A
DISSERTATION
ON

Retrofitting Of RC Beams Using FRP (Fiber Reinforced Polymer) and Ferrocement Laminates

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SUBMITTED BY:

NITIN MODI

COLLEGE ROLL NO: 13/STR/08
UNIVERSITY ROLL NO: 9093

Under the esteemed Guidance of:

DR. AWADHESH KUMAR

(ASSOCIATE PROFESSOR)

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(FORMLY DELHI COLLEGE OF ENGINEERING)
(UNIVERSITY OF DELHI)
DELHI

CERTIFICATE

DELHI COLLEGE OF ENGINEERING
(Govt. of National Capital Territory of Delhi)
BAWANA ROAD, DELHI – 110042

Date: ______________

This is to certify that the major project entitled **"Retrofitting Of RC Beams Using FRP (Fiber Reinforced Polymer) System and Ferrocement Laminates"** being submitted by me is the bonafied record of my own work carried under the guidance and supervision of Dr. Awadhesh Kumar, Associate Professor, in the partial fulfillment of Master of Engineering in civil engineering with specialization in STRUCTURAL ENGINEERING from the University of Delhi, Delhi.

The matter embodied in this major project has not been submitted for the award of any other degree

NITIN MODI
Enroll No. 13/Str/08
Roll No. 9093

This is to certify that the above statement made by NITIN MODI bearing roll no. 9093 is correct to the best of my knowledge.

Dr. AWADHESH KUMAR
(Project Guide)
Associate Professor
Delhi Technical University

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NITIN MODI

Master of Engineering
(Structure Engineering)
College Roll No: - 13/STR/08
University Roll No: - 9093
Department of Civil and Environmental Engineering
Delhi College of Engineering, Delhi-110042

ABSTRACT

Now a days it is common observation that structures are unable to give service as much as they are expected as per design. This is because of deterioration of the concrete and reinforcements caused by various environmental factors or due to an increase in applied loads.

As a result of structural rehabilitation needs, strengthening and retrofitting of concrete structural parts becomes the major research area for the researchers. The Retrofitting can be used as a cost-effective alternative to the replacement of these structures and is often the only feasible solution.

The main objectives of investigation are to study the structural behavior of reinforced concrete beams strengthened with different Fiber-reinforced polymer (FRP) mainly Glass Fiber-reinforced polymer (GFRP) and Carbon Fiber-reinforced polymer (CFRP) and ferrocement laminates. The objective was achieved by casting and testing of unstrengthened and strengthened beam specimens in flexural and shear, respectively using FRP wrap configration and ferrous cement laminates. The experimental results are analysed and discussed in the light of load deformation behavior and load enhancement characteristics.

Worldwide, a great deal of research is currently being conducted concerning the use of fiber reinforced plastics wrap, laminates and sheets in the repair and strengthening of reinforced concrete members. The experimental results of the present investigation suggests that Fiber-reinforced polymer (FRP) application is a very effective way to repair and strength structures that have become structurally weak over their life span. FRP repair systems provide an economically viable alternative to traditional repair systems and materials.

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CHAPTER-1

INTRODUCTION

1.1 GENERAL

The maintenance, rehabilitation and upgrading of structural members, is perhaps one of the most crucial problems in civil engineering applications. Moreover, a large number of structures constructed in the past using the older design codes in different parts of the world are sometimes structurally unsafe according to the new design codes. Since replacement of such deficient elements of structures incurs a huge amount of public money and time, strengthening has become the acceptable way of improving their load carrying capacity and extending their service lives. Infrastructure decay caused by premature deterioration of buildings and structures has lead to the investigation of several processes for repairing or strengthening purposes. One of the challenges in strengthening of concrete structures is selection of a strengthening method that will enhance the strength and serviceability of the structure while addressing limitations such as constructability, building operations, and budget. Structural strengthening may be required due to many different situations.

• Additional strength may be needed due to a deficiency in the structure's ability to carry the original design loads. Deficiencies may be the result of deterioration (e.g., corrosion of steel reinforcement and loss of concrete section), structural damage (e.g., vehicular impact, excessive wear, excessive loading, and fire), or errors in the original design or construction (e.g., misplaced or missing reinforcing steel and inadequate concrete strength).

• Additional strength may be needed to allow for higher loads to be placed on the structure. This is often required when the use of the structure changes and a higher load-carrying capacity is needed. This can also occur if additional mechanical equipment, filing systems, planters, or other items are being added to a structure.

• Strengthening may be needed to allow the structure to resist loads that were not anticipated in the original design. This may be encountered when structural strengthening is required for loads resulting from wind and seismic forces or to improve resistance to blast loading.

When dealing with such circumstances, each project has its own set of restrictions and demands. Whether addressing space restrictions, constructability restrictions, durability demands, or any number of other issues, each project requires a great deal of creativity in arriving at a strengthening solution.

The majority of structural strengthening involves improving the ability of the structural element to safely resist one or more of the following internal forces caused by loading: flexure, shear, axial, and torsion. Typical strengthening techniques such as section enlargement, externally bonded reinforcement, post-tensioning, and supplemental supports may be used to achieve improved strength and serviceability.

Strengthening systems can improve the resistance of the existing structure to internal forces in either a passive or active manner. Passive strengthening systems are typically engaged only when additional loads, beyond those existing at the time of installation, are applied to the structure. Bonding steel plates or fiber-reinforced polymer (FRP) composites on the structural members are examples of passive strengthening systems. Active strengthening systems typically engage the structure instantaneously and may be accomplished by introducing external forces to the member that counteract the effects of internal forces. Examples of this include the use of external post-tensioning systems or by jacking the member to relieve or transfer existing load. Whether passive or active, the main challenge is to achieve composite behavior between the existing structure and the new strengthening elements.

The selection of the most suitable method for strengthening requires careful consideration of many factors including the following engineering issues:

• Magnitude of increase in strength;

• Effect of changes in relative member stiffness;

• Environmental conditions (methods using adhesives might be unsuitable for applications in high-temperature environments, external steel methods may not be suitable in corrosive environments);

• In-place concrete strength and substrate integrity (the effectiveness of methods relying on bond to the existing concrete can be significantly limited by low concrete strength);

• Dimensional/clearance constraints (section enlargement might be limited by the degree to which the enlargement can encroach on surrounding clear space);

• Accessibility;

• Availability of materials, equipment, and qualified contractors;

• Construction cost, maintenance costs, and life-cycle costs;

• Load testing to verify existing capacity or evaluate new techniques and materials.

1.2 STRENGTHENING USING FRP COMPOSITES

In recent times, the construction market started to use FRP for structural reinforcement, generally in combination with other construction materials such as wood, steel, and concrete. FRPs exhibit several improved properties, such as high strength-weight ratio, high stiffness-weight ratio, flexibility in design, non-corrosiveness, high fatigue strength, and ease of application. The use of FRP sheets or plates bonded to concrete beams has been studied by several researchers. Strengthening with adhesive bonded fiber reinforced polymers has been established as an effective method applicable to many types of concrete structures such as columns, beams, slabs, and walls. Because the FRP materials are non-corrosive, non-magnetic, and resistant to various types of chemicals, they are increasingly being used for external reinforcement of existing concrete structures. From the past studies conducted it has been shown that externally bonded fiber-reinforced polymers (FRPs) can be used to enhance the flexural, shear and torsional capacity of RC beams. Due to the flexible nature and ease of handling and application, combined with high tensile strength-weight ratio and stiffness, the flexible glass fiber sheets are found to be highly effective for strengthening of RC beams. The use of fiber reinforced polymers (FRPs) for the rehabilitation of existing concrete structures has grown very rapidly over the last few years. Research has shown that FRP can be used very efficiently in strengthening the concrete beams weak in flexure, shear and torsion. Unfortunately, the current Indian concrete design standards (IS Codes) do not include any provisions for the flexural, shear and torsional strengthening of structural members with FRP materials. This lack of design standards led to the formation of partnerships between the research community and industry to investigate and to promote the use of FRP in the flexural, shear and torsional rehabilitation of existing structures. FRP is a composite material generally consisting of high strength carbon, aramid, or glass fibers in a polymeric matrix (e.g., thermosetting resin) where the fibers are the main load carrying element.

Among many options, this reinforcement may be in the form of preformed laminates or flexible sheets. The laminates are stiff plates or shells that come pre-cured and are installed by bonding them to the concrete surface with a thermosetting resin. The sheets are either dry or pre-impregnated with resin (known as pre-preg) and cured after installation onto the concrete surface. This installation technique is known as wet lay-up. FRP materials offer the engineer an outstanding combination of physical and mechanical properties, such as high tensile strength, lightweight, high stiffness, high fatigue strength, and excellent durability. The lightweight and formability of FRP reinforcement make FRP systems easy to install. Since these systems are non-corrosive, non-magnetic, and generally resistant to chemicals, they are an excellent option for external reinforcement. The properties of FRP composites and their versatility have resulted in reduction in shut down time of facilities as compared to the conventional strengthening methods (e.g., section enlargement, external post-tensioning, and bonded steel plates).

Strengthening with externally bonded FRP sheets has been shown to be applicable to many types of RC structural elements. FRP sheets may be adhered to the tension side of structural members (e.g., slabs or beams) to provide additional flexural strength. They may be adhered to web sides of joists and beams or wrapped around columns to provide additional shear strength. They may be wrapped around columns to increase concrete confinement and thus strength and ductility of columns. Among many other applications, FRP sheets may be used to strengthen concrete and masonry walls to better resist lateral loads as well as circular structures (e.g., tanks and pipelines) to resist internal pressure and reduce corrosion. As of today, several millions of square meters of surface bonded FRP sheets have been used in many strengthening projects worldwide.

1.3 STRENGTHENING USING FERROCEMENT

Ferro-cement is a composite material consisting of rich cement mortar matrix uniformly reinforced with one or more layers of very thin wire mesh with or without supporting skeletal steel.

American Concrete Institute Committee 549 has defined ferrocement in broader sense as "a type of thin wall reinforced concrete commonly constructed of hydraulic cement mortar, reinforced with closely spaced layers of continuous and relatively small diameter mesh". The mesh may be metallic or may be made of other suitable materials. Ferrocement possesses a degree of toughness, ductility, durability, strength and crack resistance which is considerably greater than that found in other forms of concrete construction .These properties are achieved in the structures with a thickness that is generally less than 25 mm, a dimension that is nearly unthinkable in other forms of construction and a clear improvement over conventional reinforced concrete.

The construction of ferrocement can be divided into four phases:

1. Fabricating the skeletal framing system
2. Applying rods and meshes

3. Plastering
4. Curing phase

Phase 1 and 3 requires special skill while phase 2 is very labour intensive. The development of ferrocement evolved from the fundamental concept behind reinforced concrete i.e. concrete can withstand large strains in the neighbourhood of the reinforcement and magnitude of the strains depends on the distribution and subdivision of the reinforcement throughout the mass of mortar. Ferrocement behaves as a composite because the properties of its brittle mortar matrix are improved due to the presence of ductile wire mesh reinforcement. Its closer spacing of wire meshes (distribution) in the rich cement sand mortar and the smaller spacing of wires in the mesh (subdivision) impart ductility and better crack arrest mechanism to the material. Due to its small thickness, the self weight of ferrocement elements per unit area is quite small as compared to reinforced concrete elements. The thickness of ferrocement elements normally ranges from 10mm to 40mm whereas in reinforced concrete elements the minimum thickness used for shell or plate element is around 75mm. Low self weight and high tensile strength make ferrocement a favourable material for fabrication. With the distribution of small diameter wire mesh reinforcement over the entire surface, a very high resistance to cracking is obtained and other properties such as toughness, fatigue resistance, impermeability also get improved.

In the past 20 years there has been an increase in the field applications and the laboratory research with this type of construction .The major differences between a conventional reinforced concrete structural element and a ferrocement member can be enumerated as follows:

1. Ferrocement structural elements are normally consists of thin sections with thickness rarely exceeding 25mm. On the other hand conventional concrete members consist of relatively thick sections with thickness often exceeding 100 mm.

2. Matrix in ferrocement mainly consists of cement and sand instead regular concrete consist of coarse aggregate.

3. The reinforcement provided in the ferrocement consists of large amount of smaller diameter wire or wire meshes instead of directly-placed reinforcing bars used in reinforced concrete. Moreover, ferrocement normally contains a greater percentage of reinforcement, distributed throughout the section.

4. In terms of structural behaviour, ferrocement exhibits a very high tensile strength and superior cracking performance.

5. In terms of construction, form work is very rarely needed for fabrication.

Metallic meshes are the most common type of reinforcement. Meshes of alkali resistant glass fibers and woven fabric, of vegetables fibers such as jute burlaps and bamboo have also been tried as reinforcement.

1.4 ADVANTAGES AND DISADVANTAGES OF FIBER COMPOSITE STRENGTHENING

1.4.1 ADVANTAGES

The benefits of composite materials have fueled growth of new applications in markets, such as transportation, construction, corrosion-resistance, marine, infrastructure, consumer products, electrical, aircraft and aerospace and appliances and business equipment. The benefits of using composite materials include:

High Strength – Composite materials can be designed to meet the specific strength requirements of an application. A distinct advantage of composites over other materials is the ability to use many combinations of resins and reinforcements, and therefore custom tailor the mechanical and physical properties of a structure.

Light Weight – Composites are materials that can be designed for both light weight and high strength. In fact, composites are used to produce the highest strength to weight ratio structures known to man.

Corrosion Resistance – Composites products provide long-term resistance to severe chemical and temperature environments. Composites are the material of choice for outdoor exposure, chemical handling applications, and severe environment service.

Design Flexibility – Composites have an advantage over other materials because they can be molded into complex shapes at relatively low cost. The flexibility of creating complex shapes offers designers a freedom that hallmarks composites achievement. Composites can be custom tailored to have strength in a specific direction. If a composite has to resist bending in one direction, most of the fiber can be oriented at 90^0 to the bending force. This creates a very stiff structure in one direction. What actually happens is that more of the material can be used where it counts. With metals, if greater strength is required in one direction, the material must be made thicker overall, which adds weight.

Durability – Composite structures have an exceedingly long life span. Coupled with low maintenance requirements, the longevity of composites is a benefit in critical applications. In a half-century of composites development, well-designed composite structures have yet to wear out.

1.4.2 DISADVANTAGES

The main disadvantage of externally strengthening structures with fiber composite materials is the risk of fire, vandalism or accidental damage, unless the strengthening is protected. A particular concern for bridges over roads is the risk of soffit reinforcement being hit by over-height vehicles. However, strengthening using plates is generally provided to carry additional live load and the ability of the unstrengthened structure to carry its own self-weight is unimpaired. Damage to the plate strengthening material only reduces the overall factor of safety and is unlikely to lead to collapse.

Experience of the long-term durability of fiber composites is not yet available. This may be a disadvantage for structures for which a very long design life is required but can be overcome by appropriate monitoring.

A perceived disadvantage of using FRP for strengthening is the relatively high cost of the materials. However, comparisons should be made on the basis of the complete strengthening exercise; in certain cases the costs can be less than that of steel plate bonding.

A disadvantage in the eyes of many clients will be the lack of experience of the techniques and suitably qualified staff to carry out the work. Finally, a significant disadvantage is the lack of accepted design standards.

1.5 APPLICATIONS

It has many applications in aerospace and automotive fields, as well as in sailboats, and notably in modern bicycles and motorcycles, where these qualities are of importance. It is becoming increasingly common in small consumer goods as well, such as laptop computers, tripods, fishing rods, paintball equipment, racquet sports frames, stringed instrument bodies, classical guitar strings, and drum shells.

1.5.1 APPLICATION OF FRP COMPOSITES

- **Column Strengthening:**


FRP System can be used to increase the structural performance of both reinforced concrete, wood and steel encased columns.

The potential structural uses include the following:

- Shear Strengthening
- Displacement-ductility Enhancement
- Single-bending, Double-bending, Flexural/moment Increase
- Axial Load (circular, rectangular) Enhancement
- Torsion Strengthening
- Correction of an Existing Construction and/or Design Error

- **Beam Strengthening:**


FRP Systems can be used to increase the structural performance of both reinforced concrete, steel and wood beams.

The potential structural uses include the following:

- Shear Strengthening
- Positive Moment Enhancement
- Negative Moment Enhancement
- Torsion Strengthening
- Supplement Cut Steel/Openings
- Correction of an Existing Construction and/or Design Error

- **Wall Strengthening:**

FRP Systems can be used to increase the structural performance of both reinforced concrete and masonry walls. The potential structural uses include the following:

- In-plane Shear Strengthening
- In-plane Flexural Enhancement
- Out-of-Plane Flexural Enhancement
- Shear Transfer between Wall Panels
- Supplement Cut Steel/Openings
- Correction of an Existing Construction and/or Design Error

- **Slab Strengthening:**

FRP Systems can be used to increase the structural performance of both reinforced concrete and pre-stressed/post-tensioned slabs. The potential structural uses include the following:

- Positive Moment Enhancement
- Negative Moment Enhancement
- Diaphragm Shear Strengthening
- Punching Shear

- **Chimneys, Tanks, Silos & large diameter Pipelines:**


The FRP System can be used to strengthen Chimneys, Tanks, Silos & large diameter Pipelines. The high strength to weight ratio of these composite materials makes them an ideal alternative to the more cumbersome steel and concrete retrofits.

FRP Systems can be used for the following design goals:

- Seismic Retrofit
- Shear Strengthening
- Flexural Strengthening
- Confinement
- Repair of Corrosion or other Structural Degradation

- **Structural Connections:**


FRP Systems can be used to increase the structural performance of reinforced concrete structural connections. Connections are more complex than other designs and all relevant project parameters must be properly understood before proceeding. We have completed connection strengthening between floor panels and roof panels. We can also enhance wall-to-diaphragm connections and also various beam-column connections. The potential structural uses include the following:

- Joint shear strengthening
- Shear transfer
- Force transfer / Progressive collapse prevention
- Correction of an existing construction and/or design error

1.5.2 Potential Applications for Ferrous Cement

In the last two decades ferrocement has been extensively used in different types of structure as follows:

- **Housing Applications**

Ferrocement has found wide spread applications in housing particularly in roofs, floors, slabs, and walls. Some researches were also made on the use of ferrocement in beams and columns. Ferrocement roofs investigated included shell roofs, folded plates and the channel shaped roofs, box girders and secondary roofing.

Kaushik (1987) investigated the behaviour of ferrocement cylindrical shell units as roofing elements and found that they can be used as roofing elements for low cost housing and satisfy Indian requirements of loading, deflections and crack width with economy.

Jagdish and Radhakrishna (1977) investigated the suitability and effectiveness of using the ferrocement hyperbolic paraboloid shall roofing units for short spans of 4 m. They recommended that the ferrocement hyperbolic paraboloid shell with two layers of chicken mesh is quite adequate.

Other Applications:

Ferrocement applications to water resources structures are numerous. Ferro-cement has been used for:-

1. Water tanks
2. Canal linings
3. Aqueducts
4. Pipes
5. Ferrocement gates
6. Culverts

In India, Structural Engineering Research Centre (SERC) Ghaziabad has conducted extensive research on development of ferrocement for rural applications. This centre had concentrated efforts towards solving problems of farmers.viz grain storage and water storage structures by conducting research on how ferrocement could economically be used for the manufacture of bins, silos and water tanks.

CHAPTER-2

LITERATURE REVIEW

2.1 GENERAL

To provide a detailed review of the body of literature related to retrofitted reinforced cement concrete structures in its entirety would be too immense to address in this thesis. However, there are many good references that can be used as a starting point for research. This literature review and introduction will focus on recent contributions related to retrofitting techniques of the RCC structures, material used for retrofit and past efforts most closely related to the needs of the present work.

2.2 RETROFITTING OF RC BEAMS BY USING FRP

M.C. Sundarraja and Rajamohan (2009) carried out the research by strengthening the RC beams deficient in shear by using GFRP sheets. In this study the response of RC beams strengthened in shear using bi-directional GFRP fabrics was found out. The retrofitting was done by two ways:

1. Using inclined side GFRP strips
2. By providing inclined U-strips of GFRP.

This experiment was aimed at understanding the best wrapping style for retrofitting the deficient beams. In his study five control beams were taken having cross-sectional dimensions of 100 mm ×150 mm and 1000 mm length. From these five beams one beam was fully strengthened. But the other four beams were so designed such that they were shear deficient. The experimental program aimed at raising the strength of the shear deficient beams to that of the fully strengthened beams by externally bonding inclined GFRP strips to the beams. These beams were then raised to the strength of that of the fully strengthened beams by externally bonding the beams with GFRP strips on sides as well as using U-wrap fashion. For the testing of these beams two point loading was adopted. For testing three sets of beams were casted in which one set was of control beam, second set was of beams which were externally bonded with inclined GFRP strips on the sides of shear span and third set of beams were those which was given inclined U-wrap of GFRP strips in the shear span as shown in **fig 2.2 and 2.3.**

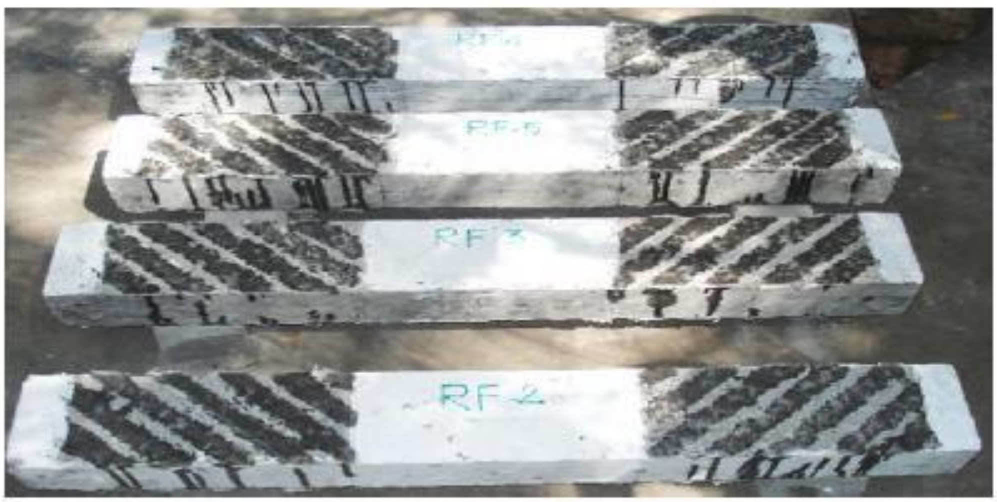


Fig 2.2 GFRP inclined strips of various widths.

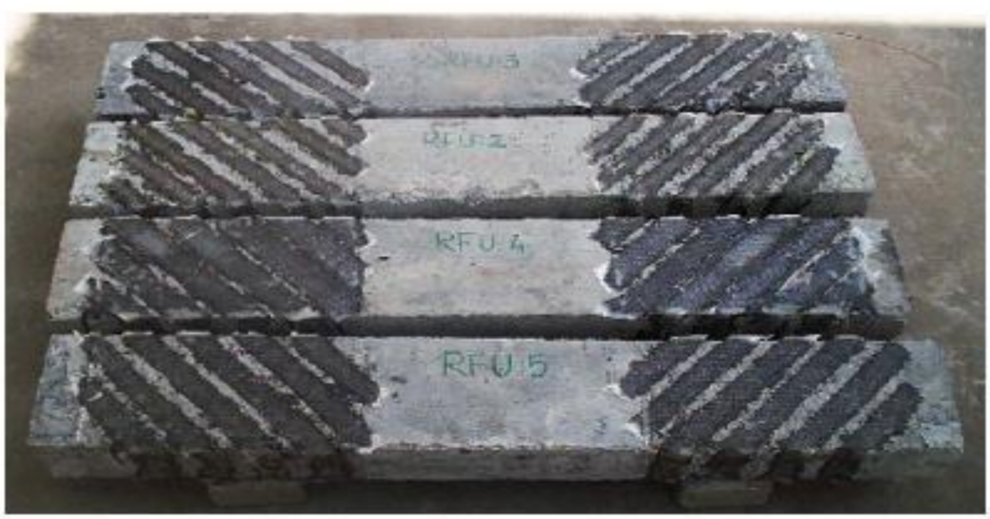


Fig 2.3 GFRP inclined U strips of various widths

Fig 2.4 Experimental Setup

After testing, failure mode and load carrying capacities were observed. Following type of failures were observed, shear failure due to GFRP rupture, shear failure without GFRP rupture, crushing of concrete at the top and flexure failure. Flexural kind of failure was prominent when retrofitting was done using both the wrapping schemes with inclined GFRP strips. Beams retrofitted with GFRP inclined U strips had flexure cracks caused due to rupture of FRP. The retrofitted beams when tested for their ultimate loads were found to have greater load carrying capacity than their corresponding control beams. It was noted that the all the retrofitted beams had ultimate load carrying capacity similar to that of the fully strengthened beam. This is due to the use of GFRP strips. Maximum percentage of increase in ultimate strength of 50% was observed in the beams retrofitted with GFRP inclined strips. Similarly, there is more than 50% increase in strength was observed in the beams retrofitted with GFRP U inclined strips. Initial cracks were delayed in shear deficient beams retrofitted with GFRP strips as compared to their respective control beams. It showed that use of GFRP strips are more effective in the case of strengthening of structures in shear. The ultimate strength of beams can be increased by the use of GFRP inclined strips. The ultimate loads of beams retrofitted with U-wrapping were greater than the beams retrofitted by bonding the GFRP strips on the sides alone as shown in **fig2.5.** The load carrying capacity of the retrofitted beams were found to be greater than that of the control beams, thus the externally bonded FRPs were able to help in taking more load.

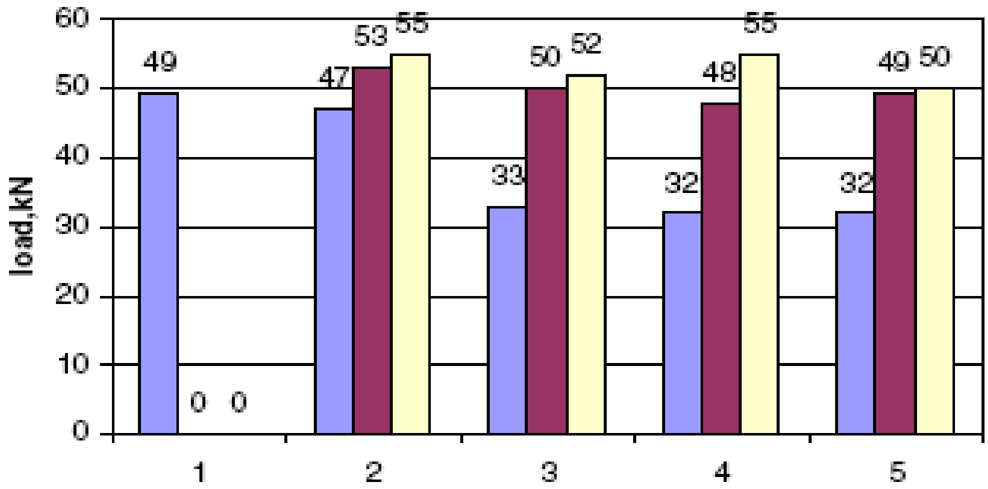


Fig 2.5 Ultimate Loads taken by control beams and retrofitted beams

Blue Graph -Control beams

Red Line –Beams retrofitted with GFRP Inclined Strips

Yellow Line-Beams Retrofitted with GFRP U Inclined Strips.

M. R. Kianoush and M. R. Esfahani (2007) investigated the Flexural behaviour of reinforced concrete beams strengthened by CFRP sheets. In this research they found the effect of reinforcing bar ratio on the flexural strength of the strengthened beams. Reinforcing bar ratio was the main factor that was considered in the research. Twelve concrete beam specimens were casted having dimensions of 150 mm width, 200 mm height, and 2000 mm length .Three different reinforcing ratios were used in these beam sections .Nine specimens were strengthened in flexure by CFRP sheets and the other three specimens were considered as control specimens. The width, length and number of layers of CFRP sheets were varied in different specimens. Bars of size 8,10,12,16 and 20 mm were used in the specimens. CFRP sheets were used for strengthening the beams and adhesive used was hand mixed epoxy. Reinforcing bar ratio in the beams were 30%, 60%, 80% of the tensile reinforcement. At the top two 10 mm diameter deformed bars were used in all the specimens and plain bars of 8 mm diameter were used in transverse reinforcement. Number of layers of CFRP and width of CFRP layers were varied in each specimen. All the specimens were tested under the two point load system by using hydraulic Jack. Displacements measured were the mid span displacements. It was found that as the diameter of bar is increased load carrying capacity of control beams increased. Also when the beams are strengthened by CFRP they exhibit large stiffness as compared to control beams. After yielding of reinforced bars the strength and stiffness of strengthened specimen was larger as compared to control beams. After failure of CFRP, the load–displacement curve of most of the strengthened specimens dropped and almost corresponded to those of the control specimens.

Manuel A.G. Silva and Hugo Biscaia (2007) studied the degradation of bond between FRP and RC beam. The effects of cycles of salt fog, temperature and moisture as well as immersion in salt water on the bending response of beams externally reinforced with GFRP or CFRP, especially on bond between FRP, reinforcement and concrete was considered. Temperature cycles (-10^oC to 10^oC) and moisture cycles were associated with failure in the concrete substrate, while salt fog cycles originated failure at the interface of concrete–adhesive. Immersion in salt water and salt fog caused considerable degradation of bond between the GFRP strips and concrete. However, immersion did not lower the load carrying capacity of beams, unlike temperature cycles that caused considerable loss. No significant differences were detected on the behavior of the systems strengthened with GFRP and CFRP, perhaps because the design of the tests impeded failure of the fibers.

Ayman S. Mosallam and Swagata Banerjee (2007) studied on shear strength enhancement of reinforced concrete beams externally reinforced with fiber-reinforced polymer (FRP) composites. A total of nine full-scale beam specimens of three different classes, as-built (unstrengthened), repaired and retrofitted were tested in the experimental evaluation program. Three composite systems namely carbon/epoxy wet layup, E-glass/epoxy wet layup and carbon/epoxy precured strips were used for retrofit and repair evaluation. Experimental results indicated that the composite systems provided substantial increase in ultimate strength of repaired and strengthened beams as compared to the pre-cracked and as-built beam specimens.

Aouicha Bedday and Benjeddou (2006) studied the damaged reinforced concrete beams repaired by external bonding of carbon fiber reinforced polymer (CFRP) composite laminates to the tensile face of the beam. Two sets of beams were tested in this study: control beams (without CFRP laminates) and damaged and then repaired beams with different amounts of CFRP laminates by varying different parameters (damage degree, CFRP laminate width, concrete strength class). All beams were tested in two-point loading system over a span of 1800 mm. The beams were 120 mm wide, 150 mm high and 2000 mm long. The span of the beam (1800 mm) is limited by the testing machine configuration. After testing these beams were repaired using unidirectional carbon fibers laminates “SIKA CARBODUR LAMELL’’.

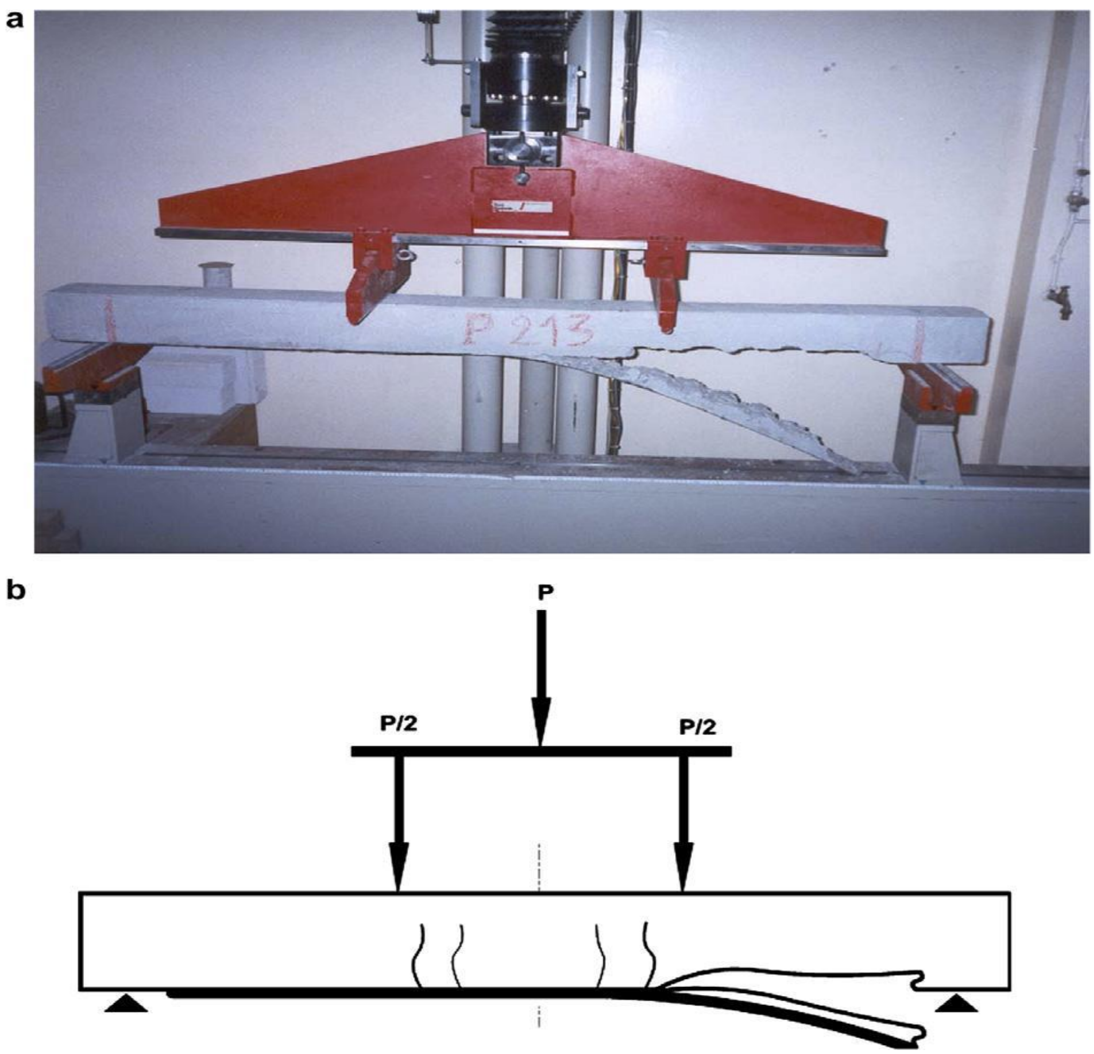


Fig. 2.6 Repaired beam failure by peeling off. (Benjeddou et al, 2006)

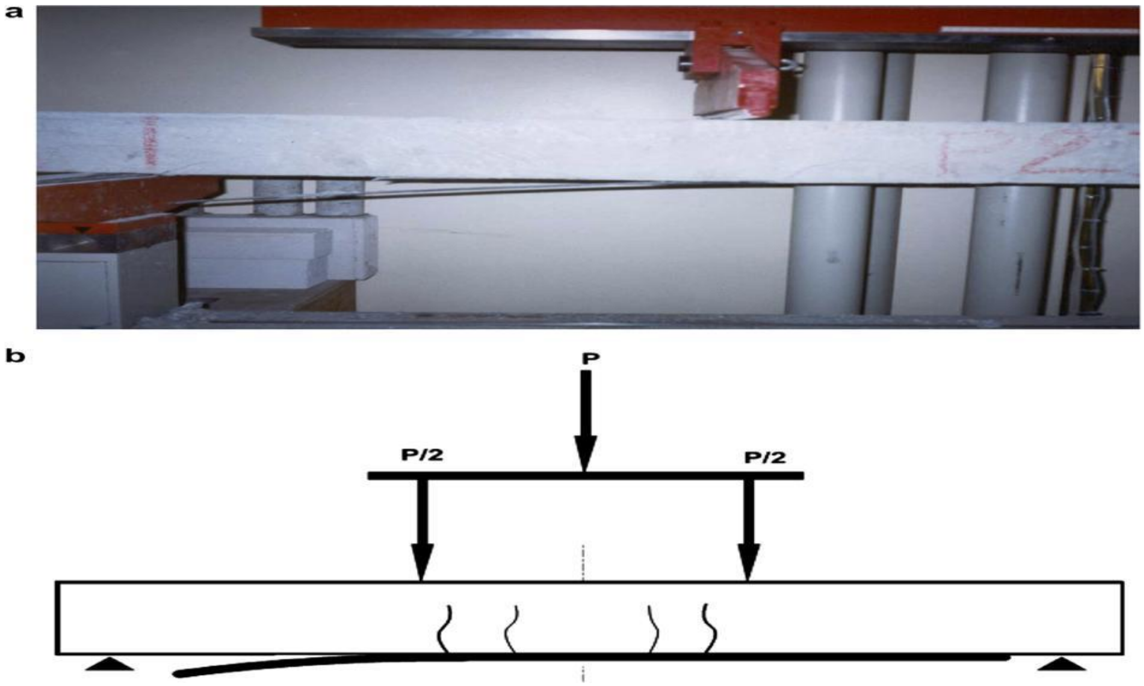


Fig.2.7 A repaired beam failure by interfacial debonding and (b) schematic drawing

Authors concluded that the mechanical performance of the repaired RC beams is highly increased by using the CFRP laminates. Therefore, this technique is effective to at least restore the mechanical performance of cracked or damaged RC beams. The laminate width affects the failure modes of the repaired beams. These failure modes change from interfacial de-bonding to the peeling-off when the width increases from 50 mm to 100 mm **fig.2.6 and fig.2.7**. Also for a load capacity improvement, reinforcement with a CFRP having about a half width of the beam is satisfactory, even when interfacial de-bonding occurs.

L. C. Bank and Dushyant Arora (2006) have done the experimental work in which FRP strips, reinforced with a combination of carbon and E-glass unidirectional fibers and continuous strand mats, were fastened to the concrete beams with steel powder-actuated (PA) fasteners and expansion anchors (EA) and were tested to different failure mode. The strengthened RC beams were designed to fail in a ductile manner. Test results implies that the strengthened beams showed increases in yield and ultimate moments of up to 25% and 58%, respectively over an unstrengthened beam. All strengthened beams failed, as intended, in a ductile manner with the ultimate failure mode due to concrete compression failure at large deflections with the FRP strip still firmly attached.

J.H. Bungey and L.J. Li (2005) performed experimental and numerical analysis to predict the load carrying capacity of reinforced concrete beams strengthened with carbon fiber reinforced plastics (CFRP) composites. Two-point loading system was carried out for rectangular beams in a large testing frame of 2000 KN capacity. Dimensions of the beams were b × h = 120 × 200 mm, length = 2000 mm, clear span = 1800 mm, which were designed as under reinforced. From the tests, it was concluded that CFRP can effectively increase initial cracking loads, ultimate loads, stiffness and ductility of concrete beams and improve crack patterns. The distance from the end of fiber to the support point is the main influencing parameter on de-bonding failure when a single layer fiber is used for strengthening. When the two-layer fibers are used for strengthening, the effect of increase of the length of the second layer of the fiber on performance of beams approaches a constant value if the length of the second layer reaches some limit. CFRP strengthening will have a low ratio of performance to cost under this condition. De-bonding failure of concrete beams strengthened with CFRP occurs before the normal ultimate load, and the high strength property of CFRP cannot be fully utilized. De-bonding failure has greater influence on initial cracking loads than on stiffness, ductility and ultimate loads of concrete beams and it has a lesser influence on crack patterns, but it does affect these behaviour significantly. They concluded that it will greatly influence the performance of strengthened concrete beams and it must be considered sufficiently during the design process. Construction procedures and anchorage design procedures may not avoid de-bonding failure completely.

M. N. S. Hadi (2003) studied the load carrying capacity of beams failed in shear by retrofitting them by Carbon fibers. In his research he studied two objectives, first he investigated the effectiveness of two types of wrapping material in enhancing the shear capacity of reinforced concrete beams, and the second objective was to investigate the increase in the strength and ductility of reinforced concrete beams, where their compressive zone is confined by helical reinforcement. For this work total of sixteen reinforced concrete beam specimens of dimension 1.2m ×100×150 mm were casted. The specimens were designed into four distinct groups, depending on the beams reinforcement arrangement. Group 1 consisted of beams reinforced with 2 bars of 16 mm diameter (500 MPa tensile strength and normal ductility) longitudinal bars.

Group 2 consisted of beams reinforced with 2 bars of 16 mm diameter bars and helices within the compressive zone. While Groups 3 and 4 consisted of 2 bars of 20 mm diameter and 2 bars of 24mm diameter longitudinal bars respectively each with helical reinforcement within the beams in compressive region. 8 beams were retrofitted with CFRP and 8 beams with E glass fiber. Under reinforced beams had two wrapping layers of CFRP and E glass and over reinforced beams and balanced reinforced beams had three layers of CFRP and E glass fiber. All testing specimens were subjected two-point loading. The tested beam specimens which were deficient in shear strength and did not achieve their ultimate flexural strength under loading were to retrofitted for shear strength, the strengthening materials were only applied on the beam at pure shear span as shown in **fig2.8.**

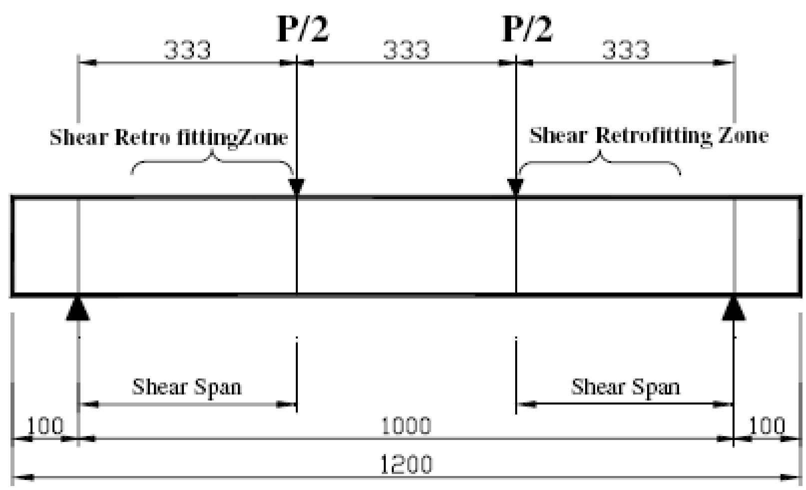


Fig 2.8 Shear Strengthening Configuration (Hadi, 2003)

After all the testing, he concluded that the inclusion of the helical reinforcement proved to increase the performance of the beam in both load carrying capacity and flexural strength, a 3% of strength increment was observed from the test results for beam that failed in bending . It is indicated that retrofitting with FRP provides a feasible rehabilitation technique for repair as well as strengthening and beams strengthened with CFRP display an increase in the beams maximum flexural strength of up to 31% higher compared to that of beams strengthened with E-glass.

Ahmed Khalifa and Antonio Nanni (2000) studied the shear performance of reinforced concrete (RC) beams with T-section. Different configurations of externally bonded carbon Fiber-reinforced polymer (CFRP) sheets were used to strengthen the specimens in shear. The experimental program consisted of six full-scale, simply supported beams. One beam was used as a bench mark and five beams were strengthened using different configurations of CFRP. The parameters investigated in this study included wrapping schemes, CFRP amount, 90°/ 0° ply combination, and CFRP end anchorage.

The test results indicated that the externally bonded CFRP reinforcement can be used to enhance the shear capacity of the beams. For the beams tested in the experimental program, increase in shear strength of 35-145% was achieved. The experimental results show that externally bonded CFRP can increase the shear capacity of the beam significantly. In addition, the results indicated that the most effective configuration was the U-wrap with end anchorage.

V.P.V. Ramana (2000) studied the results of experimental and analytical studies on the flexural strengthening of reinforced concrete beams by the external bonding of high-strength, light-weight carbon fiber reinforced polymer composite (CFRPC) laminates to the tension face of the beam. Four sets of beams, three with different amounts of CFRPC reinforcement by changing the width of CFRPC laminate, and one without CFRPC were tested in four-point bending over a span of 900 mm. The tests were carried out under displacement control. At least one beam in a set was extensively instrumented to monitor strains and defections over the entire range of loading till the failure of the beam. The increase in strength and stiffness provided by the bonded laminate was assessed by varying the width of laminate.

The results indicate that the flexural strength of beams was significantly increased as the width of laminate increased. The first crack ultimate moments of strengthened beams were significantly higher than that of virgin beam indicating the reinforcing effect of the CFRPC laminate. The maximum increase in first crack and ultimate moments were about 150 and 230%, respectively.

Koji Takeda and Hiromichi Sakaiof (1996) studied on flexural behaviour of reinforced concrete (RC) beams strengthened with carbon fibre (CF)-reinforced plastic sheets. The CF sheets were bonded on the soffit of the beam using epoxy resin adhesive. Six medium-sized RC beams were tested in bending to evaluate reinforcing effects of the CF sheets. A large-sized RC beam which was initially Crack-damaged by pre-loading and subsequently repaired by injection of epoxy resin was also tested to simulate the performance in real structures.

The results indicated that the flexural rigidity and strength of the RC beams are increased by reinforcing with the CF sheets. The ultimate strength of the strengthened beams was about 1.9 to 2.4 times higher than that of the virgin beam. However, the reinforcing effect of the sheet had a tendency to be saturated with increase in number of sheets because of separation of the sheets. Beneficial reinforcing effects were also observed for the crack-damaged RC beam.

***M. Arockiassamy and M.A. Shahawy (*1995)** studied the effect of CFRP laminates on reinforced concrete rectangular beams. In their study Flexural behavior of reinforced concrete rectangular beams with epoxy bonded carbon fiber reinforced plastic (CFRP) laminate was experimentally investigated. Four reinforced concrete rectangular beams of size 2.744 × 0.203×0.305 m were casted. First beam was tested and was failed, and then CFRP laminates were applied to the beam. Experiment was conducted by varying the number of laminates .On first beam only one laminate was applied and consequently on others beams number of laminates applied were increased. It was observed that cracking moment for the laminated beams was significantly higher than that of the control beam. The percentage increase in the measured cracking moment was 12%, 61% and 105% for the beam with one, two and three CFRP laminate layers, and the ultimate capacity increased was 13% for beam with one layer of CFRP, 66% and 92 % for the beams with two and three layers of CFRP. The moment capacity increased significantly with the increase in number of CFRP laminates.

2.3 RETROFITTING OF RC BEAMS BY USING FERROUS CEMENT

Hani H. Nassif and Husam Najm (2004) tested on 24 simply supported composite beams under a two-point loading system. All beams are designed to be minimally-reinforced. The beam specimens are classified into two groups. Group (A1) consists of a total of four beams: three composite beams having 4, 6, and 8 layers of square mesh in the one inch thick ferrocement layer, respectively, and one reinforced concrete beam. Group (A2) consists of a total of four beams: three are composite having 4, 6, and 8 layers of hexagonal mesh in the one inch thick ferrocement layer, respectively, and one reinforced concrete beam. Beam specimens with square mesh (Group A1) exhibited better cracking capacity than the control beam as well as beams with hexagonal mesh (Group A2). However, the change in the ultimate capacity was not significant.

M.A. Al-Kubaisy and P.J. Nedwel, (1999) presented the study on the behaviour and strength of ferrocement beams under shear. The results of thirty simply supported beams tested under single concentrated load are presented. The influence of the following variables; shear span to depth ratio (a/h), volume fraction of reinforcement (V_f), and the strength of mortar ($f_{c'}$) on crack patterns, modes of failure and the cracking shear strength were examined . The results indicated that the cracking shear strength of ferrocement beams increases as the a/h ratio is decreased and as $f_{c'}$ and V_f are increased.

An empirical equation is proposed to predict the cracking shear strength. This equation takes into account the effect of variables covered in this study. The proposed equation for computing the cracking shear strength is compared with other test results and also with the ACI Code provisions which are shown to be very conservative.

They had concluded that the mode of shear failure can only be predicted on the basis of a/h and V_f alone. The shear force at failure cannot be relied upon to exceeding the cracking shear. Accordingly the shear force at critical cracking must be considered as the useful shear capacity of beam, moreover we can say that the cracking shear force may be predicted by the lower bound line given by equation

$$\mathbf{V_{cr} / bh = 0.1\, f_{c'}^{1/2} + 55.5\, V_f .h / X_c}$$

Where $X_c = 198\,(a/h)/f_{c'}^{1/2} - 14$

S.F.A. Rafeeqi, S.H. Lodi and Z.R. Wadalawala (1998) Shear mode of failure in beams is undesired mainly being a brittle failure. Therefore, an attempt has been made by S.F.A. Rafeeqi, S. H. Lodi and Z.R. Wadalawala to explore the potentials of ferrocement in transferring the brittle mode to ductile mode.

Ferrocement wrap and equally spaced strips with one or two layers of woven square mesh are presented and compared with RC beam designed as shear deficient (in both) . These researchers from their studies had concluded that the strengthened beam showed a marked improvement in performance at service load, greatly improved ductility at ultimate with either a ductile shear failure or seemingly a transition from shear to flexure mode of failure. Moreover ferrocement wraps are more effective than ferrocement strips.

Another thing of importance deduced is that the enhancement in load carrying capacity is not substantial, however is present. Service range had been able to increase the stiffness of strengthened beams and also reduces the crack width and deflection in comparison with un-strengthened beam.

S.K. Kaushik and V.K Garg (1994) tested reinforced concrete beams to study the effectiveness of externally bonded precast ferrocement plates in strengthening beams showing shear distress. The relative efficacy of the bonding mediameter (C-S mortar, epoxy) used in bonding the pre-cast F.C Plates to the sides of beams were studied. Ferrocement was considered attractive for this application due to its thigh tensile strength, low weight economy in cost, long life of treatment and precise assessment of the additional strength gained by its use.

Cement sand mortar bonding medium was found less effective than epoxy repaired beams, which showed a 20.5 % increase ultimate strength over original beams when subjected to identical loading. This specimen showed 25 % lower deflections than the original beams at the ultimate stage. The studies showed that the technique can be advantageously used for rehabilitation of RC beams failing in shear.

They had concluded from their studies that Ultimate strength characteristics of RC beams can be significantly increased with ferrocement laminates, the increase being 3.5 % corresponding to cement sand mortar and its 20.5 % corresponding to Epoxy bonded specimens. Reduction in deflection was less at working loads strengthened in shear, however 2 % and 25 % reduction was noted corresponding to beams strengthened with cement sand mortar and Epoxy respectively.

Mansur and Ong (1987) found that the shear strength of ferrocement depends on the strength of mortar volume fraction and strength of wire mesh. Shear strength of ferrocement beams with welded wire mesh was found to be more than the shear strength of ferrocement beams reinforced with woven or hexagonal wire mesh. They investigated the behaviour and strength of ferrocement in transverse shear by conducting flexural tests on beams under two symmetrical point loads. The beams were reinforced with only welded wire mesh, with the various layers of mesh lumped together in layers at the top and bottom. Test results indicate that diametergonal cracking strength ferrocement increases as the span to depth ratio is decreased and volume fraction of reinforcement, strength of mortar and amount of reinforcement near compression face is increased. Ferrocement beams are susceptible to shear failure at small span to depth ratios when volume fraction of reinforcement and strength of mortar are relatively high.

Al – Sulaimani (1977) studied the behaviour of hollow box beams under transverse shear conducting flexural tests on 15 numbers beam specimens. The major parameters used were amounts of wire mesh reinforcements in web and in flanges of the beam and shear span to depth ratio. The test results indicate that the cracking and ultimate shear forces increases as wire mesh in web is increased. Placing wire mesh in flanges in web also increases the shear resistance through arresting of the tension cracks and causing them to be finer.

Hence, the shear behaviour is studied with relation to the total volume of wire mesh reinforcement which includes wire mesh in both webs and flanges. The cracking and ultimate shear strength also increases as shear span to depth ratio is decreased. ACI equation for shear strength for conventional reinforced concrete beams without web reinforcement underestimates the cracking shear strength of ferrocement box beams.

The behaviour of ferrocement under direct shear was investigated by Al-Sulaimani by conducting axial compression test on z- shaped specimens reinforced with woven wire mesh producing pure shear on the shear lane .The major study parameters were the volume fraction of wire mesh reinforcement , the shear span and mortar strength.

Conclusions were made from the studies of the behaviour of ferrocement under direct shear as two stages of behaviour namely cracked and uncracked, while ferrocement under flexure exhibits a third stage i.e. ultimate or plastic stage in addition to the uncracked and cracked stages.

Hence ferrocement is less ductile under shear than flexure. The presence of cracked stage in ferrocement behaviour under direct shear increases with increasing amount of wire mesh reinforcement.

They have also found out that the cracking and ultimate shear stresses of ferrocement increases with increasing mortar strength and wire mesh reinforcement, and can be predicted by the following empirical formulae:

$$\boldsymbol{\tau_{cr} = f_t + 450\,V_f}$$

$$\boldsymbol{\tau_{ult} = f_t + 900\,V_f}$$

Where f_t = Mortar tensile strength

V_f = Volume fraction of wire mesh

τ_{cr} = Cracking shear stress.

τ_{ult} = Ultimate shear stress.

The shear stiffness in the un-cracked stage is not significantly affected by the amount of wire mesh when it is significantly affected in the cracked stage. However, the shear stiffness in both the stages is affected by the mortar strength. Regarding ductility of ferrocement in shear they had said that with increasing wire mesh reinforcement ultimate shear displacement increases while with the increase in mortar strength ductility reduces but toughness represented by the area under the shear load and shear displacement curve is not significantly effected. Toughness however increases with increasing wire mesh reinforcement.

Test results indicate that the shear strength of ferrocement in flexural cracking, web shear cracking and web shear failure increased as the shear span to depth ratio was decreased and the volume fraction of wire mesh and volume fraction of longitudinal steel bars in tension flange increased.

CHAPTER-3

MATERIALS AND EXPERIMENTAL SETUP

3.1 GENERAL

The main objective of this experimental program is to study the behavior of under reinforced concrete beams in flexure and shear, when these are strengthened with GFRP and CFRP sheets and ferrocement laminates. The typical results are analyzed in the light of flexure and shear strength enhancement at first crack load and ultimate load and failure mechanism respectively.

3.1.1 TESTING PROGRAMME

The objective of testing programme was to find out the load versus deformation behavior of retrofitted and control beams. The test program involved:

BEAM SPECIMENS FOR FLEXURAL CAPACITY ENHANCEMENT

One set of the beam specimens were tested for flexural capacity enhancement. The set comprised of 12 beam specimens in M20 grade concrete and dimensions 1500× 200× 150 mm. Three beam specimens served as control specimens while rest of the beams were first stressed upto its first crack load then strengthened with CFRP, GFRP sheets and ferrocement laminates.

BEAM SPECIMENS FOR SHEAR CAPACITY ENHANCEMENT

One set of the beam specimens were tested for shear capacity enhancement. The set comprised of 12 beam specimens in M20 grade concrete and dimensions 1500× 200× 150 mm. Three beam specimens served as control specimens while rest of the beams were first stressed upto its first crack load then strengthened with CFRP, GFRP sheets and ferrocement laminates.

3.2 MATERIALS

Cement, fine aggregates, coarse aggregates, reinforcing bars are used in casting of beams and MS welded wire mesh, GFRP and CFRP, cement slurry are used for retrofitting of these beams. Primer is used for preparing base and saturant is used for fixing fibers with beam. The specifications and properties of these materials are as under:

Cement

Ordinary Portland cement of 43 grade from a single lot was taken for the study. The physical properties of cement as obtained from various tests are listed in Table 3.1as per IS: 8112-1989.

Fine Aggregates

The sand used for the experimental works was locally procured and conformed to grading zone III. Sieve Analysis of the Fine Aggregate was carried out in the laboratory as per IS 383-1970. The sand was first sieved through 4.75mm sieve to remove any particle greater than 4.75 mm sieve and then was washed to remove the dust. The physical properties of the sand are shown in Table 3.2 and 3.3.

Coarse Aggregates

Crushed stone aggregate (locally available) of 20mm down are used throughout the experimental study. The physical properties of coarse aggregate are given in Table 3.4 and 3.5.

Water

Fresh and clean water is used for casting the specimens in the present study.

Reinforcing Steel

Mild steel of grade Fe-250 of 12mm and 8mm diameter were used as longitudinal steel. 12mm diameter bars are used as tension reinforcement and 8mm bars are used as compression steel. 8mm diameter bars are used as shear stirrups.

Wire Mesh

MS welded steel wire mesh of 2.4mm diameter with square grids was used in ferrocement jacket. The grid size of mesh was 40X40 mm.

Fiber Reinforced Polymers

The Tyfo SEH 51(GFRP) and Tyfo SCH 11(CFRP) high strength fabric consisted of glass and carbon fibers respectively in the primary direction and Kelvar fibers at 90 degree to the primary fiber direction. Standard rolls of fabric are available.The structural properties of two materials as given by the Fyfe Co. LLC. are given in Table 3.6.

Saturant Epoxy

The Tyfo S Epoxy is a two-component epoxy material for bonding between FRP reinforcement and RC specimen in order to have a composite material. Tyfo component ‘A’ and ‘B’ were mixed in 1:0.42 proportions by volume to have Tyfo epoxy material. Properties of the epoxy material are supplied by Fyfe Asia, Singapore are given in Table 3.7.

Concrete Mix

M20 grade concrete mix is designed as per standard design procedure using the properties of materials as discussed and provided in Table 3.1 to 3.6.The water-cement ratio used in the design is 0.5. The mix proportion of material comes out to be 1:1.72:2.86 (cement: sand: aggregate). The average compressive strength of the concrete was 29 N/mm^2.

Mortar Mix

The range of mix proportion recommended for common ferrocement application are between 1:1.5 to 1:2.5 (cement:sand) by weight, but not greater than 1:3 and water cement ratio by weight, 0.35 to 0.5. The higher the sand content higher is the required water contents to maintain same workability. Fineness modulus of the sand, water cement ratio and sand-cement ratio should be determined from trial batches to ensure a mix that can infiltrate the mesh and develop a strong and dense matrix. In the present study the proportion of cement-sand mortar used for the ferrocement sheets is 1:2 (cement:sand) and the water-cement ratio for mortar taken as 0.40.

Table 3.1 Properties of cement

Sr No.	Characteristics	Values obtained	Indian Standard(IS: 8112-1989) values
1.	Standard consistency	32.5	-
2.	Fineness of cement as retained on 90 micron sieve (%)	4%	Not more than10%
3.	Setting time 1. Initial 2. Final	 55 mins 275 mins	 Not less than30 mins Not more than 600 mins
4.	Specific gravity	3.14	3.15
5.	Compressive strength (N/mm^2) 1. 7days 2. 28 days	 34 44	 <33 <43

Table 3.2: Sieve Analysis of Fine Aggregates

Total weight taken = 1000gm

Sr.No.	Sieve Size	Mass Retained (gm)	Percentage Retained	Cumulative Percentage Retained	Percent Passing
1.	4.75mm	95.0	9.5	9.5	90.5
2.	2.36mm	42.5	4.25	13.75	86.25
3.	1.18mm	110.5	11.05	24.8	75.2
4.	600µm	128.5	12.85	37.65	62.35
5.	300µm	308.0	30.8	68.45	31.55
6.	150µm	281.0	28.1	96.55	3.45
7.	Pan	34.5	3.45		
				Σ = 250.70	Fineness modulus =2.507

Table 3.3 Physical properties of fine aggregates

Sr.No.	Characteristis	Value
1.	Type	Natural Sand
2.	Specific Gravity	2.65
3.	Water absorption	1.02%
4.	Fineness Modulus	2.5
5.	Grading Zone	III

Table 3.4: Sieve Analysis of Coarse Aggregates

Total weight taken = 3000gm

Sr.No.	Sieve Size	Mass Retained (kg)	Percentage Retained	Cumulative Percentage Retained	Percent Passing
1.	20mm	0	0	0	100
2.	12.5mm	2.1865	72.883	72.883	22.117
3.	10 mm	0.6745	22.483	95.366	4.634
4.	4.75mm	0.1300	4.33	99.69	0.31
5.	2.36mm	0.009	0.3	100	-
6.	1.18mm	0	-	100	-
7.	600 µm	0	-	100	-
8.	300 µm	0	-	100	-
9.	150 µm	0	-	100	-
10.	Pan	0	-		-
				Σ = 767.93	Fineness modulus =7.68

Table 3.5 Properties of coarse aggregates

Sr.No.	Characteristics	Value
1.	Type	Crushed
2.	Specific Gravity	2.61
3.	Water absorption	2.37%
4.	Maximum Size	20 mm

Table3.6: Composite gross laminate properties

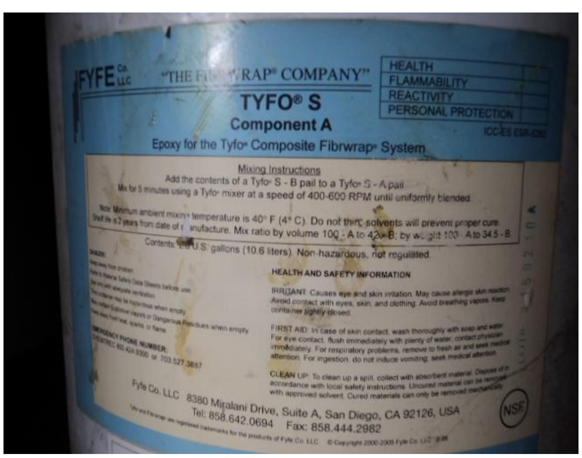
Sr. No.	Properties	ASTM method	Tyfo SCH 11 UP		Tyfo SEH 51	
			Typical test value	Design value	Typical test value	Design value
1.	Ultimate tensile strength in Primary fiber direction(MPa)	D-3039	827	690	575	460
2.	Elongation at break (%)	D-3039	1.0	0.5	2.2	1.76
3.	Tensile Modulus(GPa)	D-3039	82.7	74.5	26.1	20.9
4.	Ultimate tensile strength 90^0 to primary fiber(MPa)	D-3039	0	0	43	34.4
5.	Laminate Thickness(mm)	D-3039	0.6	0.6	1.3	1.3

Fig.3.1: Tyfo SCH 11(Carbon) FRP

Fig.3.2: Tyfo SEH 51(Glass) FRP

Table 3.7: Epoxy Component properties

EPOXY COMPONENT PROPERTIES	
Curing Schedule 72 hours post cure at 140^{o} F (60^{o} C).	
PROPERTY	**TYPICAL TEST VALUE**
Color	Component A is clear to pale yellow Component B is clear
Viscosity	Component A at 77^{o} F (25^{o} C) is 11,000-13,000 cps Component B at 77^{o} F (25^{o} C) is 11 cps
Pot Life	3 to 6 hours at 68o F (20^{o} C)
Viscosity of Mixed Product	600-700 cps
Density at 68^{o} F (20^{o} C) Pound/Gallon	Component A = 9.7 (1.16kg/L) Component B = 7.9 (0.95kg/L) Mixed product = 9.17 (1.11kg/L)



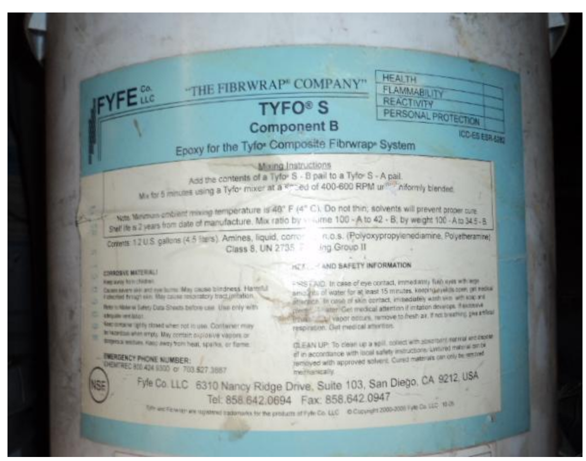


Fig 3.3: Tyfo S Component A **Fig 3.4: Tyfo S Component B**

3.3 RCC BEAM DESIGN

In the present study a total of 24 RCC beams are designed using M20 grade concrete and Fe 250 steel. The RCC beam is designed using limit state method considering it to be an under-reinforced section. Details of the reinforcement are given in table 3.8.

Table 3.8: Details of reinforcement

Sr. no.	**Beam Specimen**	**Longitudinal reinforcement**	**Transverse/Shear reinforcement**
1.	Flexural	2 bars of 8mm diameter (Top) 2 bars of 12mm diameter (Bottom)	8 mm diameter @130 C/C
2.	Shear	2 bars of 8mm diameter (Top) 2 bars of 12mm diameter (Bottom)	8 mm diameter @190 C/C

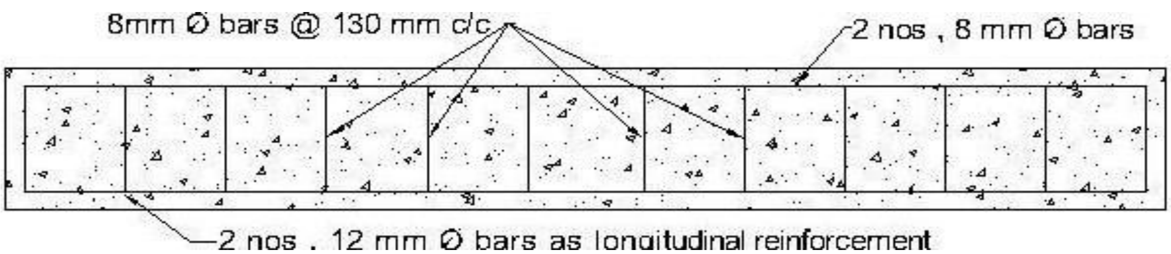


Fig 3.5: Reinforcement detail of beam in flexure

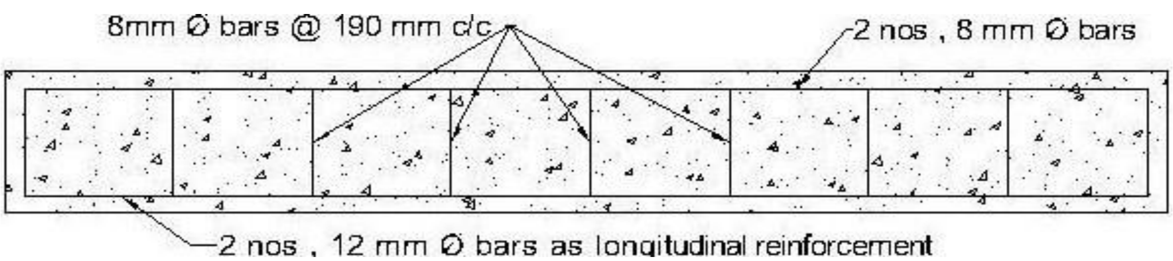
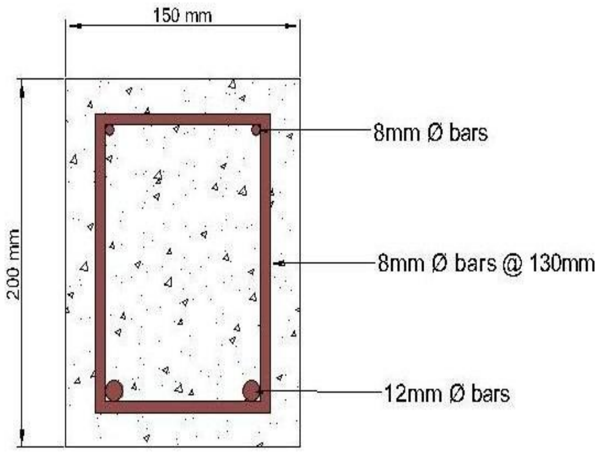


Fig 3.6: Reinforcement detail of beam in shear



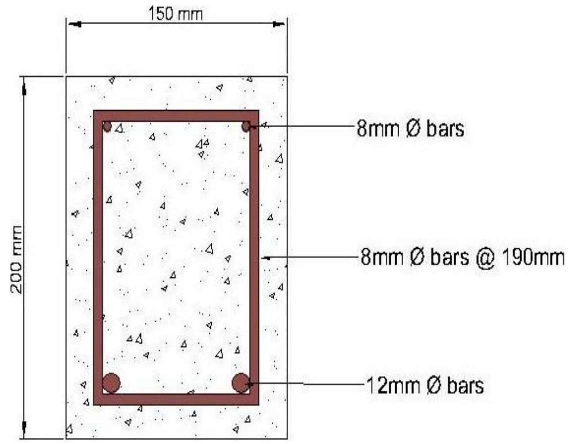


Fig 3.7: Section of beam in flexure **Fig 3.8: Section of beam in shear**

3.3.1 CASTING OF COMPOSITE BEAMS

The casting of beams was done in single stage. Spacers of size 25mm are used to provide uniform cover to the reinforcement. When the bars have been placed in position as per design concrete mix is poured in the mould and vibrations are given with the help of needle vibrator, so that the mix gets compacted. The vibration is done until the mould is completely filled and there is no gap left. The beams are then de-mould after 48 hours. After de-moulding, the beams are cured for 28 days using jute bags.

Fig 3.9: Casting and Curing of RCC Beams

3.3.2 APPLICATION OF FRP COMPOSITE

The FRP composite comprised of woven fiber mat namely Tyfo SEH 51(GFRP) and SCH 11(CFRP), respectively which were saturated in epoxy resin. The specimen surface was saturated with epoxy and woven fiber mat was applied to surface of the member manully by exerting a uniform pressure that distributed across the entire width of the fabric surface so that all air bubbles or air pockets are come out to ensure a uniform and smooth final surface. The FRP composite materials require air curing for 72 hours. All specimens were carefully staggared without any contact with each other and without any contact with the floor or any object to avoid any sticking, for air curing as shown in **fig 3.10**.

Fig 3.10: Application of FRP composites

3.3.3 APPLICATION OF FERROCEMENT

First of all surface of beam is cleaned and after cleaning the surface, the cement slurry is applied on beam for bonding between ferrocement laminate and beam. All 6 beams are retrofitted with wire-mesh at an orientation of 45^0. After that 20 mm plaster in the form of 1:2 cement mortar (w/c=0.4) is applied on three faces of beams. After this the beam is cured for 7 days. Then with the same procedure as of control beam, testing of beams is done under two-point loading in order to calculate ultimate load and corresponding deflections.

3.4 EXPERIMENTAL SETUP

The experimental investigations were carried out on beam specimens to determine shear and flexure capacity under two point load and simply supported end conditions.

3.4.1 TESTING OF BEAM SPECIMEN UNDER FLEXURE

The unstrengthened and strengthened beam specimens were tested under two point loads on the loading frame as illustrated in **fig 3.11**.

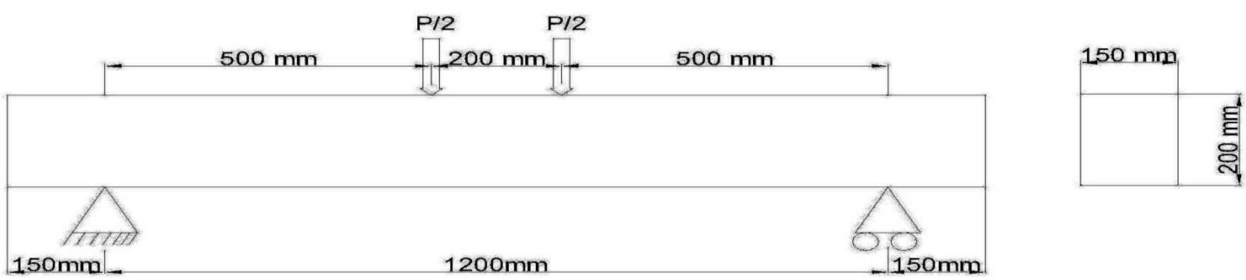


Fig 3.11: Loading arrangement under flexure

The load was applied through 1000 kN hydraulic jack at 500 mm from both the support ends, with simple supports placed at 150 mm from ends. The load was then applied gradually at a constant rate and load versus deflection values were recorded at an interval of 10 kN. The first crack load, ultimate load and corresponding percentage increase in case of unstrengthened and strengthened beam specimens are given in table 3.10.

Table 3.10: Details of beam under flexure

Beam specimen	**First crack load,Pcr (kN)**	**Average value (kN)**	**%age increase**	**Ultimate Load,P_{ul}(kN)**	**Average value (kN)**	**%age increase**	**Remarks**
F1	45	42.33	-	98.4	3.66	-	Control specimen
F2	42			89.2			
F3	40			93.4			
F4C	50	49.66	14.7	112.8	112.6	20.22	Cracked Carbon fiber specimen
F5C	48			108.4			
F6C	51			116.6			
F7G	54	56.33	24.8	125.4	125.53	34	Cracked Glass fiber specimen
F8G	58			130.8			
F9G	57			120			
F10F	45	46.33	8.6	108.6	103.4	10.39	Cracked Ferrous cement specimen
F11F	48			103.2			
F12F	46			98.5			

3.4.2 TESTING OF BEAM SPECIMEN UNDER SHEAR

The unstrengthened and strengthened beam specimens were tested under two point loads on the loading frame as illustrated in **fig 3.12**.

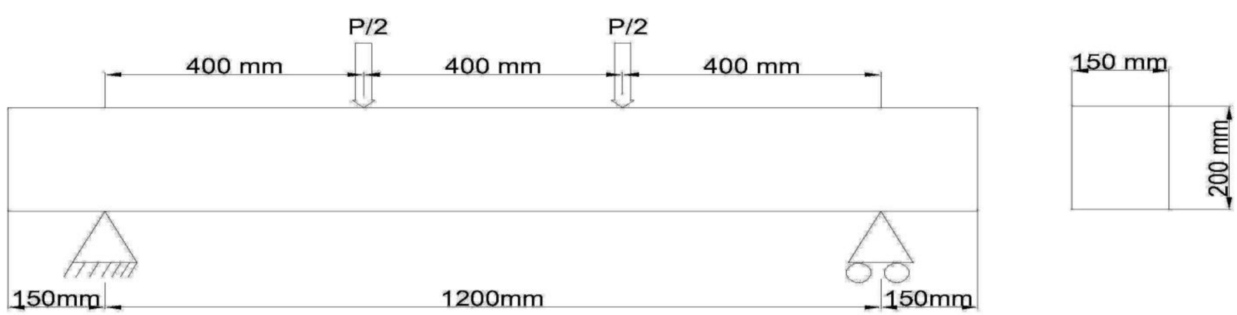


Fig 3.12: Loading arrangement under shear

The load was applied through 1000 kN hydraulic jack at 400 mm from both the support ends, with simple supports placed at 150 mm from ends. The load was then applied gradually at a constant rate and load versus deflection values were recorded at an interval of 10 kN. The first crack load, ultimate load and corresponding percentage increase in case of unstrengthened and strengthened beam specimens are given in table 3.11.

Table 3.11: Details of beam under shear

Beam specimen	First crack load, Pcr (kn)	Average value (kn)	%age increase	Ultimate Load, P_{ul} (kn)	Average value (kn)	%age increase	Remarks
S1	60	62.66	-	125	130.76	-	Control specimen
S2	62			135.5			
S3	66			131.4			
S4C	75	78	19.66	160.5	156.26	16.3	Cracked Carbon fiber specimen
S5C	78			150			
S6C	81			155.8			
S7G	90	92.33	32	175.7	171.1	30.8	Cracked Glass fiber specimen
S8G	95			172.4			
S9G	92			165.2			
S10F	69	70	10.4	150.6	149.5	14.3	Cracked Ferrous cement specimen
S11F	71			152.5			
S12F	70			145.8			

CHAPTER-4

ANALYSIS OF RESULTS AND DISCUSSION

4.1 GENERAL

An extensive experimental programme was planned to investigate structural characteristics of retrofitted beams and control beams in flexure and shear. A total of 24 beam specimens were cast and tested as discussed in Chapter in 3. The typical results are analyzed in the light of flexure and shear strength enhancement at first crack load and ultimate load and failure mechanism respectively.

4.2 BEHAVIOUR IN FLEXURE

4.2.1 LOAD AT INITIAL CRACK

The typical values of first crack load (P_{cr}) and ultimate load (P_{ul}) for the strengthened and unstrengthened beams using one layer of Tyfo SCH 11 (CFRP) and Tyfo SEH 51(GFRP) laminate and ferrocement laminate at beam soffit are given in table 3.10. It was observed that average values of first crack load are found to be 42.33 kN, 49.66 kN, 56.33 kN and 46.33 kN, for control beam, cracked Carbon fiber specimen, cracked Glass fiber specimen and cracked ferrocement specimen respectively , thereby illustrating an increase of load values by about 14.7%, 24.8%, and 8.6 % as shown in **fig.4.1**. This illustrates that the beam retrofitted with Tyfo SEH 51 (GFRP) increases the first crack load, significantly, as compared to Tyfo SCH 11(CFRP) and ferrocement laminates.

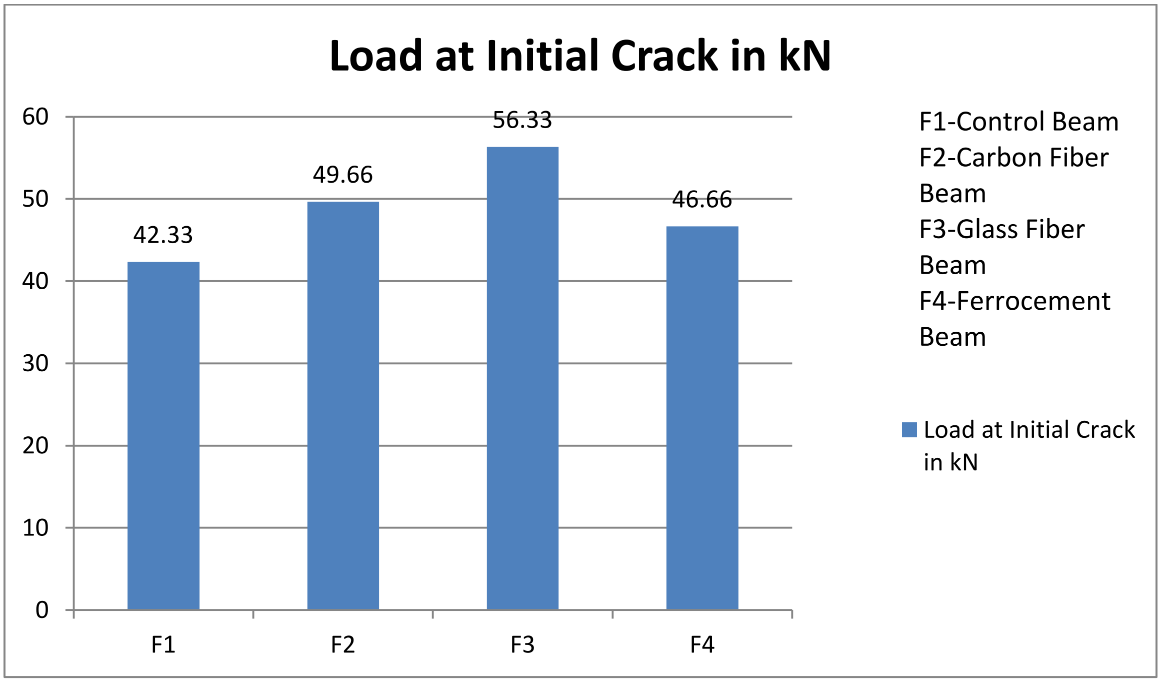


Fig4.1: Load at initial cracks of beams in flexure

4.2.2 ULTIMATE LOAD CARRYING CAPACITY

The ultimate load values similarly, for the strengthened and unstrengthened beam specimens were found to be 93.66 kN, 112.6 kN, 125.33 kN and 103.4 kN for control beam, cracked Carbon fiber specimen, cracked Glass fiber specimen and cracked ferrocement specimen respectively, thereby increasing ultimate load values in strengthened beams by about 20, 34 and 10% respectively as shown in **fig. 4.2**. This illustrates that the beam retrofitted with Tyfo SEH 51(GFRP) increases the ultimate load capacity of beam specimens in flexure, significantly, as compared to the beam retrofitted with Tyfo SEH 51(CFRP) and ferrocement laminates. The Tyfo SEH 51(GFRP) may be therefore used advantageously to enhance flexure capacity of beams and hence to strengthen existing flexural members for increased flexural loads. The Tyfo SEH 51(GFRP), however may also be used for retrofitting of the structures in which case the strength enhancement is significantly marginal.

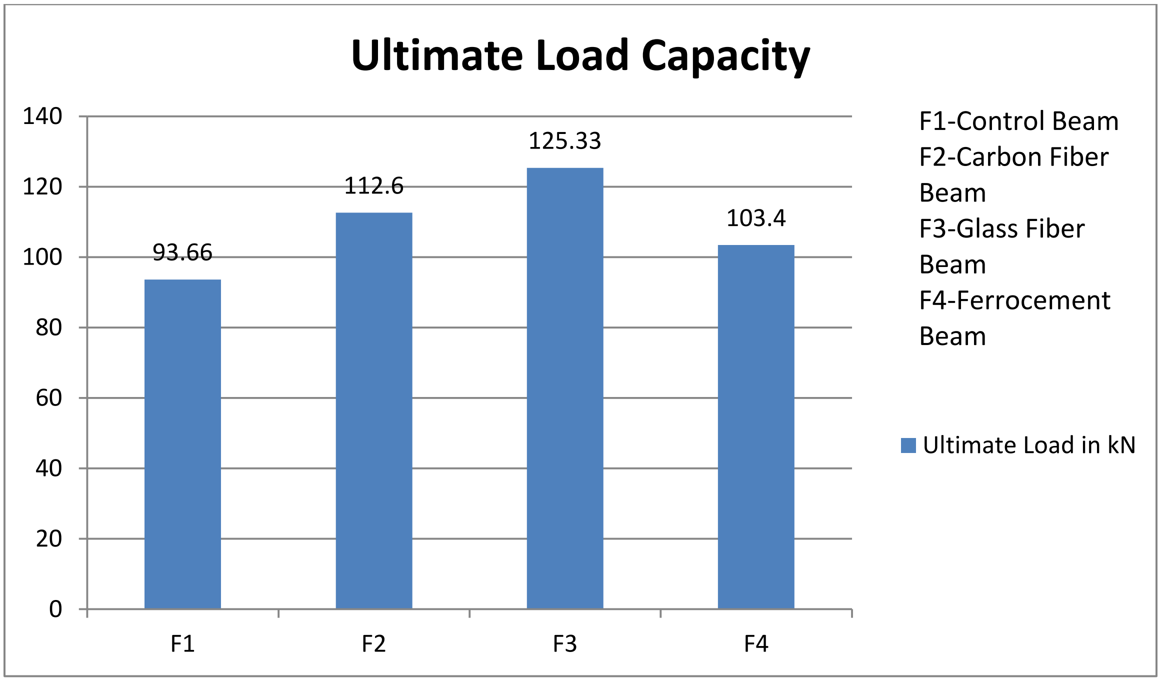


Fig4.2: Ultimate Load Capacity of beams in flexure

4.2.3 LOAD DEFORMATION BEHAVIOUR

The load deformation behaviour of beams in flexure with FRP and ferrrocement laminates is compared with that of control beam specimens. The load deformation curves at mid span are presented in figure from **fig.4.3 to fig.4.7**.

The specimens strengthened with Tyfo SEH 51(GFRP) showed first crack within the constant moment of region of beam. Therefore, a large linear phase was recorded with the development of numerous flexural cracks. In this phase, the deflection `in the FRP sheet increased considerably. The specimens showed debonding failure at both ends. It therefore be concluded that Tyfo SEH 51(GFRP) is considerably effective type of fiber system.

The specimens strengthened with Tyfo SCH 51(CFRP) showed debonding started at one of the flexure cracks in the constant moment region and propagated towards the sheet and until total delamination occurred resulting in rupture of fiber system. It can therefore be concluded that the

Tyfo SCH 11(CFRP) sheet is a more brittle composite material. This type of fiber can be used for light and secondary beam strengthening only. In case of ferrocement specimens, marginal increase in load was observed.

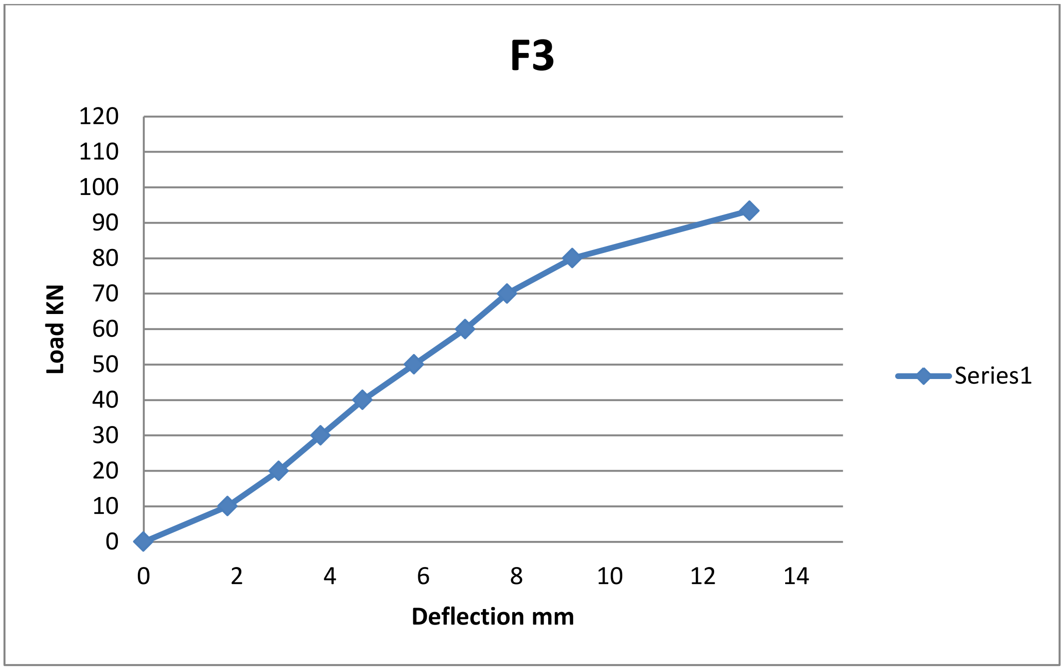


Fig4.3: Load-deflection curve of Control beam in flexure

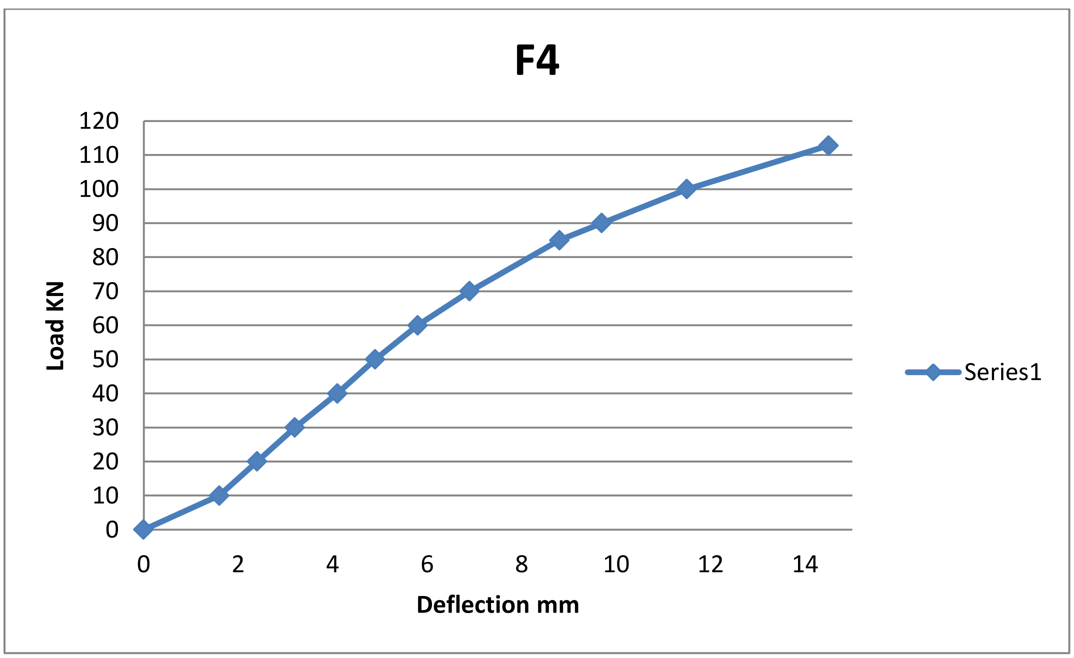


Fig4.4: Load-deflection curve of Tyfo SCH 11 (CFRP) strengthened beam in flexure

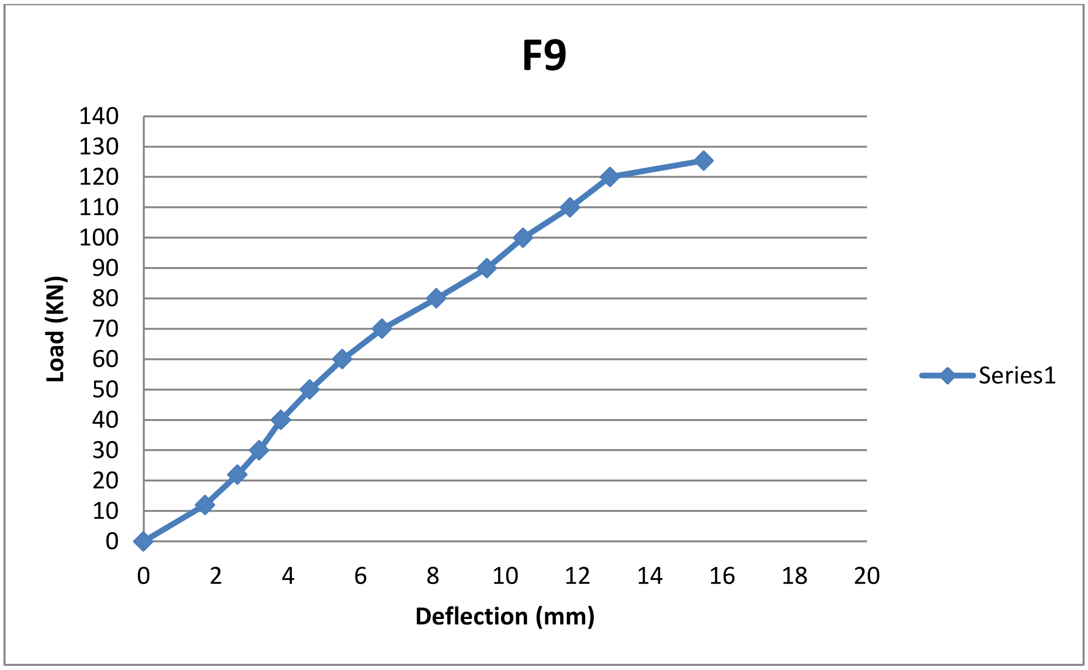


Fig4.5: Load-deflection curve of Tyfo SEH 51 (GFRP) strengthened beam in flexure

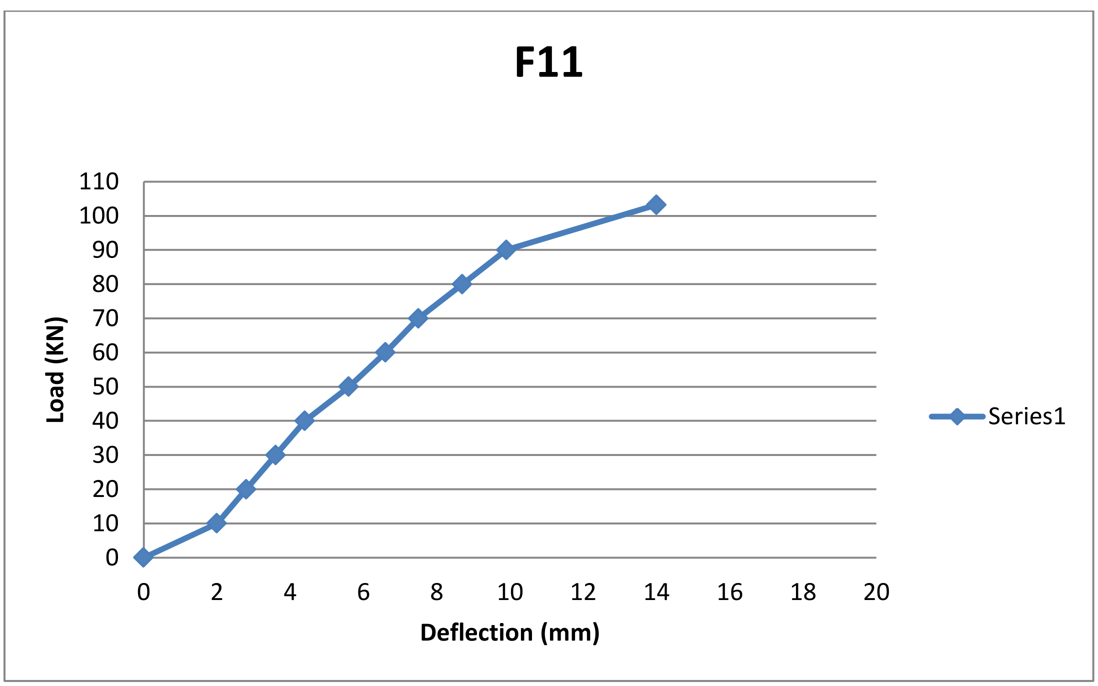


Fig4.6: Load-deflection curve of Ferrocement strengthened beam in flexure

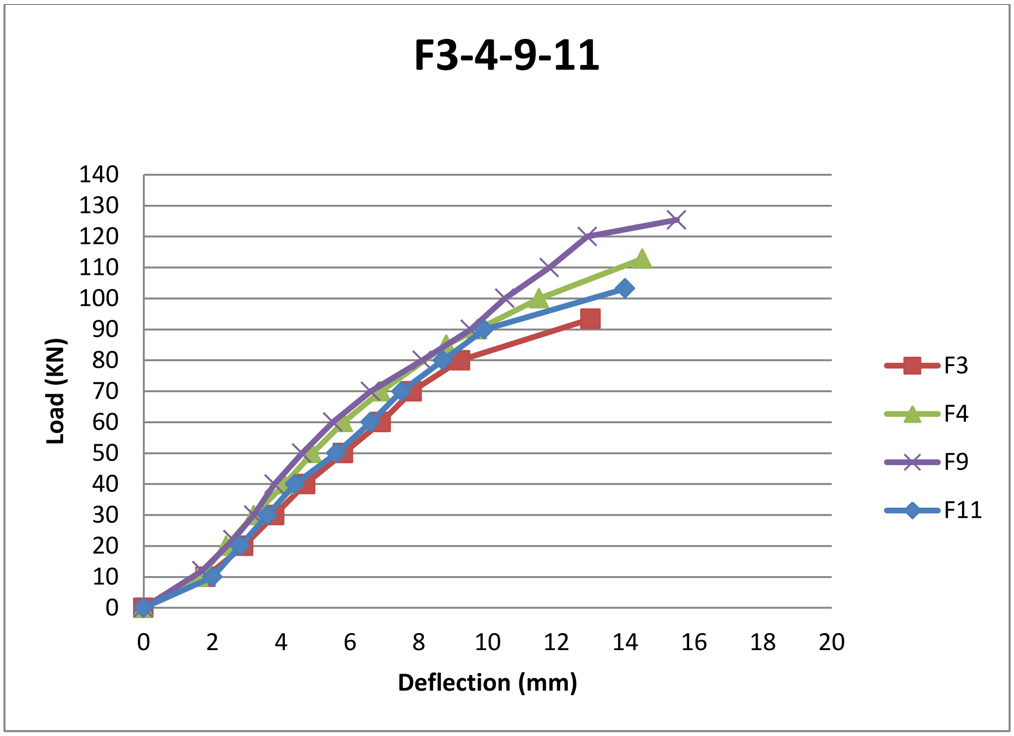


Fig4.7: Load-deflection curves of control and retrofitted beams in flexure

4.2.4 GENERAL FAILURE CHARACTERISTICS

The typical appearance of control beam and retrofitted beams after failure were shown in **fig.4.8** and **fig.4.9**. Flexural cracks were observed initiated randomly in the constant moment region. As load is increased, cracks were observed along the entire length of the beam.

The beam specimen retrofitted with Tyfo SEH 51 at beam soffit exhibit a gradual failure though the final mode of failure was due to debonding.

The beam specimen retrofitted with ferrocement, initial cracks started a higher load as compared to the control beam. Further with increase in loading, propagation of the cracks took place. In beam flexural cracks were developed and finally the beam failed by flexure and crushing of concrete.

a)

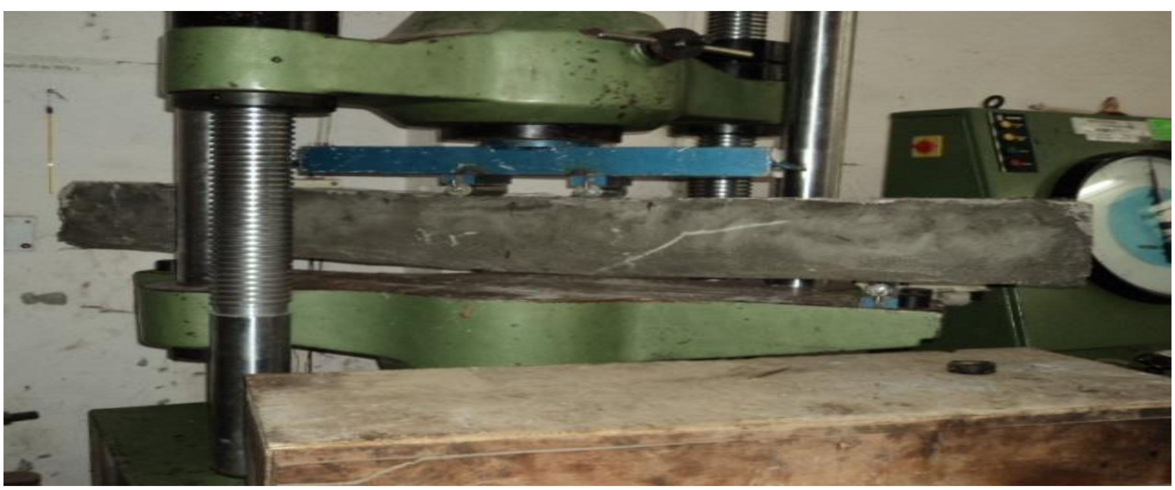
b)

c)

Fig4.8: Failure modes of control beam in flexure

a) **b)**

c)



d)

Fig4.9: Failure modes of strengthened beam in flexure

4.3 BEHAVIOUR IN SHEAR

4.3.1 SHEAR CAPACITY ENHANCEMENT

The typical values of first crack load (P_{cr}) and ultimate load (P_{ul}) for the strengthened and unstrengthened beams using one layer of Tyfo SCH 11 (CFRP), Tyfo SEH 51(GFRP) laminate and ferrous cement laminate at beam soffit are given in table 3.10. It was observed that average values of first crack load are found to be 62.66 kN, 78 kN, 92.33 kN and 70 kN, respectively thereby illustrating an increase of load values by about 19.66%, 32%, and 10.4% respectively as shown in fig.4.16. The ultimate load values similarly, for the strengthened and unstrengthened beam specimens were found to be 130.76 kN, 156.26 kN, 171.1 kN and 149.5 kN for control, Tyfo SCH 11(CFRP), Tyfo SEH 51(GFRP) and ferrocement beam specimen respectively, thereby increasing ultimate load values in strengthened beams by about 16.3, 30.8 and 14.3% respectively as shown in **fig.4.10**. The overall performance of the beam retrofitted with Tyfo SEH 51 was found to be better as compared to Tyfo SCH 11 as well as with ferrocement system.

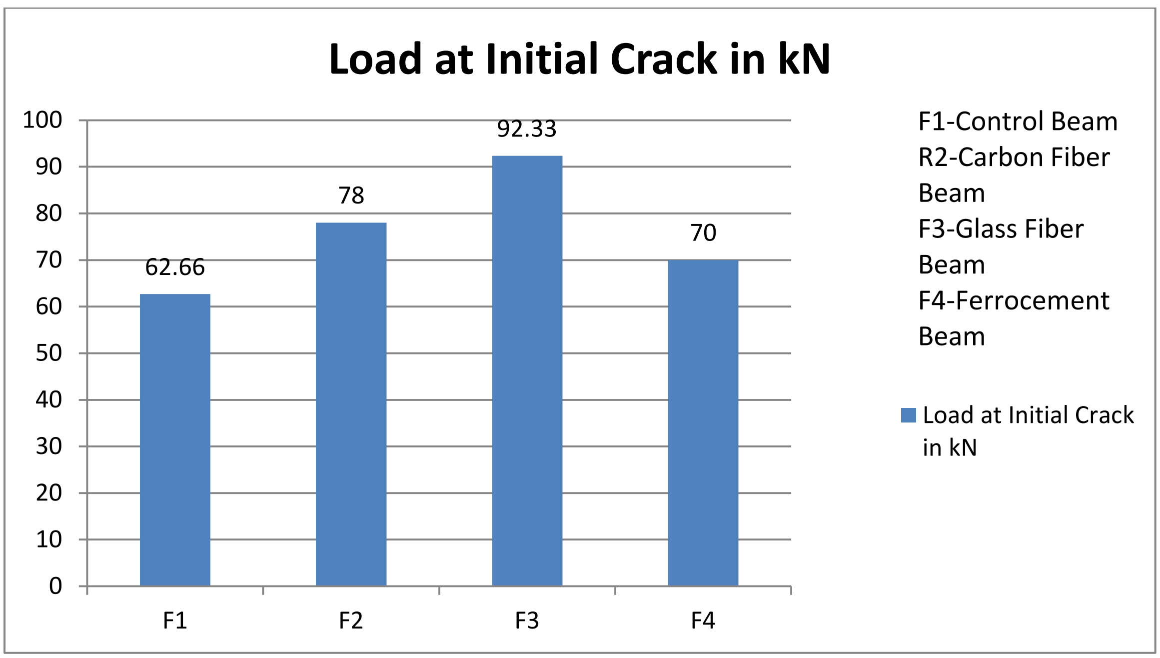


Fig.4.10: Load at initial cracks of beams in shear

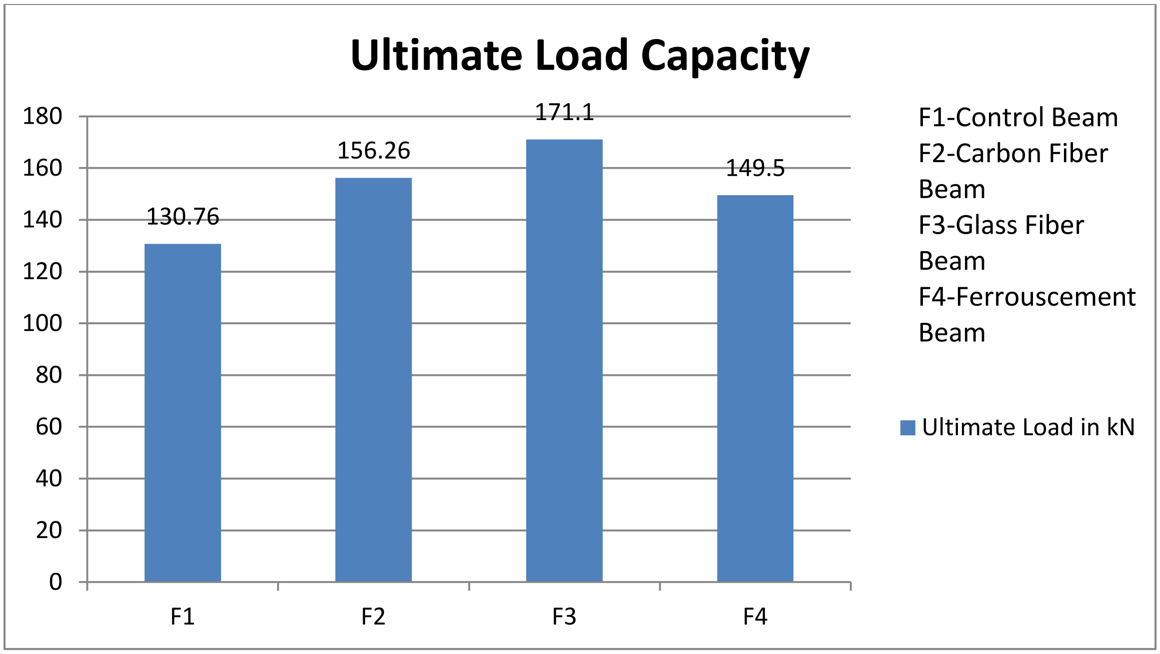


Fig4.11: Ultimate Load Capacity of beams in shear

4.3.2 LOAD DEFORMATION BEHAVIOUR

The load deflection history of all the beams was recorded. The mid-span deflection of each beam was compared with that of their respective control beams as shown in **fig.4.12 to fig.4.16**. It has been observed that all the beam specimens experienced brittle shear failure mode by developing diagonal tension cracks in the constant shear span. The diagonal cracking was followed by debonding of fiber wrapping system. The beams with Tyfo SEH 51(GFRP) system with full wrap are found to be more effective when compared with Tyfo SCH 11(CFRP) system and ferrocement laminate. The ultimate deformations found to be more in case of Tyfo SEH 51(GFRP) as compared to others. It may be therefore concluded that Tyfo SEH 51(CFRP) is more effective in increasing the ultimate load carrying capacity of the beam.

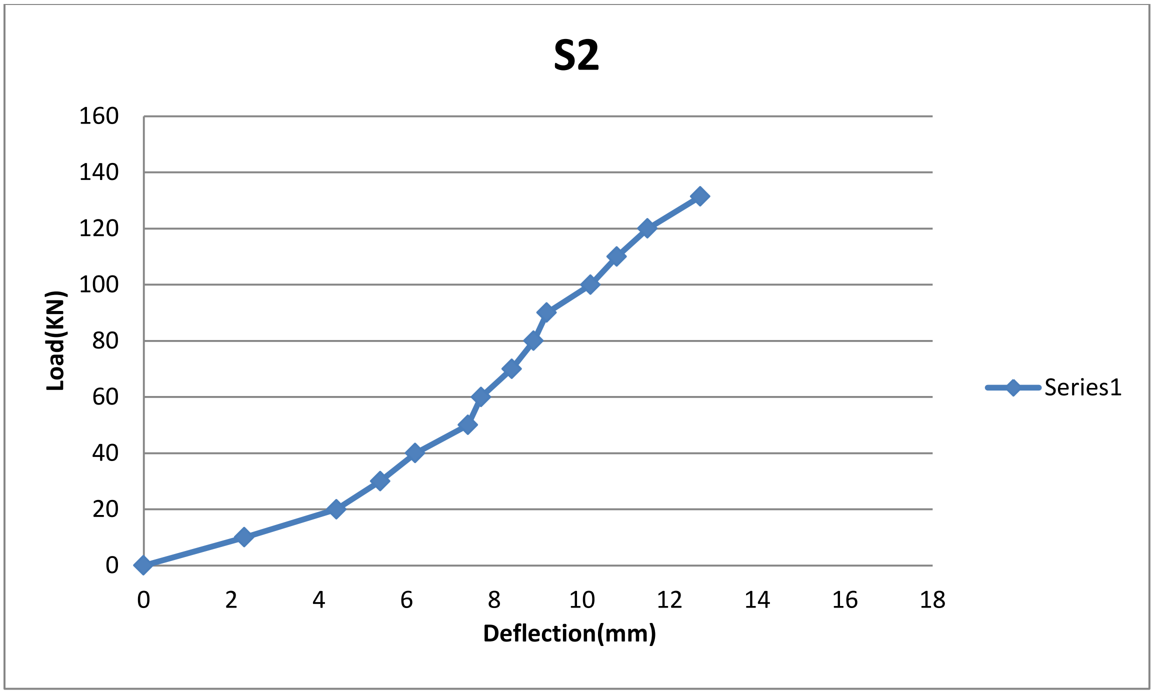


Fig4.12: Load-deflection curve of Control beam in shear

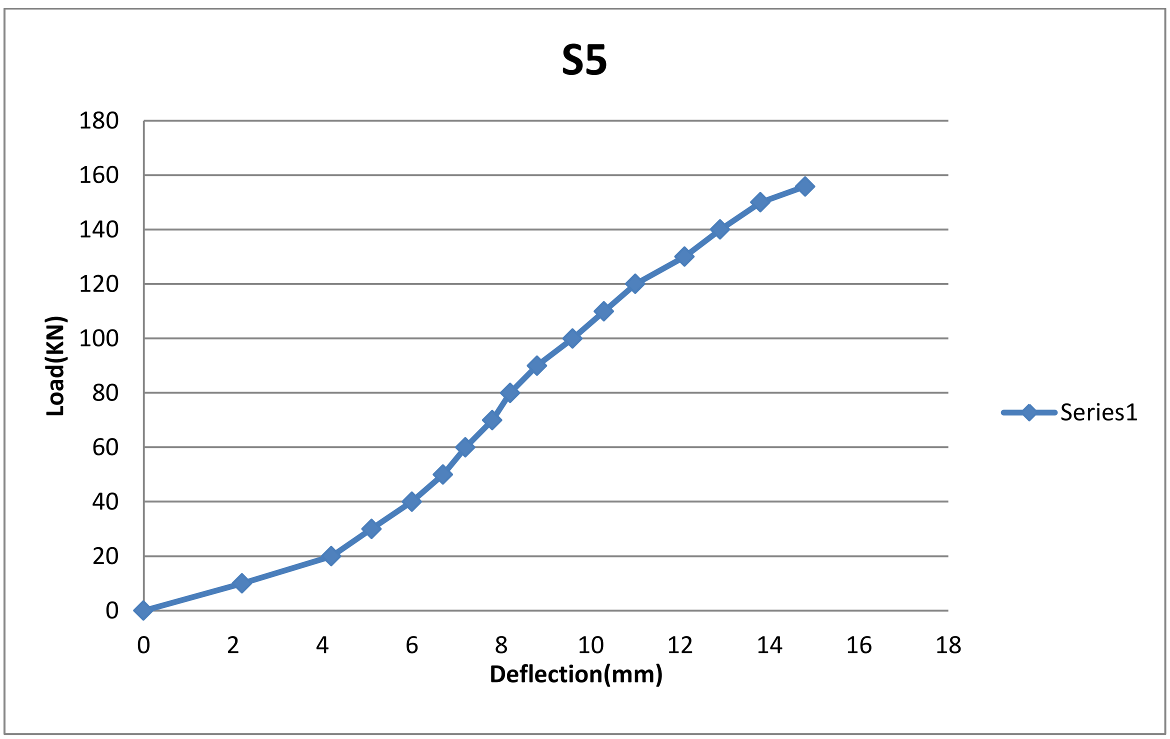


Fig4.13: Load-deflection curve of Tyfo SCH 11 (CFRP) strengthened beam in shear

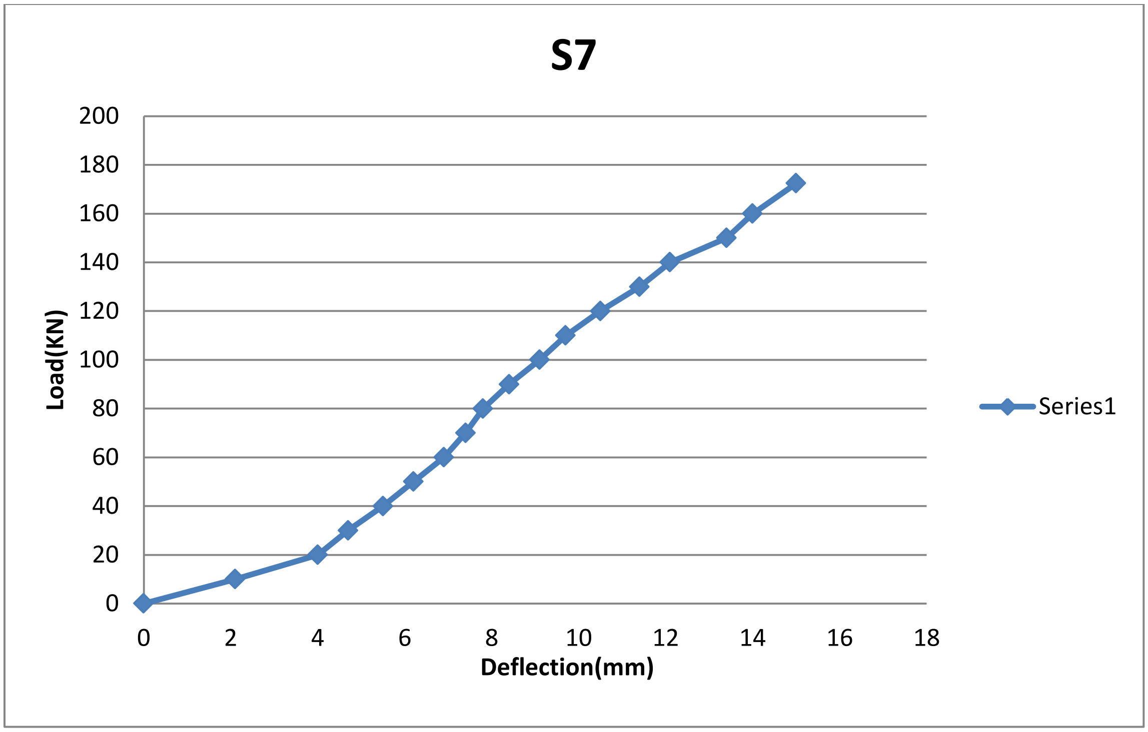


Fig4.14: Load-deflection curve of Tyfo SEH 51 (GFRP) strengthened beam in shear

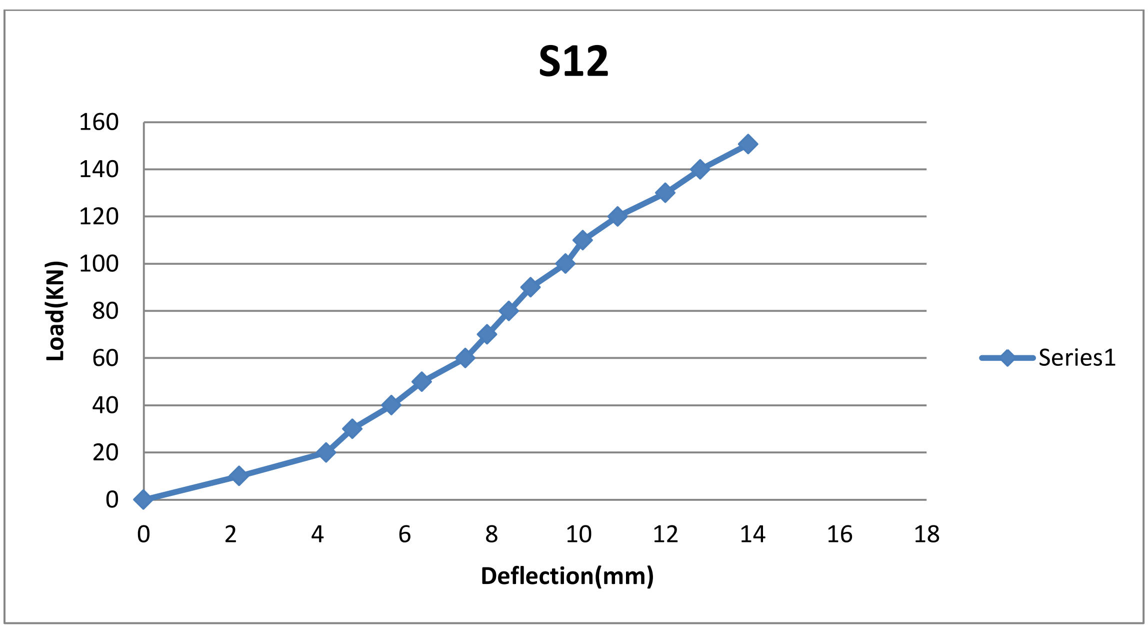


Fig4.15: Load-deflection curve of Ferrocement strengthened beam in shear

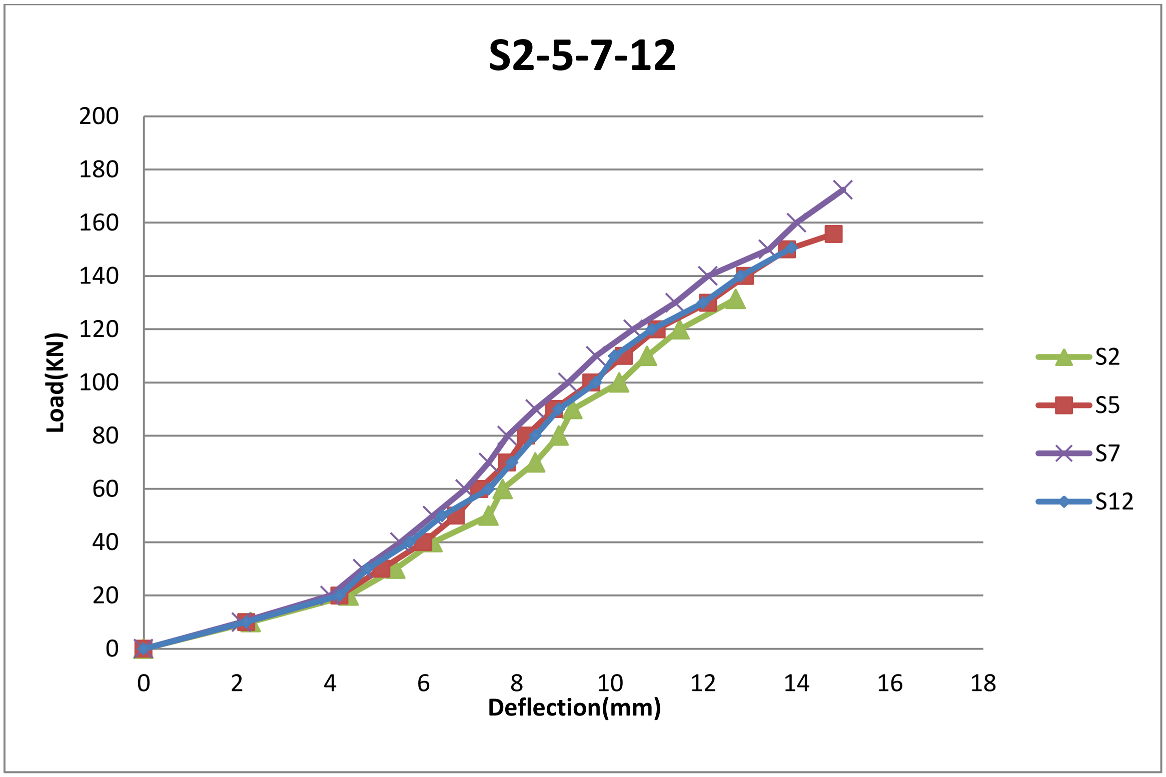


Fig4.16: Load-deflection curves of control and retrofitted beams in shear

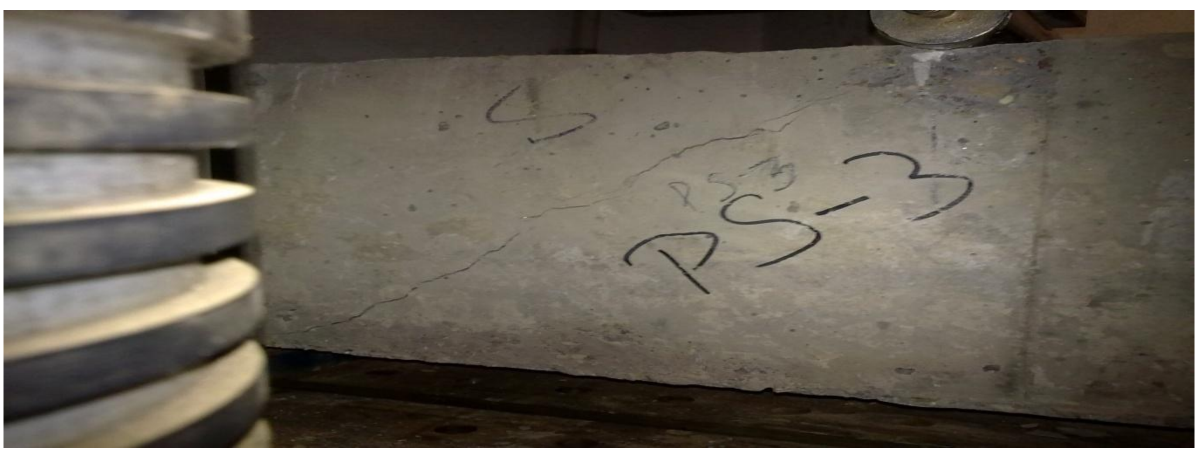
4.3.3 GENERAL FAILURE CHARACTERISTICS

Failure modes of the strengthened and unstrengthened beam specimens are shown in **fig.4.17** and **fig.4.18.** Shear failure of the control beam specimens showed that the diagonal crack was uniformly distributed between the loading points towards the supports as shown in **fig.4.17.**

Shear failure of RC beams strengthened with FRP is found to be similar to those of unstrengthened beams by diagonal tension failure and with main inclined shear cracks. The beam specimens strengthened with Tyfo SCH 11 and Tyfo SEH 51, shown in **fig.4.18**, illustrated that large number of cracks are observed in fiber wrap and de-lamination started simultaneously.

a)

b)



c)

Fig4.17: Failure modes of control beam in shear

a)

b)

c)

Fig4.18: Failure modes of strengthened beam in shear

CONCLUSION

An extensive experimental study has been conducted to investigate flexural and shear behavior of beam specimens. The experimental results are analysed and discussed in the light of load enhancement characteristic, load deformation behaviour and general failure characteristics. Based upon the results of the experimental study, the following conclusions may be drawn:

- The load carrying capacity of the retrofitted beams were found to be greater than that of the control beams.
- The cracks at ultimate load of strengthened beam were more in number compared to cracks of virgin beam indicating clearly the composite action due to retrofitting.
- Initial flexural cracks appear at a higher load by strengthening the beam at soffit. First crack load are found to be 42.33 kN, 49.66 kN, 56.33 kN and 46.33 kN, for Tyfo SCH 11 (CFRP), Tyfo SEH 51(GFRP) laminate and ferrous cement laminate respectively, thereby illustrating an increase of load values by about 14.7%, 24.8%, and 8.6% .
- The ultimate load values for the retrofitted beams specimens in flexure were increased by about 20%, 34% and 10% for Tyfo SCH 11(CFRP), Tyfo SEH 51 and ferrocement beam specimen respectively.
- The ultimate load values for the retrofitted beams specimens in shear were increased by about 16.3%, 30.8% and 14.3% for Tyfo SCH 11(CFRP), Tyfo SEH 51(GFRP) and ferrocement beam specimen respectively.
- The ductile behaviour of the FRP can give us enough warning before the ultimate failure. The use of FRP can delay the initial cracks and further development of cracks in the beam.
- Due to debonding total utilization of strength of laminates was not achieved.
- Tyfo SEH 51(GFRP) is found to be more superior than Tyfo SCH 11(CFRP) and ferrocement in increasing overall performance of the structural elements in flexural and shear.

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