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Seismic Upgradation of RC Beams Strengthened with Externally Bonded Spent Catalyst Based Ferrocement Laminates

R. Balamuralikrishnan [1*], A. S. H. Al-Mawaali [1], M. Y. Y. Al-Yaarubi [1], B. B. Al-Mukhaini [1], Asima Kaleem [1]

[1] *Department of Civil and Environmental Engineering, College of Engineering, National University of Science and Technology, Muscat, Oman.*

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Abstract

Globally, since there are more systems of civil infrastructure, there are also more degraded buildings and structures. If upgrading or strengthening is a practical option, complete replacement is likely to be an escalating financial burden and may be a waste of natural resources. It is necessary to repair or strengthen a number of reinforced concrete buildings and structures in order to boost their load-bearing capabilities or improve their ductility under seismic stress. Additionally, due to changes in service circumstances, a structure might need to be modified to reduce deflections or manage cracking. Strengthening may be preferable to limiting usage, capping applied loads, and regularly inspecting the structure rather than removing the existing structure or part and building a new one. This study aims to examine the flexural, shear, and combined effect of flexural and shear behavior of reinforced concrete (RC) beams strengthened with externally bonded spent catalyst-based ferrocement laminates and compare them to the control beams (unstrengthened) under two-point loading conditions. This study involves researching laminates with various spent catalyst doses, such as 3, 6, 9, and 12%, in an effort to determine the best amounts that will improve the structural performance of ferrocement laminates. Twelve spent catalyst-based ferrocement laminates measuring 500(L) × 125(B) × 20 mm (thickness) with 3% volume fraction of meshes each were cast and tested in the lab as part of the preliminary investigation. For repeatability, three laminates per case were employed. Eight numbers of under-reinforced RC beams measuring 75(L) × 100(B) × 150(D) mm were cast for the main study; six numbers were strengthened with optimized spent catalyst-based ferrocement laminates bonded with flexible epoxy systems at the tension zone, shear zone, and combination of tension and shear zone. Two of the beams were cast as control specimens. The beams were then evaluated using a Universal Testing Machine (UTM) with a 1000 kN capacity under two-point loading conditions. As a result, the strength, yield load, ultimate load, stiffness, ductility, and related failure modes of all tested beams' flexural and shear performances were examined. According to a preliminary analysis of laminates made of spent catalyst, the dosage of 9% provides good flexural strength in comparison to other doses. In comparison to the strengthened beam, the control beam's initial cracks appeared earlier. In comparison to the control beam, the strengthened beam has an increase in load-carrying capacity of 18% for flexure, 16% for shear, and 30% for the combined impact of flexure and shear. In comparison to the control beam, the deflection of the strengthened beam was decreased by close to 20 to 40% for flexure, 10 to 30% for shear, and 15 to 20% for the combined effects of flexure and shear at the same load level. In relation to control beams, the ductility also improved up to 30% for flexure, 25% for shear, and 25% for the combined impact of flexure and shear. Similar to this, the retrofitted beam is stiffer than the control beam by approximately 40% for flexure, 48% for shear, and 30% for the combined effect of flexure and shear. Theoretical formulation by section analysis is also derived and it gives close agreement with control and strengthened beams. The flexural and shear strengthening of the RC beam retrofitting system is effectively increased by using spent catalyst-based ferrocement laminates. No beam showed signs of premature and brittle failure. According to the test findings, it can be said that spent catalyst-based ferrocement reinforced beams perform better in every way than control beams.

Keywords: Ferrocement Laminates; Flexural Retrofit; Shear Retrofit; Two-Point Loading; RC Beams.

* Corresponding author: balamuralikrishnan@nu.edu.om

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1. Introduction

The expense of the civil infrastructure contributes significantly to national wealth. Due to its fast deterioration, there is a critical need for the development of creative, durable, and affordable technologies for new construction as well as for repair, rehabilitation, renovation, and retrofitting. Today, extending the lifespan of structures-especially those with RC frames-through strengthening is a crucial task. Over time, a variety of strengthening systems must be created and adopted. The particular performance criteria determine which strengthening strategy should be used. Globally, since there are more systems of civil infrastructure, there are also more degraded buildings and structures. If upgrading or strengthening is a practical option, complete replacement is likely to be an escalating financial burden and may be a waste of natural resources.

In order to enhance their capacity for holding more weight or improve their ductility under seismic loading, a number of reinforced concrete buildings and structures need to be repaired or strengthened. Additionally, due to changes in service circumstances, a structure might need to be modified to reduce deflections or manage cracking. Compared to removing the existing structure or part and building a new one, limiting usage, reducing applied loads, and regularly monitoring the structure, strengthening can be preferable. Ferrocement is a type of reinforced concrete that is built from hydraulic cement mortar and reinforced with thin layers of mesh separated at regular intervals. It can be made of metal or other suitable materials. Ferrocement is recognized as a construction material with good characteristics in fracture control, toughness, and impact resistance because of the compact spacing and homogeneous distribution of reinforcement inside the material. Additionally, the application of ferrocement enhances properties such as energy absorption, ductility, stiffness, and load-bearing capability. As a result, it can be used as a reinforcing element in the rehabilitation of reinforced concrete buildings. A few examples of structural applications for ferrocement include tanks, boats, roofs, silos, and the repair and reinforcement of structures. The number of layers, type, and orientation of the wire mesh, as well as the type of mesh material, all affect how ferrocement behaves. Lamination is a term that is occasionally used to describe plate bonding, which entails wrapping comparatively thin sheets around a component. The plate materials used for repair may include steel laminates, such as corrosion-resistant steel plate and thin stainless steel plate, cementitious laminates (composites), such as HPFRCCs (SIFCON, SIMCON), and thin ferrocement plate or laminates, as well as polymer-based laminates, such as polymer impregnated concrete (PIC), polymer cement concrete (PCC), and polymer or resin concrete (PC), as well as resin-based laminates, such as Beam strengthening is frequently used in the strengthening of reinforced concrete structures since the failure of a beam has major implications for structural stability. Section enlargement, steel wrapping, FRP wrapping, and wrapping with high-performance fiber reinforced cementitious composites are alternatives for reinforcing beams.

1.1. Problem Statement

The ferrocement technique uses meshes with varying volume fractions (Vf) to strengthen a motor. Small-diameter meshes can be manufactured from metallic or other appropriate materials. Due to the compact spacing and consistent dispersion of reinforcement inside the material, it is typically utilized for fracture control, toughness index, and impact resistance. Additionally, the use of ferrocement will aid in enhancing the qualities of energy absorption, ductility, stiffness, and load-bearing capability.

Therefore, it can be used as a strengthening component for the rehabilitation of reinforced concrete structures. The columns and beams are the most significant structural members in any structure that transfers the entire load to the foundation. Reinforced columns in a structure get damaged due to various reasons like overloading, corrosion of steel, earthquakes, higher wind loads, fire, impact loads, etc. Therefore, the strengthening of deficient columns is necessary to increase the load carrying capacity and prevent spalling, which can be achieved by confinement of columns externally. Some of the materials that are used in the jacketing of columns and beams are ferrocement, glass fiber, aramid fiber, carbon fiber, etc. Ferrocement is a special form of reinforced concrete that exhibits uniform dispersion of reinforcement in the matrix and offers improved tensile and flexural strength, fracture toughness, crack control, and impact resistance [1]. Ferrocement composites are widely used for structural strengthening and rehabilitation in developing countries. The uniform distribution and high surface area-to-volume ratio of the reinforcement (wire mesh) of such composites improve the crack-arresting mechanism [2].

It is clear that CFRP and GFRP do not exhibit any failure strain and do not exhibit any ductility either [3]. Strengthening reinforced concrete structures will typically include beam strengthening since the failure of a beam has severe consequences for structural stability [4]. The Potential and requirements for cement manufacture in developing countries are tremendously high. However, in the meantime, Portland cement manufacturing has become the world's most infecting industry with respect to CO_2 emissions.

In general, it costs a lot of money and harms the environment to produce Portland cement clinker. The primary source of greenhouse gas (GHG) emissions is the manufacture of Portland cement. For instance, it is believed that 5% of the carbon dioxide produced by humans worldwide comes from the manufacture of Portland cement for concrete structures. Every ton of Ordinary Portland Cement (OPC) produced results in the emission of around 0.8 tons of carbon dioxide from the calcination of limestone and the burning of fossil fuels. Numerous initiatives are being made to increase the usage of Portland cement in concrete in order to combat the issues of global warming. These include using extra cementing materials, including fly ash, silica fume, granulated blast furnace slag, rice husk ash, and metakaolin, as well as creating substitutes for Portland cement. Extra cementing resources include used catalysts from petroleum refineries, fly ash, silica fume, and fly ash. There are two oil refineries in Oman, one each in Mina Al-Fahl (MAF) and Sohar (SR). In order to lower the levels of sulphur, new catalysts are introduced to the oil cracker. Spent catalysts are the by-products that result from a reaction. Catalysts that have been used up have certain physical and chemical qualities in common with sand and Portland cement. Silicate and aluminate make up more than 80% of the chemical makeup of wasted catalysts. Due to the alteration in pozzolanic characteristics, partial cement substitution in concrete mixes utilising used catalysts will alter the hydration process.

1.2. Spent Catalyst

Through the release of increased quantities of hydrated calcium silicate gel and aluminates in interaction with calcium hydroxide, the pozzolanic qualities of the catalyst contribute to the hydration process of cement [5, 6]. When introduced into solution, ions such [SiO $(OH)_3$] and [Al $(OH)_4$] react with calcium ions to generate hydrated calcium silicates and aluminates [7]. The aforementioned events improved cement's microstructure and caused it to harden [8, 9]. As a result, the structure of the material will alter, improving its primary mechanical strength [10–12].

Sohar (SR) & Mina Al-Fahl (MAF) Refineries in Oman can provide samples of used catalyst. Zeolite and other additions make up the majority of the original catalysts used in fluidized catalytic cracking units (FCCUs) in refineries [13]. The zeolite catalyst is responsible for about 1/5 of the world's catalyst production [14]. When refining and breaking crude oil, refineries use fluid catalytic cracking (FCC) catalysts to increase the production of higher-octane gasoline. The deactivated catalyst must be replaced with an active or new catalyst when the FCC catalyst's catalytic components decay [15, 16]. Waste materials are active silica (SiO_2) and alumina (Al_2O_3), which make up the majority of the spent FCC catalyst. An important portion of the solid waste generated by the petrochemical sector is spent FCC catalyst [17]. Fluid catalytic cracking (FCC), wasted hydro-processing, and catalyst improvement have all been done commercially for many years. After multiple cycles, the catalyst activity has not recovered enough to justify regeneration. Wasted catalyst is deposited in landfills in large quantities, posing an environmental risk. As waste products from the Sohar and Mina Al-Fahl refineries, respectively, around 20 metric tons of RFCC and 200–500 kg of wasted alumina catalyst are produced daily, according to Oman Oil Refineries and Petroleum Industries Company (ORPIC). The majority of used catalysts are simply disposed of on-site or at disposal sites close by without being reused or treated further. Near the Sohar Refinery, more than 20,000 metric tons of used catalysts have been collected, raising serious disposal and environmental issues. To address this issue and conserve natural resources and energy, much research has been carried out on the reuse of used catalysts. Without causing any negative effects, the catalytic cracking catalyst may be used to replace 10% of the sand or 15% to 20% of the cement content [18, 19]. To strengthen the strength of structural elements, ferrocement was adhered to their surfaces [20, 21]. It reduces concrete permeability and prevents cracking brought on by drying shrinkage and thermal expansion [22]. The study's variables included the attachment techniques, the volume proportion of reinforcement in the ferrocement laminates, and the degree of beam damage [23]. The capillary sorption, surface absorption, porosity, total water absorption, compressive strength, and other properties of various concrete mixes [24].

The industrial waste product of oil refineries is spent catalysts. The landfill disposal of these deactivated catalysts severely harms the ecology. Spent catalysts may be used as building materials in the creation of concrete due to their physical and chemical characteristics. The alternate use of spent alumina catalysts (SAC) and spent fluid cracking catalysts (SFCC) in the manufacturing of concrete. Utilising used catalyst, cement may be replaced in part to a degree of around 15% [25].

1.3. Beam Retrofitting System

The similar loading conditions-based flexural strengthening of an RCC beam using various ferrocement laminate combinations. This is accomplished by employing a single layer of steel-fibers square welded mesh, two layers of woven mesh, and a single layer of square welded mesh. In general, four 250 mm × 125 mm × 3200 mm beams were cast for the experiments, with one serving as a control beam and the other three being strengthened with ferrocement laminates of 25mm thickness and different mesh arrangements. The combination of woven and square mesh produced a stronger outcome, according to Bitaraf et al. [26]. In this study, continuously reinforced concrete (RC) beams will be strengthened using precast laminates and a high-performance fiber reinforced cementitious composite (HPFRCC). In order to determine the impact of strengthening, eight continuous (two-bay) RC beams were tested under monotonic load in the center of spans. Two of the beams served as control specimens, and the other six served as strengthened specimens. The HPFRCC laminates were prepared with a 25 mm thickness and then adhered to the tensile surface of the beams using mechanical anchorage. According to the analysis, employing HPFRCC laminates is a good technique to boost the flexural capacity of continuous RC beams, especially when longitudinal bars are employed [27].

The test results of carbon fiber reinforced polymer (CFRP) laminates that were applied to reinforced concrete beams utilizing near-surface mounting (NSM) technology to increase their flexural strength. The RC beams with a cross-section of 200 × 400 mm will be tested using a four-point bending approach. To reinforce the concrete cover on the bottom side of two RC beams, one NSM CFRP laminate was added. The findings indicate that all of the reinforced beams collapsed due to the internal steel reinforcement giving way and the CFRP laminates collapsing. When compared to a non-strengthened beam, the high strengthening efficacy of NSM strengthening for beams was validated by 109 percent and 130 percent, respectively [28].

To analyse the flexure behavior of a reinforced concrete beam enhanced with externally bonded FRP strips at the bottom, this study employed a three-dimensional (3D) finite element model, and its accuracy was confirmed by comparing it to the analytical design specifications of ACI 40.2R. This work will contribute to the improvement of a method for using FRP in real-world settings. The stress in FRP exceeded the estimated stress in the design guidelines. However, as compared to the calculated and FE-simulated service stress, the FRP's design stress is very high [29]. The significant reduction in CO_2 emissions arising from the cementitious composites industry is one of the highest priorities for the construction sector's movement towards climate neutrality and sustainable development. One of the approaches to coping with this issue is to partially substitute cement with supplementary cementitious materials. Recently, various oil refinery wastes (ORW) have attracted researchers' attention in terms of being investigated for such an application [30].

RC beams' behavior in terms of strength, ductility, and high absorption ability under the impact of fiber in ferrocement laminate acting as a reinforcing fabric. Furthermore, the relevance of ferrocement is that it strengthens structural elements like beams, columns, and column joints. However, the cracks in the ferrocement-encased beam have been more numerous and smaller in size [31]. The results of this experiment show that reinforced concrete T-beams upgraded with ferrocement have significantly greater flexural strength capabilities. The findings show that all of the improved T-beams had higher flexural strengths as compared to the control beams. The undamaged and strengthened T-beams had a 37.48 percent better ultimate flexural strength capacity as compared to the control beams [32].

1.4. The Problem Statement

The nation has been split into two seismic zones, with Muscat, Sohar, Diba, and Khasab designated as zone 1's highest seismic danger areas. Nizwa, Sur, and Salalah are located in Zone 2, which has a reduced seismic risk (Figure 1).

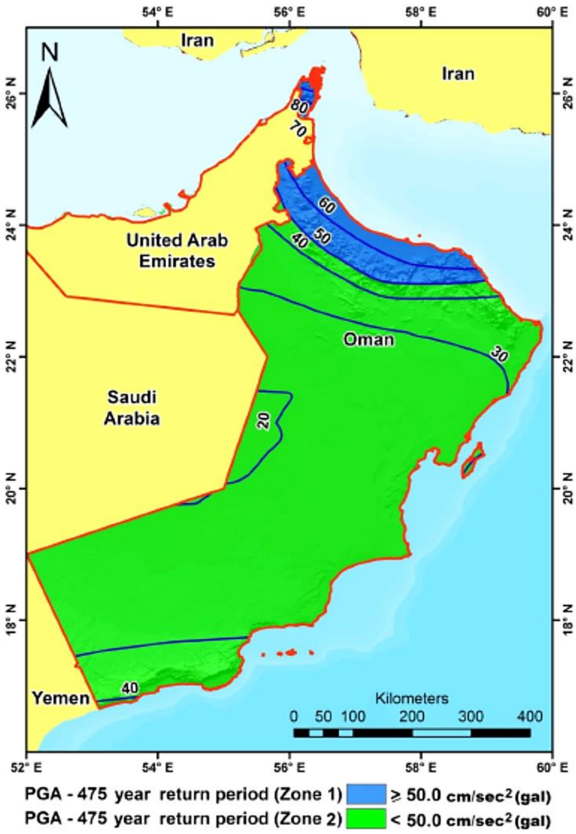

Figure 1. Oman Zonal map

The design earthquake considered in the Oman Seismic Design Code is identified as having a probability of exceedance to an earthquake with a return period of 475 years.

1.5. Aims and Objectives

This study's objective is to examine the flexural and shear behavior of reinforced concrete (RC) beams enhanced using externally bonded spent catalyst-based ferrocement laminates and compare it to the behavior of control beams (unstrengthened) under two-point loading circumstances. This study involves researching laminates with various spent catalyst doses, such as 3%, 6%, 9%, and 12%, in order to determine the best ratios of spent catalyst that would improve the structural performance of ferrocement laminates. 12 NOS. of spent catalyst-based ferrocement laminates measuring 500 (L) × 125 (B) × 20 mm (thickness) are to be cast and tested in the lab as part of the preliminary investigation. For repeatability, three laminates will be used for each instance. 8 NOS. of under-reinforced RC beams measuring 750 mm (L) × 100 mm (B) × 150 mm (D) are to be cast for the main study, 6 nos. of which are to be strengthened with optimized spent catalyst-based ferrocement laminates bonded with flexible epoxy systems at tension zone, shear zone, and combinations of tension and shear zone. Two of the beams are to serve as control specimens. The beams will next be tested using a Universal Testing Machine (UTM) with a 1000 kN capacity under two-point loading circumstances. Finally, the strength, yield load, ultimate load, stiffness, ductility, and related failure mechanisms of the flexural and shear performances of all tested beams will be examined. Also, the objectives are:

- To optimize the spent catalyst based ferrocement laminates with fixed volume fraction (V_f) of meshes.
- To identify the flexural, shear and combination of both the behavior of RC beam without strengthening.
- To identify the flexural, shear and combination of both the behavior of RC beam strengthened with externally bonded spent catalyst based ferrocement laminates.
- To compare between strengthened and unstrengthened RC beam in terms of flexure, shear and combination of both.

2. Experimental Investigation

2.1. Preliminary Study

- To optimize the spent catalyst based ferrocement laminates with fixed volume fraction (V_f) of meshes.
- Partial replacement of cement using spent catalyst based ferrocement laminates say 3%, 6% and 9% and 12%.

2.2. Main Study

- Beam size: 750 mm (L) × 100 mm (B) × 150 mm (D)
- Number of specimens: 8 NOS.
- Control specimen: 2 NOS.
- Externally bonded spent catalyst based ferrocement strengthened beams for three studies: 6 NOS.

The details of unstrengthened and strengthened beams are shown in Figure 2.

Beam designation of Retrofitting System:

- Control Beam (Baseline specimen)
- Retrofitting of RC Beam with Flexure
- Retrofitting of RC Beam with Shear
- Retrofitting of RC Beam with Flexure and Shear.

2.3. Materials

Concrete is influenced by the kind of ingredients used, their ratios, and the mixing process. The preliminary research mixture, which consists of cement, sand, the used spent catalyst, water, and wire mesh, is called mortar. However, for the main inquiry, reinforcement-infused concrete was used to create the control and strengthening beams. 33 grade Portland cement, the industry standard, was used for the duration of the inquiry. Aggregates, sometimes referred to as granular materials and divided into sand, gravel, or crushed stone, make up a sizable component of concrete when combined with water and Portland cement. In the mortar mixture for ferrocement laminates, sand with a diameter of 2.36 mm or less is used, and both coarse and fine aggregates are used in the concrete mix.

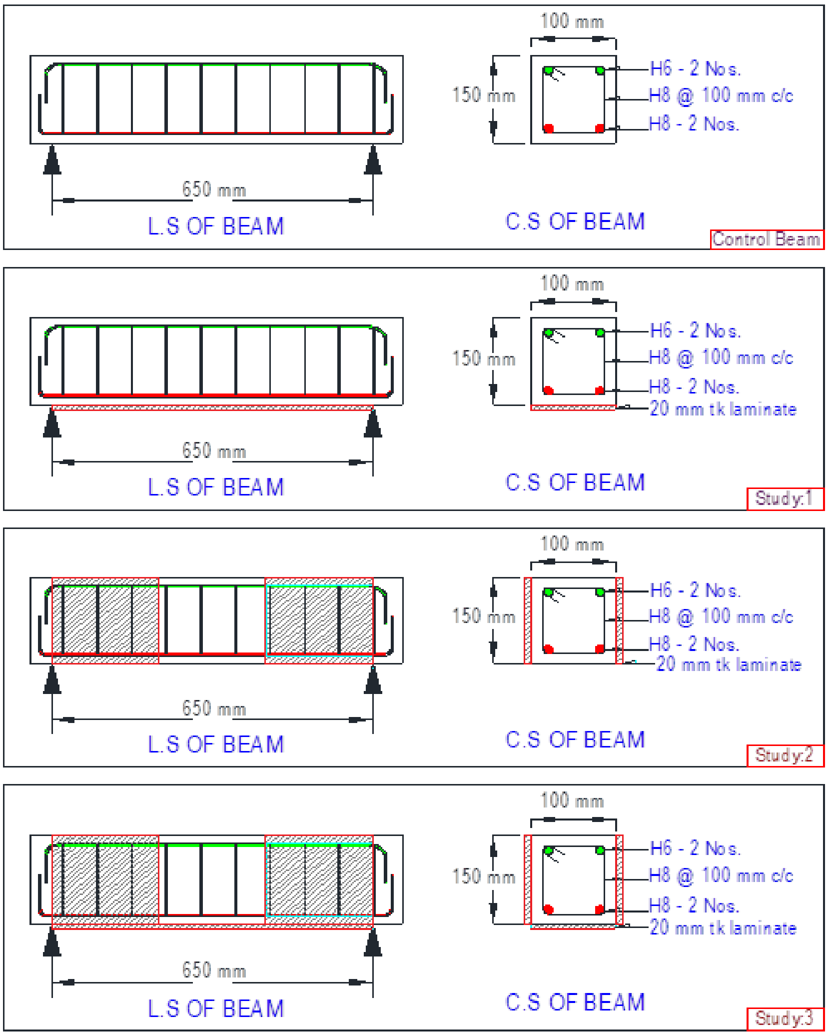

Figure 2. Strengthened and unstrengthened beams

The specific gravity of the materials used for making concrete is determined as per BS 812:2, EN 12390-7. The values obtained are given in the Table 1.

Table 1. Specific gravity

Sl. No.	Name of the Material	Specific gravity
1.	OPC Cement (33 grade)	3.15
2.	Spent catalyst (Sohar)	2.75
3.	Fine aggregate	2.71
4.	Coarse aggregate	2.78

2.4. SEM Analysis

The cementitious materials are analysed in SEM analysis to find in the materials shape and size of the samples (see Figures 3 and 4).

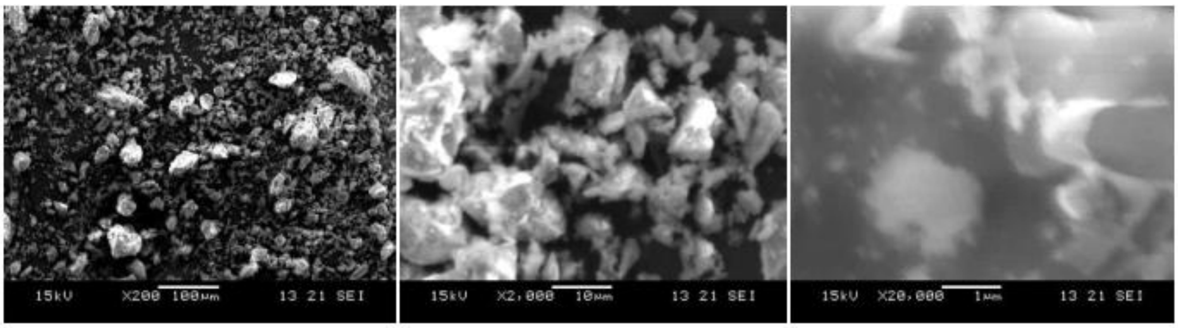

Figure 3. SEM analysis of OPC 100µ, 10µ and 1µ- OPC- 43

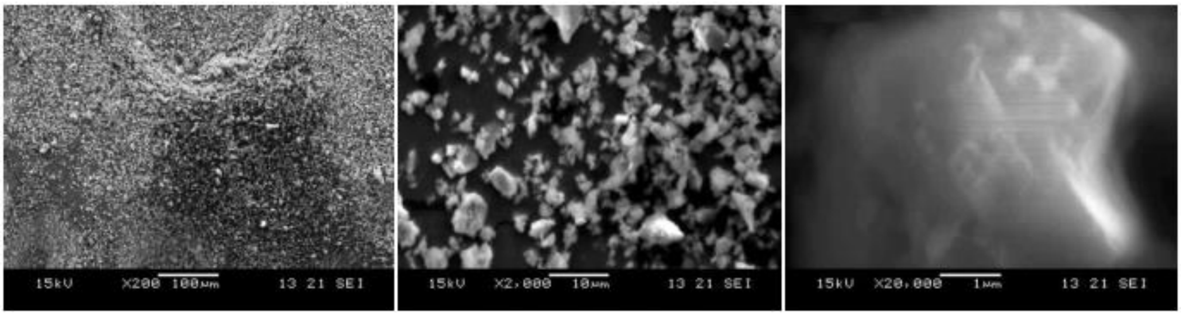

Figure 4. SEM analysis of AF 100µ, 10µ and 1µ- Spent catalyst

2.4.1. Spent Catalyst

Spent catalysts are by-products of petroleum cracking in oil refineries, it is a fine powder in grey colour in this study it is used with different dosages as a replacement of cement, as it has several physical and chemical qualities in common with Portland cement and sand. This material is available in local refineries and in this project, the material is purchased from ORPIC (Figure 5).

Figure 5. Spent catalyst

The schematic diagram of methodology is shown in Figure 6.

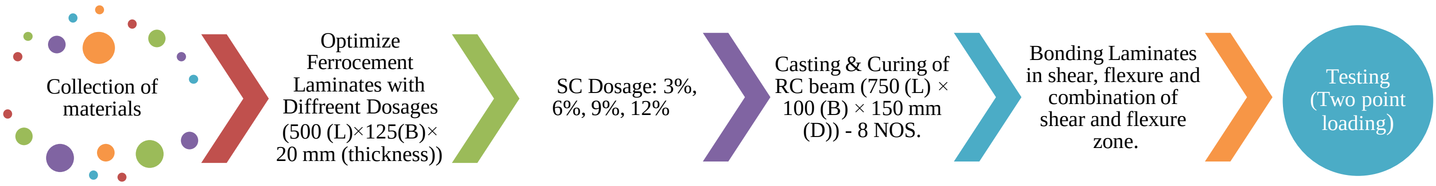

Figure 6. Schematic diagram of methodology

In this project, we conducted a preliminary study to determine what dosage of spent catalyst can be used to partially replace cement and enhance the structural performance of ferrocement laminates. For this study, eight ferrocement laminates were cast by partially replacing cement with spent catalysts at 3%, 6%, 9%, and 12%. Each number was cast with a volume fraction of mesh 3%. In this study, the laminates size was 550 mm × 150 mm × 20 mm.

2.5.1. Cement Mortar Mix

A cement sand mortar mix was used in this study to cast ferrocement laminates. It had a cement sand content of 1:2, with a water cement ratio of 0.45. A spent catalyst was used to replace 3%, 6%, 9% and 12% of the cement.

2.5.2. Preparation of Specimens

A wire mesh of the required size was cut to fit between two layers of mortar (530mm × 130mm). The size of mesh cutting to suit the laminate size with cover is shown in Figure 7.

Figure 7. Mesh Cutting for preliminary study

The casting process of spent catalyse ferrocement laminates with different dosage are shown in Figures 8 and 9. All the laminates are under 28 days curing period.

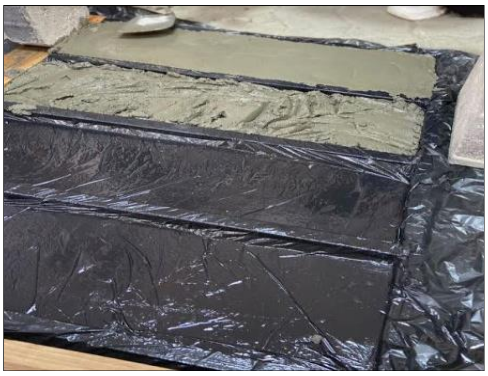

Figure 8. Casting of laminates

Figure 9. Finished laminates

2.5.3. Testing

All the laminates were tested under two point loading condition (Figures 10 to 12). The specimen was loaded gradually until failure the results were analysed.

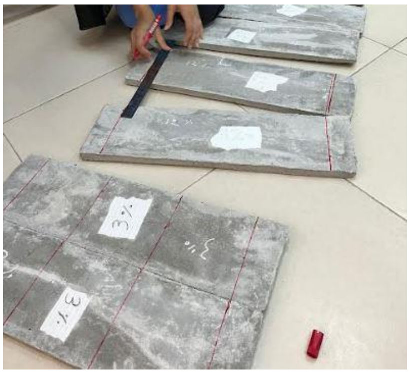

Figure 10. Marking of laminates

Figure 11. Laminates testing setup

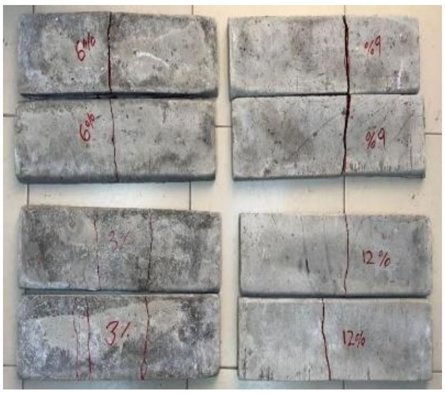

Figure 12. Tested laminates

2.5. Main Study

The main objective of this study is to compare strengthened beams to unstrengthened beam (control beams). In order to carry out this study, eight RC beams of size 750 mm (L) × 100 mm (B) × 150 mm (D) were cast, of which two beams were control beams, and the remaining six beams were strengthened with optimized spent catalyst ferrocement laminates.

2.6.1. Concrete Mix Design

The concrete mix was designed for concrete grade C30 with a water-cement ratio of 0.45 as per ACI and a mix proportion of 1: 2.04: 2.52.

2.6.2. Preparation of Specimens

Using the same previous steps, six optimized spent catalyst ferrocement laminates for flexure, shear, and flexure & shear were cast, and cured for 28 days is shown in Figure 13.

Figure 13. Optimum spent catalyst ferrocement laminates ready for bonding

For the under reinforced beam of size 725 mm (L) × 75 mm (B) × 125 mm (D), four numbers of reinforced steel were designed, the bottom steel being 2H8, nominal top steel being 2H6 and stirrups being H8 @ 75 mm c/c (Figure 14).

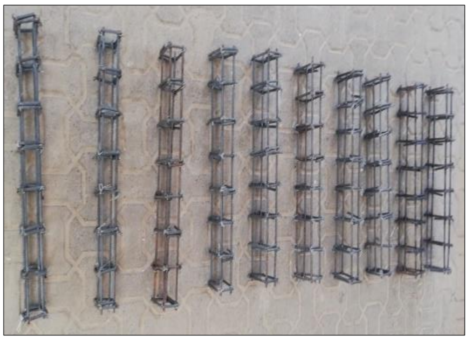

Figure 14. Reinforcement grill

A slump test was conducted before casting of beam. The slump was 50mm, therefore it is an acceptable limit for casting a beam is shown in Figure 15.

Figure 15. Slump test

Casting process of the RC beams are shown in Figures 16 to18.

Figure 16. Reinforcement grill in the mould

Figure 17. Concrete under compaction

Figure 18. Finishing concrete

2.6.3. Bonding

The laminates were attached to the beams by epoxy resin after the beams and spent catalyst ferrocement laminates were cured for 28 days. Prior to cleaning with a brush to remove dust, the soffit, both sides of the beams, and the bonding face of the laminates were roughened to eliminate surface laitance. Epoxy bonding systems with base and hardener in 1:2 ratios with filler were utilized after surface preparation, as shown in the figures. Allow them to air dry for 24 hours after that. Figures 19 and 20 depict how to mix the resin and apply it to the beams and laminates.

Figure 19. Mixing of epoxy resin (base, hardener and filler)

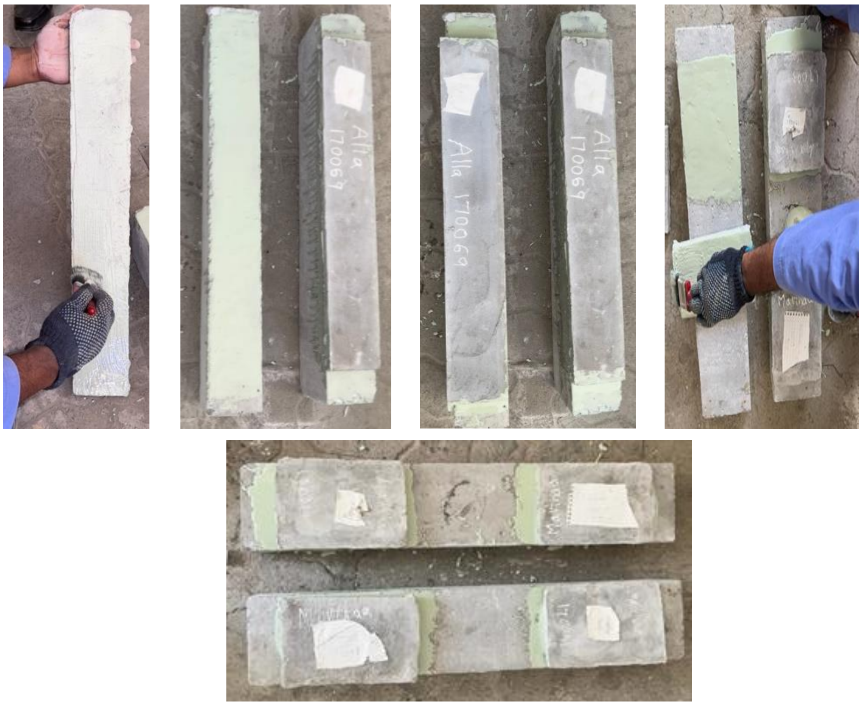

Figure 20. Roughening and bonding beams and laminates

After air curing the bonded beams for flexure, shear and combination of flexure & is ready for testing is shown in Figure 21.

Figure 21. Bonded beams ready for testing

2.6.4. Testing

Under two-point loading over an effective span of 650 mm, all beams (100 mm × 150 mm in cross section and 750 mm in length) were tested simply supported condition for both unstrengthened and strengthened beams are shown in Figures 22 to 25.

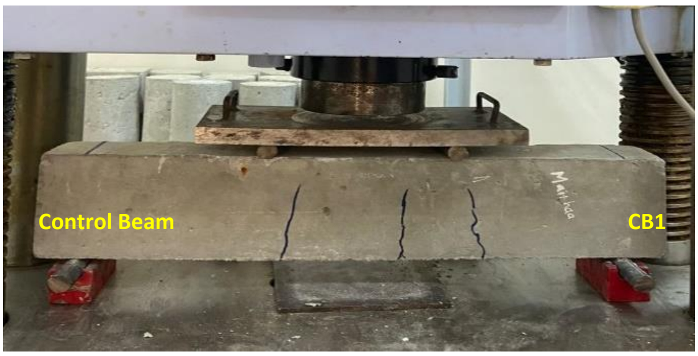

Figure 22. Testing setup for control beam

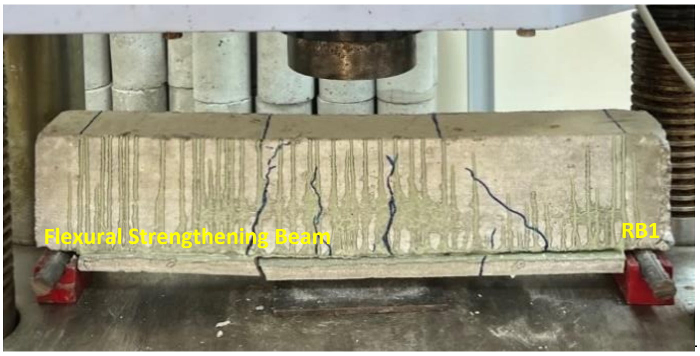

Figure 23. Testing setup for flexural strengthened beam

Figure 24. Testing setup for shear strengthened beam

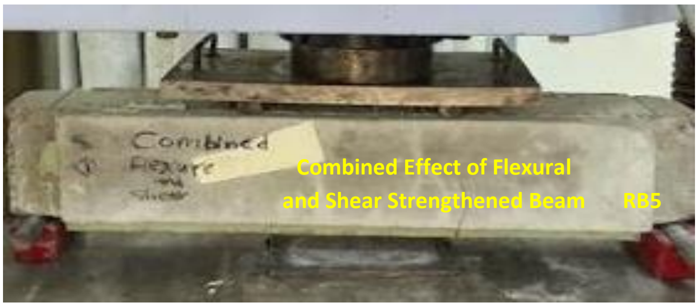

Figure 25. Testing setup for flexural and shear strengthened beam

3. Results and Discussions

Before failing, control beams and modified beams experience the first crack stage, the service stage, the yield stage, and the final stage. As seen in Figures 26 to 29, load-deflection behavior is depicted. First cracks, load-bearing capability, deflection, stiffness, and ductility ratio were a few of the metrics assessed. Tables 2 and 3 show that due to the strength of the ferrocement laminate on the RC beam, the first fractures appeared earlier in the control beam (CB) than the retrofitting beam (RB). The deflection was calculated at a specific load level. The load-carrying capacity of a ferrocement laminate in the final stage, which represents the greatest load the beam can support before failing, determines the laminate's efficacy. According to Table 2, the control beams' ultimate load (CB) is less severe than that of the retrofitting beams (RB). The retrofitted beam outperforms the control beam in terms of load-bearing capacity by 30%, proving the value of ferrocement laminates in RC beam reinforcement. Ferrocement has the capacity to contain and absorb excess strain, which is why retrofitted beams can support heavy loads.

Figures 26 to 29 and Table 2 both show that load and deflection are directly related. Deflection will rise along with an increase in load. Furthermore, at the specific load level, the retrofitted beam exhibits about 20% less deflection than the control beam. Evaluating the retrofitted RC beam at the same stage in comparison to the control beam. The control beam has modest values of deflection, according to Table 2. The control beam deflects more than the strengthened beam under the same load because the ferrocement laminates improve the combined flexural and shear behavior of the reinforced beam. We need to consider the load-deflection response while evaluating ductility. A ductility indicator can be obtained by dividing the final deflection by the yield deflection. Table 3 shows that the retrofitted beams (RB) have greater ductility than the control beams (CB). With respect to control beams, the ductility improved by up to 25%. When a beam is loaded with dispersed stresses, its stiffness determines how flexible it will be. Sturdier beams are more flexible. The stiffness of a simply supported RC beam is computed using the following equation up to the yielding point:

$$\text{Stiffness} = \frac{PL^3}{56.25 \times \delta} \tag{1}$$

Where P is load at yielding point, L is effective span = 650 mm, and δ is deflection at yielding point.

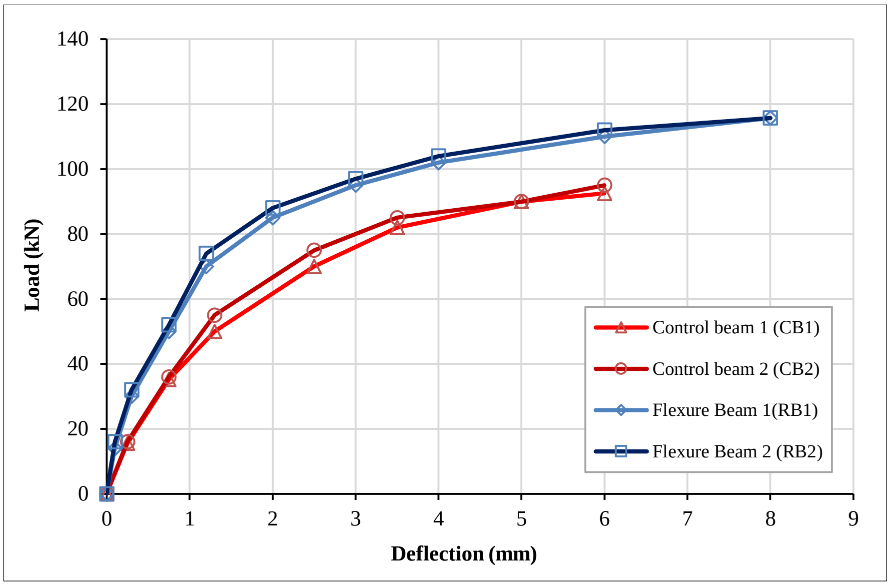

Figure 26. Load-Deflection behavior of control beams and flexural strengthened beams

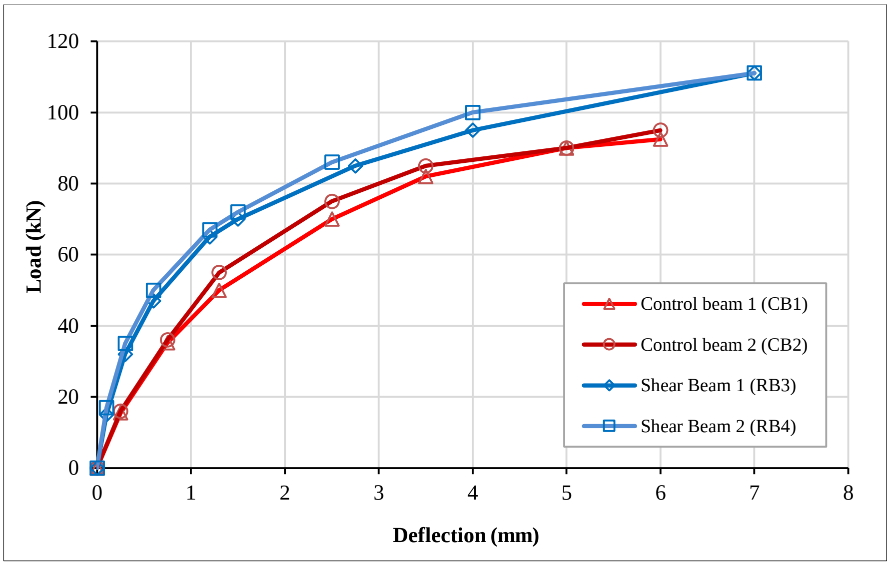

Figure 27. Load-Deflection behavior of control beams and shear strengthened beams

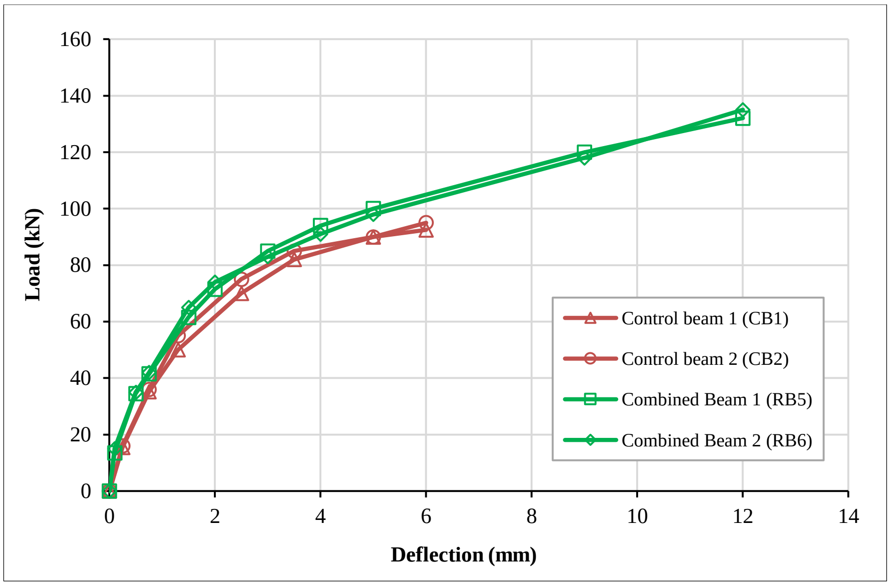

Figure 28. Load-Deflection behavior of control beams and combined flexure and shear strengthened beams

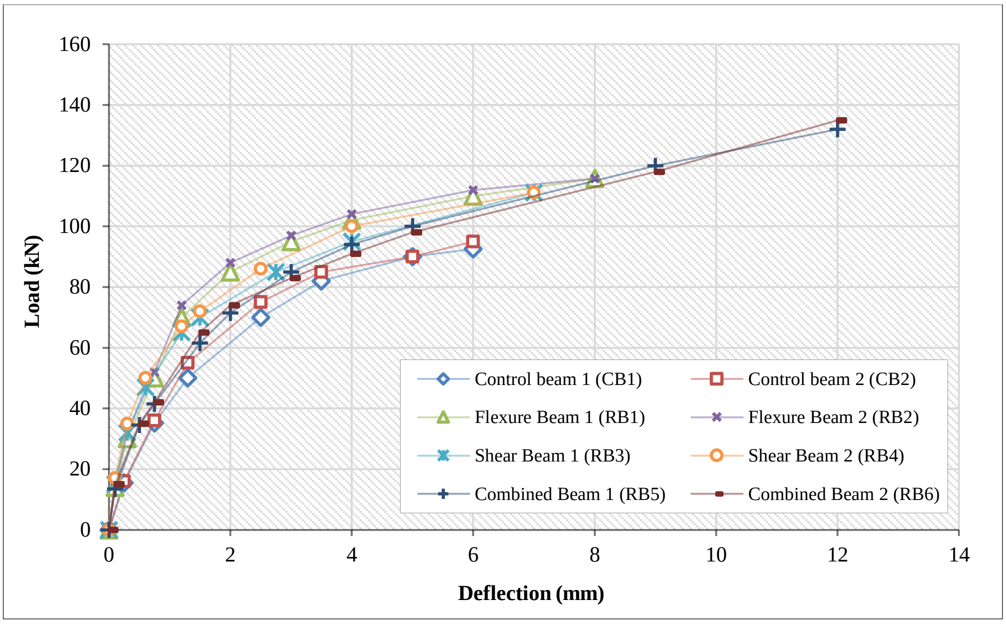

Figure 29. Load-Deflection behavior of control beams and three retrofitting system

Table 2. Test results

Beam Code	First Crack Stage		Service Stage		Yield Stage		Ultimate Stage		Average Crack Width Service Load (mm)
	Load (kN)	Central Deflection (mm)	Load (kN)	Central Deflection (mm)	Load (kN)	Central Deflection (mm)	Load (kN)	Central Deflection (mm)	
CB1	15.50	0.25	61.67	4.00	15.50	0.25	92.50	6.00	0.18
CB2	16.00	0.30	63.33	4.13	16.00	0.25	95.00	6.20	0.17
RB1	14.00	0.10	77.167	5.33	30.00	0.30	115.75	8.00	0.12
RB2	16.00	0.20	76.50	5.46	32.00	0.30	114.75	8.20	0.11
RB3	15.00	0.10	75.33	5.06	35.00	0.30	113.00	7.60	0.12
RB4	17.00	0.20	74.06	5.13	37.00	0.30	111.10	7.70	0.11
RB5	13.50	0.10	88.02	8.30	34.50	0.50	132.04	12.50	0.12
RB6	15.00	0.20	90.00	8.40	35.00	0.50	135.00	12.60	0.11

Table 3. Derived information

Beam Code	Ductility factor	Post-cracking-pre yielding stiffness (kNm^2)	Mode of failure	Type of loading
CB1	24.00	302	Flexure	Static monotonic
CB2	24.80	312	Flexure	Static monotonic
RB1	26.60	488	Flexure	Static monotonic
RB2	27.30	520	Flexure	Static monotonic
RB3	25.33	569	Flexural	Static monotonic
RB4	25.66	602	Flexural	Static monotonic
RB5	25.00	336	Flexure	Static monotonic
RB6	25.20	341	Flexure	Static monotonic

Applying the aforementioned method, it can be deduced that the control beam has a lower stiffness than the retrofitted beam, as indicated in Table 3. It demonstrates that the strengthened beam is more rigid than the control beam, with the reinforced beam using ferrocement laminates contributing greater stiffness and achieving compositeness. Tables 2 and 3 display the outcomes of the tests conducted on the control specimen and the strengthened beam. According to experimental findings, externally bonded ferrocement laminates greatly enhance strength at all load levels and minimize deflections at a given load level. All reinforced beams were also meticulously inspected both before and after testing; as a consequence, failure was not noted at the laminate-concrete interface, indicating that the laminate and concrete beams functioned as a single unit. Across the whole load range, a composite activity was seen.

The crack patterns in the beams were recorded and carefully analysed during the test. According to a preliminary analysis of spent catalyst-based ferrocement laminates, the optimal dosage, which is 9%, provides high flexural strength in comparison to alternative doses. In comparison to the strengthened beam, the control beam's initial fractures appeared earlier. In comparison to the control beam, the reinforced beam's load-carrying capacity increases by 18% for flexure, 16% for shear, and 30% for the combined impact of flexure and shear. The deflection of the strengthened beam decreased by almost 20 to 40% for flexure, 10% to 30% for shear, and 15% to 20% for the combined impact of flexure and shear in comparison to the control beam. With respect to control beams, the ductility also rose by up to 30% for flexure, 25% for shear, and 25% for the combined impact of flexure and shear. Similar to this, the retrofitted beam is stiffer than the control beam by approximately 40% for flexure, 48% for shear, and 30% for the combined impact of flexure and shear. All the tested beams failed in flexure mode only. The beams experienced considerable flexural cracking and vertical deflection near failure. Well-distributed closely spaced cracking was observed. None of the beams exhibited sudden brittle failure. These results clearly demonstrate the effect of the laminates in restraining the opening of cracks and maintaining the general integrity of the section. All the strengthened beams are also carefully examined prior to and after testing. It is found that failure does not occur at the laminate-concrete interface. This confirms that the composite action continues throughout the load spectrum.

4. Theoretical Formulation by Section Analysis

In this section, the theoretical moment - curvature and load - deflection relationships are derived using the section analysis procedure for the control beams and uncracked flexural strengthened beams (RB1) and validated with the experimental results. The theoretical multilinear moment - curvature (M-φ) relationships were derived for all the beams following the procedure given in Park and Paulay for a trilinear M-φ curve. The three important stages or points identified in the M-φ curves are the cracking stage, yielding stage (strain in steel is $f_y/E_s + 0.002$) and the ultimate stage. In this study one more stage which corresponds to the start of non - linearity in stress-strain curve of steel (strain in steel is $0.80\ f_y/E_s$) is proposed and thus making it a multilinear curve. From the multilinear M-φ relationship, multilinear load - deflection curve was derived by adopting a curvature distribution similar to that of a bending moment variation and conjugate beam method of analysis. The same procedure was adopted for uncracked beams bonded with SC based ferrocement laminates.

4.1. Moment-Curvature Relationships

The moment - curvature relationships at the four stages mentioned above can be derived as follows.

Cracking Stage

The moment and curvature corresponding to this stage can be calculated using elastic theory. The cross sections of the control beam and laminated beam are shown in Figure 30. In Figure 30, the breadth of the section is 100 mm, the depth of the section is 150 mm, the clear cover is 20mm, and the span is 750 mm.

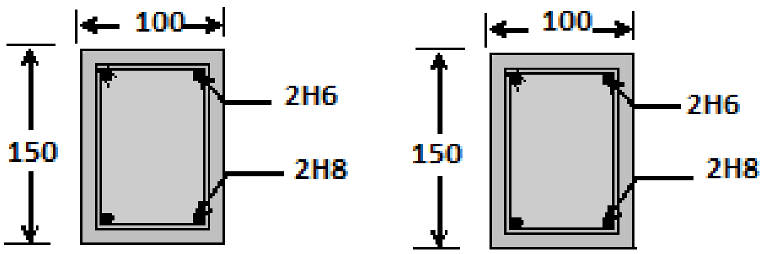

Figure 30. Cross section of control and laminated beams-(All dimensions are in mm)

Effective depth (d) =150 – [20+ (8/2)] = 126 mm (2)

Effective cover at top (d') = [20 + (6/2)] = 23 mm (3)

Cracking moment $M_{cr} = \frac{I_g f_{cr}}{Y}$ (4)

Gross moment of area $I_g = \frac{bD^3}{12}$ (5)

Modulus of rupture f_{cr}=0.7$\sqrt{f_{ck}}$ (6)

Neutral axis distance $Y = \frac{D}{2}$ (7)

Curvature $\emptyset_c = \frac{M_{cr}}{E_c I_g}$ (8)

Stage Corresponding to Start of Non-linearity

$$k = \left[(\rho + \acute{\rho})m_1^2 + 2\left(\left(\rho + \frac{\acute{\rho}d}{d}\right), m_1\right)\right]^{\frac{1}{2}} - (\rho + \acute{\rho})m_1 \tag{9}$$

The strain in concrete, stresses in steel and concrete and the lever arm *'jd'* can be evaluated from the stress - strain variation of the cross section. The stress - strain variation and the force equilibrium across the section are shown in Figure 31.

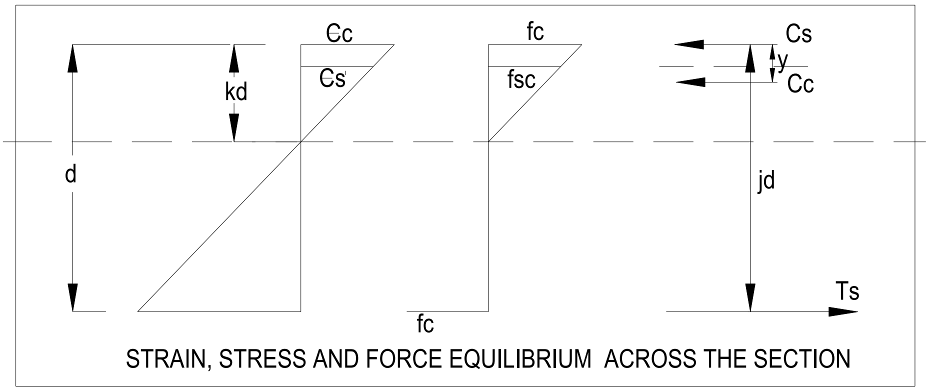

Figure 31. Strain, stress and force equilibrium across the section

At this stage the strain in steel is given by

$$\varepsilon_s = \frac{0.8f_y}{E_s} \tag{10}$$

Resisting moment, $M_{y1} = A_s(0.8f_y)jd$ (11)

Curvature, $\emptyset_{y1} = \frac{\varepsilon_c}{kd}$ (12)

For the laminated beams, Figure 32 shows the stress, strain variation, and the force equilibrium across the section.

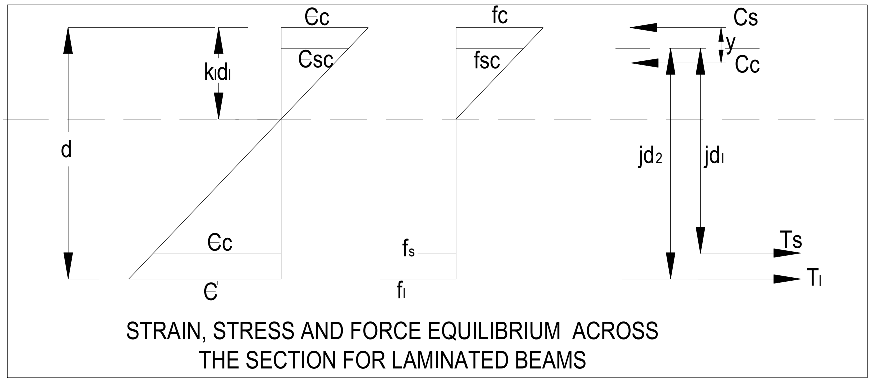

Figure 32. Strain, stress and force equilibrium across the section

The depth of neutral axis factor

$$k_1 = \left[(\rho_1 + \rho_2)^2 m_1^2 + \rho_3^2 m_2^2 + 2\left(\rho_2 \frac{\acute{d}}{d} + \rho_1\right) m_1 + \rho_2 \frac{dl}{l}\right]^{\frac{1}{2}} - [m_1(\rho_1 + \rho_2) + m_2\rho_3] \tag{13}$$

In this stage, the reinforcement in the laminates also starts to yield. The strain in steel in the starting of non - linearity stage $\varepsilon_s = \frac{0.8f_y}{E_s}$ the strain in concrete, strain in laminates, stresses in steel, concrete and laminates and the lever arm from steel and laminates can be evaluated from the stress - strain variation across the cross section.

The strain in concrete, stresses in steel and concrete and the lever arm *'jd'* can be evaluated from the stress - strain variation across the cross section.

$$\frac{\varepsilon_c}{kd} = \frac{\varepsilon_s}{d-kd} = \frac{\varepsilon_l}{dl-kd} = \frac{\varepsilon_{sc}}{kd=\acute{d}} \tag{14}$$

Resisting moment, $M_{y1} = A_s(0.8f_y)jd_1 + A_f(0.8f_y)jd_2$ (15)

Curvature, $\emptyset_{y1} = \frac{\varepsilon_c}{k_1 d_1}$ (16)

Yielding stage

The resisting moment and the corresponding curvature for this stage can be derived using the procedure followed for the previous stage. The strain in steel at this stage can be taken as

$$\varepsilon_s = \frac{f_s}{E} + 0.002 \quad (17)$$

Resisting moment at this yielding stage

$$M_{y2} = A_s\, f_y\, jd \quad (18)$$

Curvature at the yielding stage

$$\emptyset_{y2} = \frac{\varepsilon_c}{kd} \quad (19)$$

Similarly, for laminated beams,

$$M_{y2} = A_s f_y j\, d_l + A_l f_{y1} jd_2 \quad (20)$$

$$\emptyset_{y2} = \frac{\varepsilon_c}{k_l d_l} \quad (21)$$

Ultimate Stage

The ultimate strain is computed using the equation suggested by Corley's Equation, in which the effect of confinement on concrete has also been considered.

$$\varepsilon_{cu} = 0.003 + 0.02\left(\frac{b}{l_c}\right) + \left(\frac{\rho_s f_y}{138}\right)^2 \quad (22)$$

Force equilibrium equations can be considered by assuming a stress-strain curve of confined concrete similar to the one suggested by Soliman and Yu for the evaluation of force of tension and lever arm.

Ultimate moment, M_u = Force of tension × lever arm (23)

Ultimate curvature, $\emptyset_u = \frac{\varepsilon_{cu}}{kd}$ (24)

For laminated beams,

M_{u1} = Force of tension ($T_s + T_l$) × lever arm (25)

$$\emptyset_{ul} = \frac{\varepsilon_{cul}}{k_1 d_1} \quad (26)$$

Loads

For a simply supported beam subjected to two point loads (magnitude of each load is P/2) at one third spans, the maximum bending moment occurs at the middle third zone.

The maximum bending moment can be written as

$$M = PL/6 \quad (27)$$

4.2. Load - Deflection Relationships

Displacements corresponding to the loads can be found out using conjugate beam method of analysis. The theoretical M -φ curves for control beams and strengthened beams are shown in Figure 33 and 34.

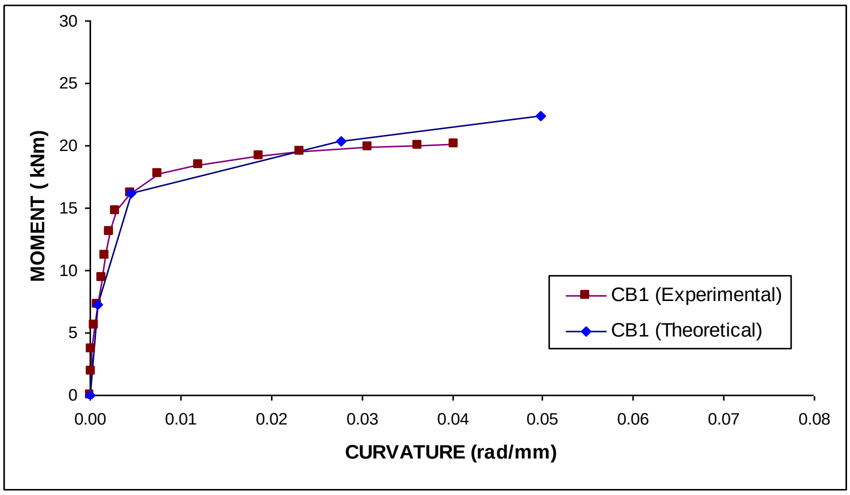

Figure 33. Comparison of theoretical moment - curvature variation for control beam CB1

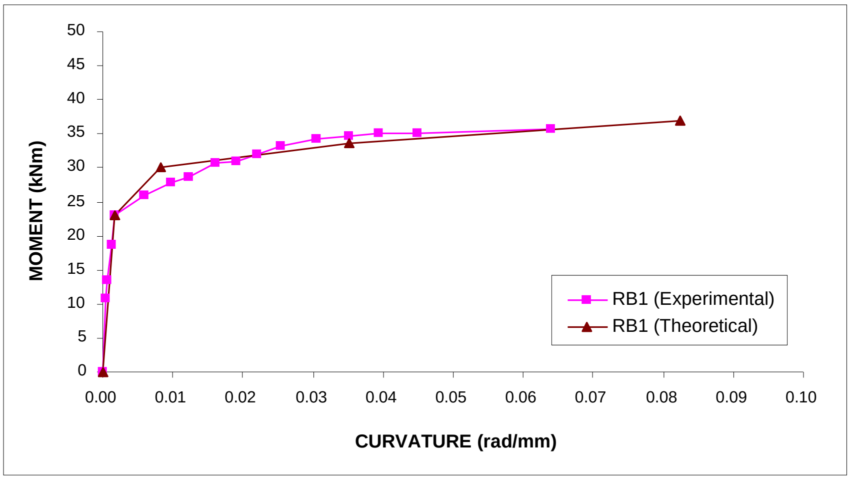

Figure 34. Comparison of theoretical moment - curvature variation for flexure strengthened beam RB1

4.3. Comparison of Experimental, and Theoretical (Section Analysis) Results

The section analysis procedure adopted also provides a simple approach for analysing RC beams bonded with SC based ferrocement laminates. The predicted results in terms of moment-curvature, load - deflection are found to be in fairly good agreement with the experimental results and the variation being 15 percent (Table 4).

Table 4. Comparison of ultimate load

Sl. No	Detail of Beam	Ultimate Loads in kN		Percentage Increase in Flexural Capacity
		Experimental	Theoretical (Section Analysis)	Experimental
1.	CB1	92.50	92.50	-
2.	RB1	115.75	98.38	15

5. Conclusions

Based on the results obtained from experiments and numerical analyses, the following conclusions are drawn:

- The strengthening beams with spent catalyst based ferrocement laminates which properly bonded to the tension, shear and combination of tension and shear face of RC beams can enhance substantially.
- From the preliminary study of spent catalyst based ferrocement laminates it is found that the 9 percent optimum dosage gives good flexural strength compared to other dosages.
- The first cracks started early in the control beam as compared to the strengthened beam. The strengthened beam exhibits an increase in the load-carrying capacity 18 percent for flexure, 16 percent for shear and 30 percent for combined effect of flexure and shear with respect to the control beam.

- At any given load level, the deflection decreases significantly which again causes increase in stiffness.
- The deflection of the strengthened beam was reduced nearly 20 to 40% for flexure, 10 to 30% for shear and 15 to 20% for combined effect of flexure and shear at the same load level with respect to control beam. The ductility also increased up to 30% for flexure, 25% for shear and 25% for combined effect of flexure and shear with respect to control beams.
- Similarly, the stiffness of the retrofitted beam is nearly 40% for flexure, 48% for shear and 30% for combined effect of flexure and shear more than the control beam.
- A flexible epoxy system will ensure that the bond line does not break before failure and participate fully in the structural resistance of the spent catalyst based ferrocement strengthened beams throughout the load spectrum.
- A theoretical (Section Analysis) results proves to be an acceptable predictive tool for the analysis of RC beams strengthened with externally bonded laminates.
- The theoretical solution in terms of ultimate load variation of control beam is matching and spent catalyst based ferrocement strengthened beams exhibits a decrease by 15% variation with the experimental results. It shows a fairly good agreement with the experimental results.
- The spent catalyst based ferrocement laminates gives good evidence about its effectiveness in increasing the flexural and shear strengthening of RC beams retrofitting system.
- None of the beam exhibited pre mature and brittle failure. From the test results it could be concluded that spent catalyst based ferrocement strengthened beams show better performance in all respects when compared to control beams.

6. Declarations

6.1. Author Contributions

Conceptualization, R.B. and A.S.; methodology, M.Y.; software, A.K.; validation, R.B., A.K., and B.B.; formal analysis, R.B.; investigation, A.S.; resources, B.B.; data curation, M.Y.; writing—original draft preparation, R.B.; writing—review and editing, A.K.; visualization, M.Y.; supervision, R.B.; project administration, A.S.; funding acquisition, R.B. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding and Acknowledgements

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6.4. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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