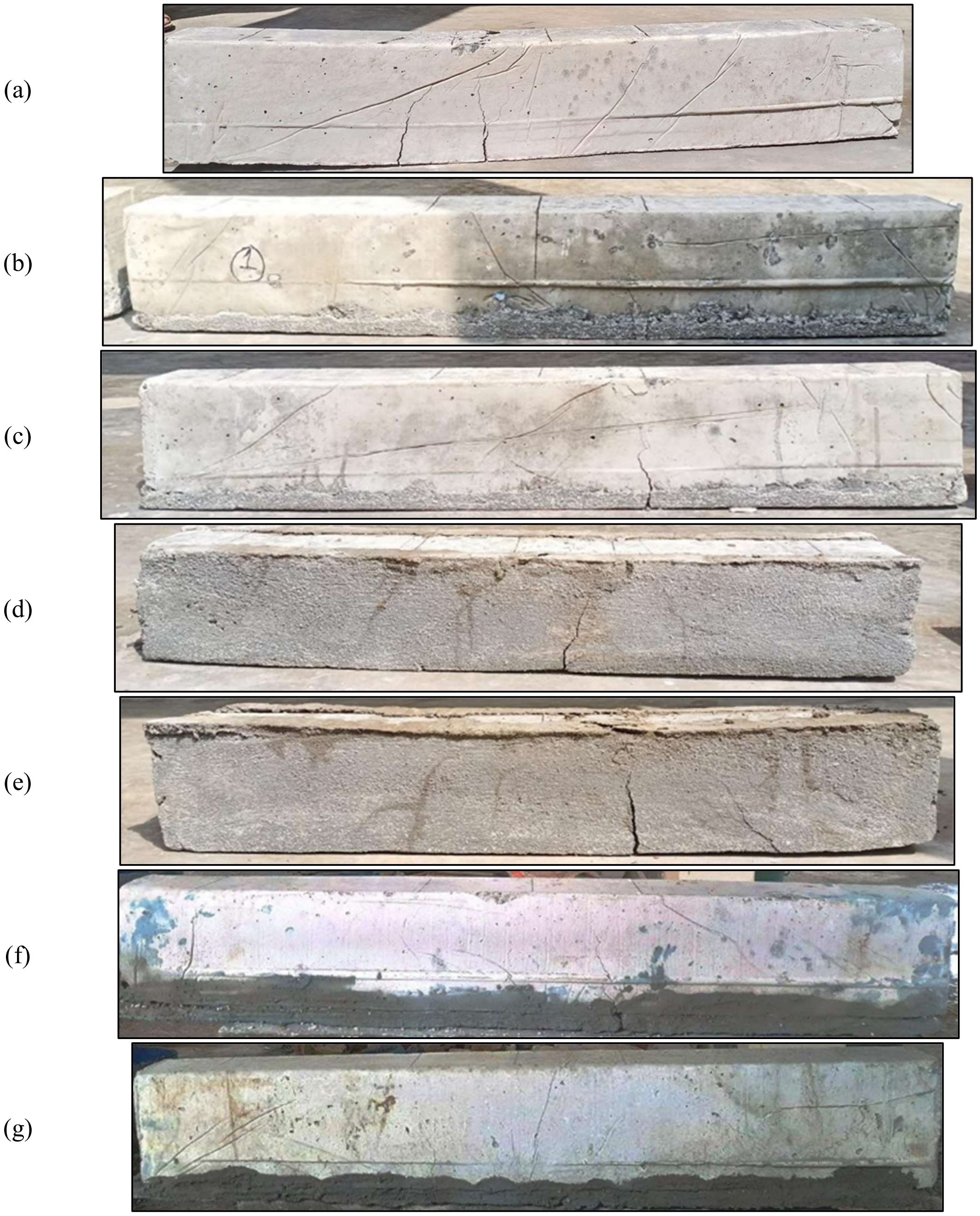

Figure 16: Failure Pattern of (a) Control Beam, (b) R1 Beam, (c) R2 Beam, (d) R3 Beam, (e) R4 Beam, (f) R5 Beam, (g) R6 Beam.

4. CONCLUSIONS

Adherence of Retrofitted Beams with Wire Mesh: The beams subjected to stress and retrofitted with wire mesh demonstrated robust adherence characteristics. Throughout the course of testing until failure, there was no evidence of debonding or detachment of the retrofitted composite materials.

Failure Characteristics of Composite Beams: The failure behaviour of the composite beams was consistently marked by the development of flexural cracks concentrated over the tension zone of the beams. These cracks were indicative of the flexural mode of failure.
Comparative Load-Carrying Capacities: Among the various retrofitting methods, beams retrofitted using epoxy resin exhibited the highest load-carrying capacity. These epoxy-retrofitted beams were capable of withstanding loads of approximately 70 kN. In contrast, beams retrofitted with U-wrapping exhibited a load capacity of 58 kN, and those retrofitted at the bottom surface displayed a load capacity of 53 kN.

Percentage Increase in Load-Carrying Capacity: The percentage increase in load-carrying capacity after retrofitting was most significant in the case of beams retrofitted with epoxy resin, representing an impressive enhancement of approximately 34.6% compared to their original load-carrying capacity.
Deflection Reduction after Retrofitting: An additional notable observation was the reduction in deflection experienced by all retrofitted specimens at their respective ultimate load conditions. In contrast to the control beam, which exhibited a deflection of 3.92 mm at the point of ultimate load, all retrofitted beams displayed lower deflections, signifying a noteworthy improvement in controlling deflection.

These findings underscore the effectiveness of retrofitting methods in enhancing the load-carrying capacity and structural performance of the tested beams. Furthermore, the results highlight the superior performance of epoxy resin retrofitting in terms of both load-carrying capacity and deflection control, making it a promising technique for the rehabilitation and strengthening of flexural-deficient reinforced concrete beams.

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