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"Strengthening Of Reinforced Concrete Beams Using Glass Fiber Reinforced Polymer Composites."

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ABSTRTACT

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

Experimental investigations on the flexural and shear behavior of RC beams strengthened using continuous glass fiber reinforced polymer (GFRP) sheets are carried out. Externally reinforced concrete beams with epoxy-bonded GFRP sheets were tested to failure using a symmetrical two point concentrated static loading system. Two sets of beams were casted for this experimental test program. In SET I three beams weak in flexure were casted, out of which one is controlled beam and other two beams were strengthened using continuous glass fiber reinforced polymer (GFRP) sheets in flexure. In SET II three beams weak in shear were casted, out of which one is the controlled beam and other two beams were strengthened using continuous glass fiber reinforced polymer (GFRP) sheets in shear. The strengthening of the beams is done with different amount and configuration of GFRP sheets.

Experimental data on load, deflection and failure modes of each of the beams were obtained. The detail procedure and application of GFRP sheets for strengthening of RC beams is also included. The effect of number of GFRP layers and its orientation on ultimate load carrying capacity and failure mode of the beams are investigated.

INTRODUCTION

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 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 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.
- 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)

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. Strengthening is accomplished by either reducing the magnitude of these forces or by enhancing the member's resistance to them. 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 strength increase;
- Effect of changes in relative member

stiffness;

- Size of project (methods involving special materials and methods may be less cost- effective on small projects);
- 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;
- Operational constraints (methods requiring longer construction time might be less desirable for applications in which building operations must be shut down during construction):
- Availability of materials, equipment, and qualified contractors;
- Construction cost, maintenance costs, and life-cycle costs; and
- Load testing to verify existing capacity or evaluate new techniques and materials.

In order to avoid the problems created by the corrosion of steel reinforcement in concrete structures, research has demonstrated that one could replace the steel reinforcement by fiber reinforced polymer (FRP) reinforcement. Corrosion of the steel reinforcement in reinforced concrete (RC) structures affects the strength of both the steel and the concrete. The strength of a corroding steel reinforcing bar is reduced because of a reduction in the cross-sectional area of the steel bar. While the steel reinforcing bars are corroding, the concrete integrity is impaired because of cracking of the concrete cover caused by the expansion of the corrosion products.

The rehabilitation of infrastructures is not new, and various projects have been carried out around the world over the past two decades. One of the techniques used to strengthen existing reinforced concrete members involves external bonding of steel plates by means of two-component epoxy adhesives. By this way, it is possible to improve the mechanical performance of a member. The wide use of this method for various structures, including buildings and bridges, has demonstrated its efficiency and its convenience. In spite of this fact, the plate bonding technique presents some disadvantages due to the use of steel as strengthening material. The principal drawbacks of steel are its high weight which causes difficulties in handling the plates on site and its vulnerability against corrosive environments. Moreover, steel plates have limited delivery lengths and, therefore, they require joints.

1.STRENGTHENING USING FRP COMPOSITES

Only a few years ago, 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 glass fiber-reinforced polymers (GFRP) 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 behighly 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 significant saving in construction costs and 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.

The materials fibers and resins are durable if correctly specified, and require little maintenance. If they are damaged in service, it is relatively simple to repair them, by adding an additional layer. The use of fiber composites does not significantly increase the weight of the structure or the dimensions of the member. The latter may be particularly important for bridges and other structures with limited headroom and for tunnels. In terms of environmental impact and sustainability, studies have shown that the energy required to produce FRP materials is less than that for conventional materials. Because of their light weight, the transport of FRP materials has minimal environmental impact.

These various factors in combination lead to a significantly simpler and quicker strengthening process than when using steel plate. This is particularly important for bridges because of the high costs of lane closures and possession times on major highways and railway lines. It has been estimated that about 90% of the market for plate strengthening in Switzerland has been taken by carbon plate systems as a result of these factors.

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.

PRESENT INVESTIGATION

The purpose of this research is to investigate the flexural and shear behavior of reinforced concrete beams strengthened with varying configuration and layers of GFRP sheets. More particularly, the effect of the number of GFRP layers and its orientation on the strength and ductility of beams are investigated. Two sets of beams were fabricated and tested up to failure. In SET I three beams weak in flexure were casted, out of which one is controlled beam and other two beams were strengthened using continuous glass fiber reinforced polymer (GFRP) sheets in flexure. In SET II three beams weak in shear were casted, out of which one is the controlled beam and other two beams were strengthened by using continuous glass fiber reinforced polymer (GFRP) sheets in shear.

MATERIALS AND METHODS

CONCRETE:-

Concrete is a construction material composed of portland cement and water combined with sand, gravel, crushed stone, or other inert material such as expanded slag or vermiculite. The cement and water form a paste which hardens by chemical reaction into a strong, stone-like mass. The inert materials are called aggregates, and for economy no more cement paste is used than is necessary to coat all the aggregate surfaces and fill all the voids. The concrete paste is plastic and easily molded into any form or troweled to produce a smooth surface. Hardening begins immediately, but precautions are taken, usually by covering, to avoid rapid loss of moisture since the presence of water is necessary to continue the chemical reaction and increase the strength. Too much water, however, produces a concrete that is more porous and weaker. The quality of the paste formed by the cement and water largely determines the character of the concrete. Proportioning of the ingredients of concrete is referred to as designing the mixture, and for most structural work the concrete is designed to give compressive strengths of 15 to 35 MPa. A rich mixture for columns may be in the proportion of 1 volume of cement to 1 of sand and 3 of stone, while a lean mixture for foundations may be in the proportion of 1:3:6. Concrete may be produced as a dense mass which is practically artificial rock, and chemicals may be added to make it waterproof, or it can be made porous and highly permeable for such use as filter beds. An air-entraining chemical may be added to produce minute bubbles for porosity or light weight. Normally, the full hardening period of concrete is at least 7 days. The gradual increase in strength is due to the hydration of the tricalcium aluminates and silicates. Sand used in concrete was originally specified as roughly angular, but rounded grains are now preferred. The stone is usually sharply broken. The weight of concrete varies with the type and amount of rock and sand. A concrete with trap rock may have a density of 2,483 kg/m3. Concrete is stronger in compression than in tension, and steel bar, called rebar or mesh is embedded in structural members to increase the tensile and flexural strengths. In addition to the structural uses, concrete is widely used in precast units such as block, tile, sewer, and water pipe, and ornamental products.

Portland slag cement (PSC) – 43 grade (Kornak Cement) was used for the investigation. It was tested for its physical properties in accordance with Indian Standard specifications. The fine aggregate used in this investigation was clean river sand, passing through 4.75 mm sieve with specific gravity of 2.68. The grading zone of fine aggregate was zone III as per Indian Standard specifications. Machine crushed granite broken stone angular in shape was used as coarse aggregate. The maximum size of coarse aggregate was 20 mm with specific gravity of 2.73. Ordinary clean portable water free from suspended particles and chemical substances was used for both mixing and curing of concrete.

For concrete, the maximum aggregate size used was 20 mm. Nominal concrete mix of 1:1.5:3 by weight is used to achieve the strength of 20 N/mm2. The water cement ratio 0.5 is used. Three cube specimens were cast and tested at the time of beam test (at the age of 28 days) to determine the compressive strength of concrete. The average compressive strength of the concrete was 31N/mm2.

Cement

Cement is a material, generally in powder form, that can be made into a paste usually by the addition of water and, when molded or poured, will set into a solid mass. Numerous organic compounds used for adhering, or fastening materials, are called cements, but these are classified as adhesives, and the term cement alone means a construction material. The most widely used of the construction cements is portland cement. It is a bluish-gray powder obtained by finely grinding the clinker made by strongly heating an intimate mixture of calcareous and argillaceous minerals. The chief raw material is a mixture of high-calcium limestone, known as cement rock, and clay or shale. Blast-furnace slag may also be used in some cements and the cement is called portland slag cement (PSC). The color of the cement is due chiefly to iron oxide. In the absence of impurities, the color would be white, but neither the color nor the specific gravity is a test of quality. The specific gravity is at least

3.10. Portland slag cement (PSC) – 43 grade (Kornak Cement) was used for the investigation.

Fine aggregate

Fine aggregate / sand is an accumulation of grains of mineral matter derived from the disintegration of rocks. It is distinguished from gravel only by the size of the grains or particles, but is distinct from clays which contain organic materials. Sands that have been sorted out and separated from the organic material by the action of currents of water or by winds across arid lands are generally quite uniform in size of grains. Usually commercial sand is obtained from river beds or from sand dunes originally formed by the action of winds. Much of the earth’s surface is sandy, and these sands are usually quartz and other

siliceous materials. The most useful commercially are silica sands, often above 98% pure. Beach sands usually have smooth, spherical to ovaloid particles from the abrasive action of waves and tides and are free of organic matter. The white beach sands are largely silica but may also be of zircon, monazite, garnet, and other minerals, and are used for extracting various elements.

Sand is used for making mortar and concrete and for polishing and sandblasting. Sands containing a little clay are used for making molds in foundries. Clear sands are employed for filtering water. Sand is sold by the cubic yard (0.76 m3) or ton (0.91 metric ton) but is always shipped by weight. The weight varies from 1,538 to 1,842 kg/m3, depending on the composition and size of grain. Construction sand is not shipped great distances, and the quality of sands used for this purpose varies according to local supply. Standard sand is a silica sand used in making concrete and cement tests. The fine aggregate obtained from river bed of Koel, clear from all sorts of organic impurities was used in this experimental program. The fine aggregate was passing through 4.75 mm sieve and had a specific gravity of 2.68. The grading zone of fine aggregate was zone III as per Indian Standard specifications.

Coarse aggregate

Coarse aggregate are the crushed stone is used for making concrete. The commercial stone is quarried, crushed, and graded. Much of the crushed stone used is granite, limestone, and trap rock. The last is a term used to designate basalt, gabbro, diorite, and other dark- colored, fine-grained igneous rocks. Graded crushed stone usually consists of only one kind of rock and is broken with sharp edges. The sizes are from 0.25 to 2.5 in (0.64 to 6.35 cm) although larger sizes may be used for massive concrete aggregate. Machine crushed granite broken stone angular in shape was used as coarse aggregate. The maximum size of coarse aggregate was 20 mm and specific gravity of 2.78. Granite is a coarse-grained, igneous rock having an even texture and consisting largely of quartz and feldspar with often small amounts of mica and other minerals. There are many varieties. Granite is very hard and compact, and it takes a fine polish, showing the beauty of the crystals. Granite is the most important building stone. Granite is extremely durable, and since it does not absorb moisture, as limestone and sandstone do, it does not weather or crack as these stones do. The colors are usually reddish, greenish, or gray. Rainbow granite may have a black or dark- green background with pink, yellowish, and reddish mottling; or it may have a pink or

lavender background with dark mottling. The density is 2,723 kg/m3, the specific gravity

2.72, and the crushing strength 158 to 220 MPa.

3. Water

Water fit for drinking is generally considered fit for making concrete. Water should be free from acids, oils, alkalies, vegetables or other organic Impurities. Soft waters also produce weaker concrete. Water has two functions in a concrete mix. Firstly, it reacts chemically with the cement to form a cement paste in which the inert aggregates are held in suspension until the cement paste has hardened. Secondly, it serves as a vehicle or lubricant in the mixture of fine aggregates and cement.

REINFORCEMENT

The longitudinal reinforcements used were high-yield strength deformed bars of 12 mm diameter. The stirrups were made from mild steel bars with 6 mm diameter. The yield

strength of steel reinforcements used in this experimental program was determined by performing the standard tensile test on the three specimens of each bar. The average proof stress at 0.2 % strain of 12 mm φ bars was 437 N/mm2 and that of 6 mm φ bars was 240 N/mm2.

FIBER REINFORCED POLYMER (FRP)

Continuous fiber-reinforced materials with polymeric matrix (FRP) can be considered as composite, heterogeneous, and anisotropic materials with a prevalent linear elastic behavior up to failure. They are widely used for strengthening of civil structures. There are many advantages of using FRPs: lightweight, good mechanical properties, corrosion-resistant, etc. Composites for structural strengthening are available in several geometries from laminates used for strengthening of members with regular surface to bi-directional fabrics easily adaptable to the shape of the member to be strengthened. Composites are also suitable for applications where the aesthetic of the original structures needs to be preserved (buildings of historic or artistic interest) or where strengthening with traditional techniques can not be effectively employed.

Fiber reinforced polymer (FRP) is a composite material made by combining two or more materials to give a new combination of properties. However, FRP is different from other composites in that its constituent materials are different at the molecular level and are mechanically separable. The mechanical and physical properties of FRP are controlled by its constituent properties and by structural configurations at micro level. Therefore, the design and analysis of any FRP structural member requires a good knowledge of the material properties, which are dependent on the manufacturing process and the properties of constituent materials.

FRP composite is a two phased material, hence its anisotropic properties. It is composed of fiber and matrix, which are bonded at interface. Each of these different phases has to perform its required function based on mechanical properties, so that the composite system performs satisfactorily as a whole. In this case, the reinforcing fiber provides FRP composite with strength and stiffness, while the matrix gives rigidity and environmental protection.

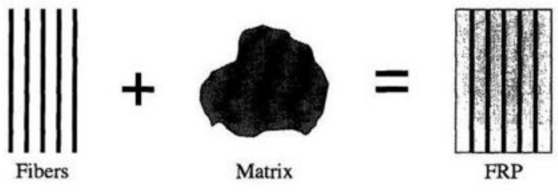


Fig. 3.1 Formation of Fiber Reinforced Polymer Composite

Fig. 3.1 Formation of Fiber Reinforced Polymer Composite

Reinforcement materials

A great majority of materials are stronger ad stiffer in fibrous form than as bulk materials.

Fiber

A fiber is a material made into a long filament with a diameter generally in the order of 10 tm. The aspect ratio of length and diameter can be ranging from thousand to infinity in continuous fibers. The main functions of the fibers are to carry the load and provide stiffness, strength, thermal stability, and other structural properties in the FRP.

To perform these desirable functions, the fibers in FRP composite must have:

i) high modulus of elasticity for use as reinforcement

ii) high ultimate strength;

iii) low variation of strength among fibers;

iv) high stability of their strength during handling; and

v) high uniformity of diameter and surface dimension among fibers.

There are three types of fiber dominating in civil engineering industry-glass, carbon and aramid fibers, each of which has its own advantages and disadvantages.

RESULTS AND DISCUSSIONS

This chapter describes the experimental results of SET I beams (weak in flexure) and SET II beams (weak in shear). Their behavior throughout the static test to failure is described using recorded data on deflection behavior and the ultimate load carrying capacity. The crack patterns and the mode of failure of each beam are also described in this chapter.

Two sets of beams were tested for their ultimate strengths. In SET I three beams (F1, F2 and F3) weak in flexure are tested. In SET II three beams (S1, S2 and S3) weak in shear are tested. The beams F1and S1 were taken as the control beams. It was observed that the beams F1 and S1 had less load carrying capacity when compared to that of the externally strengthened beams using GFRP sheets. In SET I beams F2 is strengthened only at the soffit of the beam and F3 is strengthened up to the neutral axis of the beam along with the soffit of the beam. SET II beams S2 is strengthened only at the sides of the beam in the shear zone and S3 is strengthened by U-wrapping of the GFRP sheets in the shear zone of the beam. Deflection behavior and the ultimate load carrying capacity of the beams were noted. The ultimate load carrying capacity of all the beams along with the nature of failure is given in Table 5.1.

FAILURE MODES

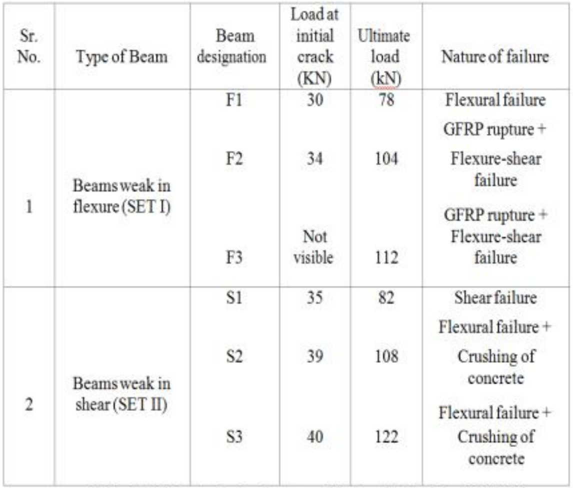
The flexural and shear strength of a section depends on the controlling failure mode. The following flexural and shear failure modes should be investigated for an FRP- strengthened section:

- Crushing of the concrete in compression before yielding of the reinforcing steel;

- Yielding of the steel in tension followed by rupture of the FRP laminate;
- Yielding of the steel in tension followed by concrete crushing;
- Shear/tension delamination of the concrete cover (cover delamination); and
- Debonding of the FRP from the concrete substrate (FRP debonding).

A number of failure modes have been observed in the experiments of RC beams strengthened in flexure and shear by GFRPs. These include flexure failure, shear failure, flexural failure due to GFRP rupture and crushing of concrete at the top. Concrete crushing is assumed to occur if the compressive strain in the concrete reaches its maximum usable strain. Rupture of the FRP laminate is assumed to occur if the strain in the FRP reaches its design rupture strain before the concrete reaches its maximum usable strain. Cover delamination or FRP debonding can occur if the force in the FRP cannot be sustained by the substrate. In order to prevent debonding of the FRP laminate, a limitation should be placed on the strain level developed in the laminate.

The GFRP strengthened beam and the control beams were tested to find out their ultimate load carrying capacity. It was found that the control beams F1 and S1 failed in flexure and shear showing that the beams were deficient in flexure and shear respectively. In SET I beam F2 failed due to fracture of GFRP sheet in two pieces and then flexural-shear failure of the beam took place. Beam F3 failed due to delamination of the GFRP sheet after that fracture of GFRP sheet took place and then flexural-shear failure of the beam. In SET I beams F2 and F3, GFRP rupture and flexural-shear kind of failure was prominent when strengthening was done using both the wrapping schemes. In SET II beams S2 and S3 failed due to flexural failure and crushing of concrete on the top of the beam. The SET II beams S2 and S3 developed major flexural cracks at the ultimate loads. In SET II beams S2 and S3 the flexural kind of failure was prominent when strengthening was done using both the wrapping schemes.



Sr. No.	Type of Beam	Beam designation	Load at initial crack (KN)	Ultimate load (kN)	Nature of failure
1	Beams weak in flexure (SET I)	F1	30	78	Flexural failure
		F2	34	104	GFRP rupture + Flexure-shear failure
		F3	Not visible	112	GFRP rupture + Flexure-shear failure
2	Beams weak in shear (SET II)	S1	35	82	Shear failure
		S2	39	108	Flexural failure + Crushing of concrete
		S3	40	122	Flexural failure + Crushing of concrete

Table 5.1 Ultimate load and nature of failure for SET I and SET II beams

LOAD DEFLECTION HISTORY

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. Also the load deflection behaviour was compared between two wrapping schemes having the same reinforcement. It was noted that the behaviour of the flexure and shear deficient beams when bonded with GFRP sheets were better than their corresponding control beams. The mid-span deflections were much lower when bonded externally with GFRP sheets. The graphs comparing the mid-span deflection of flexure and shear deficient beams and their corresponding control beams are shown in Figs 5.4 and 5.8. The use of GFRP sheet had effect in delaying the growth of crack formation. In SET I when both the wrapping schemes were considered it was found that the beam F3 with GFRP sheet up to the neutral axis along with the soffit had a better load deflection behaviour when compared to the beam F2 with GFRP sheet only at the soffit of the beam. In SET II when both the wrapping schemes were considered it was found that the beam S3 with U wrapping of GFRP sheet had a better load deflection behaviour when compared to the beam S2 with GFRP sheet only at the sides of the beam

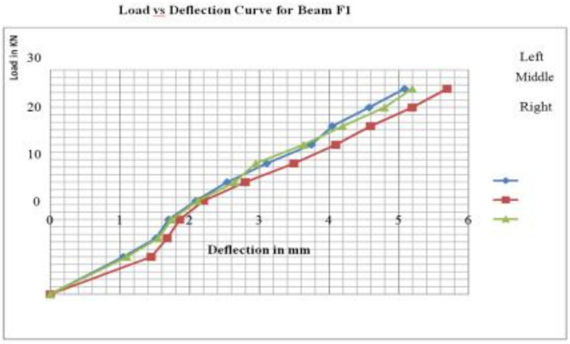


Fig. 5.1 Load vs Deflection Curve for Beam F1

Beam F1 was the control beam of SET I beams which were weak in flexure but strong in shear. In beam F1 strengthening was not done. Two point static loading was done on the beam and at the each increment of the load, deflection at the left, right and middle dial gauges were taken. Using this load and deflection of data, load vs deflection curve is ploted. At the load of 30 KN initial cracks started coming on the beams. Further with increase in loading propagation of the cracks took place. The beam F1 failed completely in flexure.

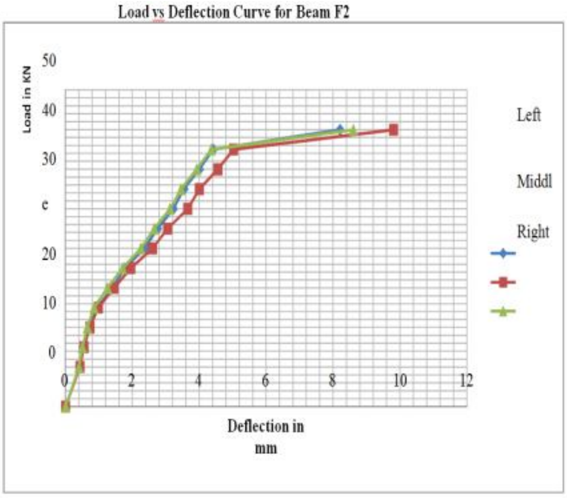


Fig. 5.2 Load vs Deflection Curve for Beam F2

Beam F2 of SET I beams which were weak in flexure but strong in shear. In beam F2 strengthening is done by application of GFRP sheet only at the soffit of the beam. Two point static loading was done on the beam and at the each increment of the load, deflection at the left, right and middle dial gauges were taken. Using this load and deflection of data, load vs deflection curve is ploted. At the load of 34 KN initial cracks started coming on the beams. Initial cracks started at a higher load in beam F2 compared to beam F1. Further with increase in loading propagation of the cracks took place. The beam F2 failed in flexural shear. Beam F2 carried a higher ultimate load compared to beam F1.

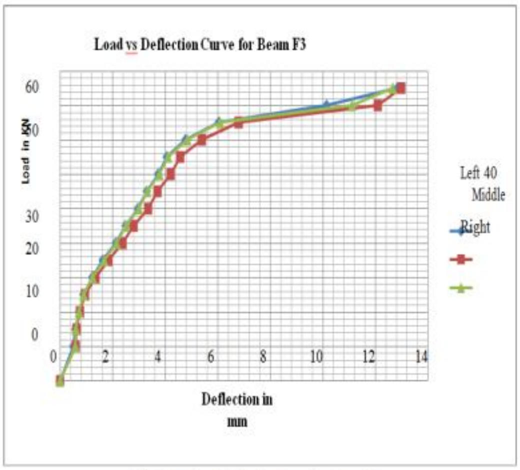


Fig. 5.3 Load vs Deflection Curve for Beam F3

Beam F3 of SET I beams which were weak in flexure but strong in shear. In beam F3 strengthening is done by application of GFRP sheet upto the neutral axis along with the soffit of the beam. Two point static loading was done on the beam and at the each increment of the load, deflection at the left, right and middle dial gauges were taken. Using this load and deflection of data, load vs deflection curve is ploted. Initial cracks are not visible on the beams. Further with increase in loading propagation of the cracks took place but it had poor visibility of cracks due to the covering of the GFRP sheet. The beam F3 also failed in flexural shear like beam F2 but beam F3 carried a higher ultimate load compared to both beam F1 and F2.

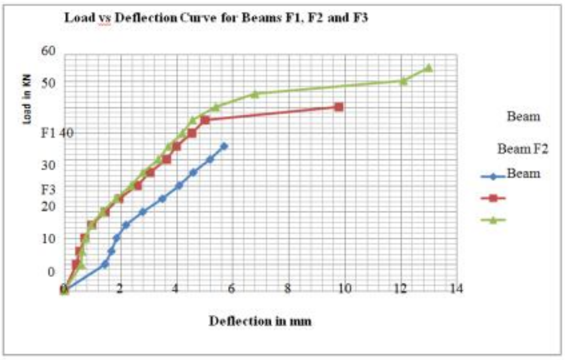


Fig. 5.4 Load vs Deflection Curves for Beams F1, F2 and F3.

From the load and deflection of data of SET I beams F1, F2 and F3, load vs deflection curve is ploted for all the three beams. From this load vs deflection curve, it is clear that beam F1 has lower ultimate load carrying capacity compared to beams F2 and F3. Beam F1 had also undergone higher deflection compared to beams F2 and F3 at the same load. Beam F2 had higher ultimate load carrying capacity compared to the controlled beam F1 but lower than beam F3. Beam F3 had higher ultimate load carrying capacity compared to the beams F1 and F2. Both the beams F2 and F3 had undergone almost same deflection upto 65 KN load. After 65 KN load beam F3 had undergone same deflection as beam F2 but at a higher load compared to beam F2. The deflection undergone by beam F3 is highest. Beam F2 had undergone higher deflection than beam F1.

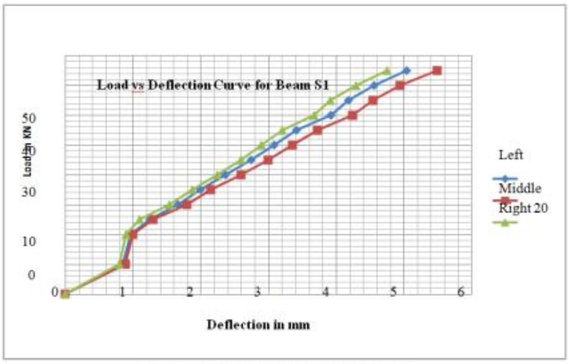


Fig. 5.5 Load vs Deflection Curve for Beam S1

Beam S1 was the control beam of SET II beams which were weak in shear but strong in flexure. In beam S1 strengthening was not done. Two point static loading was done on the beam and at the each increment of the load, deflection at the left, right and middle dial gauges were taken. Using this load and deflection of data, load vs deflection curve is ploted. At the load of 35 KN initial cracks started coming on the beams. Further with increase in loading propagation of the cracks took place. At first in beam S1 only flexural cracks were developed but ultimately the beam failed in shear.

Fig. 5.6 Load vs Deflection Curve for Beam S2

Beam S2 of SET II beams which were weak in shear but strong in flexure. In beam S2 strengthening is done by application of GFRP sheet only on the two sides of the beam. Two point static loading was done on the beam and at the each increment of the load, deflection at the left, right and middle dial gauges were taken. Using this load and deflection of data, load vs deflection curve is ploted. At the load of 39 KN initial cracks started coming on the beams. Initial cracks started at a higher load in beam S2 compared to beam S1. Further with increase in loading propagation of the cracks took place. In beam S2 only flexural cracks were developed and finally the beam failed by flexural failure and crushing of concrete. Beam S2 carried a ultimate load higher than beam S1 but lower than beam S3.

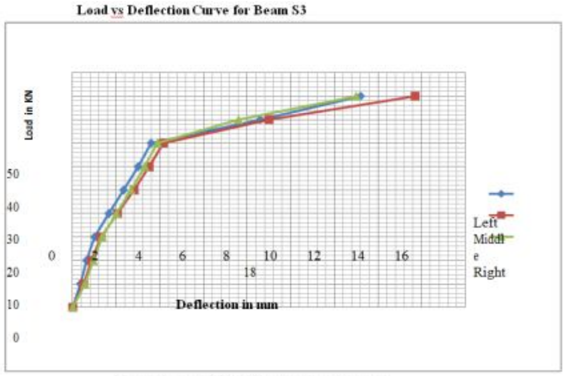


Fig. 5.7 Load vs Deflection Curve for Beam S3

Beam S3 of SET II beams which were weak in shear but strong in flexure. In beam S3 strengthening is done by application of GFRP sheet as U-wrap on the beam. Two point static loading was done on the beam and at the each increment of the load, deflection at the left, right and middle dial gauges were taken. Using this load and deflection of data, load vs deflection curve is ploted. At the load of 39 KN initial cracks started coming on the beams. Initial cracks started at a higher load in beam S3 compared to beams S1 and S2. Further with increase in loading propagation of the cracks took place. In beam S3 similar to beam S2 only flexural cracks were developed and finally the beam failed by flexural failure and crushing of concrete, but beam S3 carried a higher ultimate load compared to both beam S1 and S2.

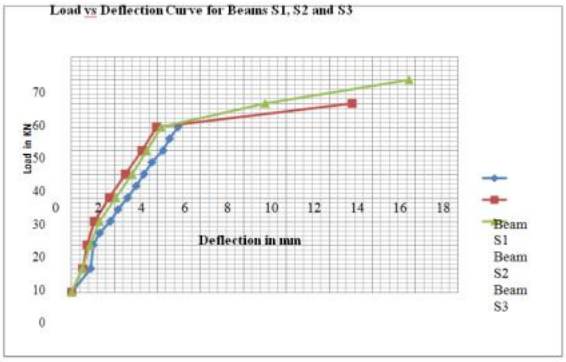


Fig. 5.8 Load vs Deflection Curves for Beams S1, S2 and S3.

From the load and deflection of data of SET II beams S1, S2 and S3, load vs deflection curve is ploted for all the three beams. From this load vs deflection curve, it is clear that beam S1 has lower ultimate load carrying capacity compared to beams S2 and S3. Beam S1 had also undergone higher deflection compared to beams S2 and S3 at the same load. Beam S2 had higher ultimate load carrying capacity compared to the controlled beam S1 but lower than beam S3. Beam S3 had higher ultimate load carrying capacity compared to the beams S1 and S2. Both the beams S2 and S3 had undergone almost same deflection upto 70 KN load. After 70 KN load beam S3 had undergone same deflection as beam S2 but at a higher load compared to beam S2. The deflection undergone by beam S3 is highest. Beam S2 had undergone higher deflection than beam S1.

The load carrying capacity of the control beams and the strengthen beams were found out and is shown in fig. 5.11 and 5.12. The control beams were loaded up to their ultimate loads. It was noted that of all the beams, the strengthen beams F2, F3 and S2, S had the higher load carrying capacity compared to the controlled beams F1 and S1. A noticed about the usage of GFRP sheets is high ductile behavior of the beams. The shear failure being sudden can lead to huge damage to the structure. But the ductile behavior obtained by the use of GFRP can give us enough warning before the ultimate failure. The use of FRP can delay the initial cracks and further development of the cracks in the beam. SET I beams F1, F2 and F3 were loaded under two point static loading. As the load was increased incrementally development of cracks takes place and ultimately the beam failed. The ultimate load of F1 beam was 78 KN which is lower than F2 beam which carried an ultimate load of 104 KN and further lower than F3 beam which carried an ultimate load of 112 KN. SET II beams S1, S2 and S3 were loaded under two point static loading. As the load was increased incrementally development of cracks takes place and ultimately the beam failed. The ultimate load of S1 beam was 82 KN which is lower than S2 beam which carriedan ultimate load of 108 KN and further lower than S3 beam which carried an ultimate load of 122 KN.

CRACK PATTERN

The crack patterns at collapse for the tested beams of SET I and SET II are shown in Fig. 5.13 to 5.18. In SET I the controlled beam F1 exhibited widely spaced and lesser number of cracks compared to strengthened beams F2 and F3. The strengthened beams F2 and F3 have also shown cracks at relatively close spacing. This shows the enhanced concrete confinement due to the GFRP strengthening. This composite action has resulted in shifting of failure mode from flexural failure (steel yielding) in case of controlled beam F1 to peeling of GFRP sheet in case of strengthened beams F2 and F3. The debonding of GFRP sheet has taken place due to flexural-shear cracks by giving cracking sound. A crack normally initiates in the vertical direction and as the load increases it moves in inclined direction due to the combined effect of shear and flexure. If the load is increased further, cracks propagate to top and the beam splits. This type of failure is called flexure-shear failure.

In SET II beam S1 the shear cracks started at the centre of short shear span. As the load increased, the crack started to widen and propagated towards the location of loading. The cracking patterns show that the angle of critical inclined crack with the horizontal axis is about 45°. For strengthened reinforced concrete beams S2 and S3, the numbers of vertical cracks were increased compared to controlled beam S1.

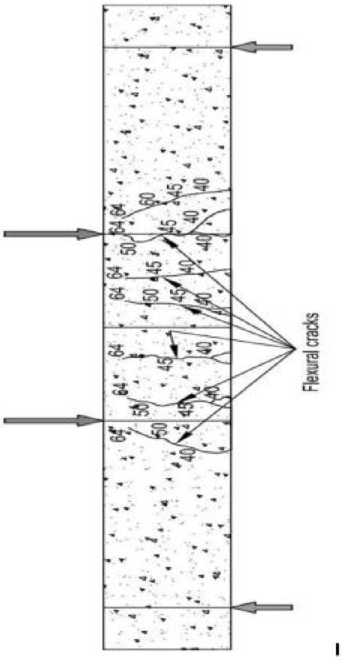


Fig. 5.13 Crack pattern of Beam F1

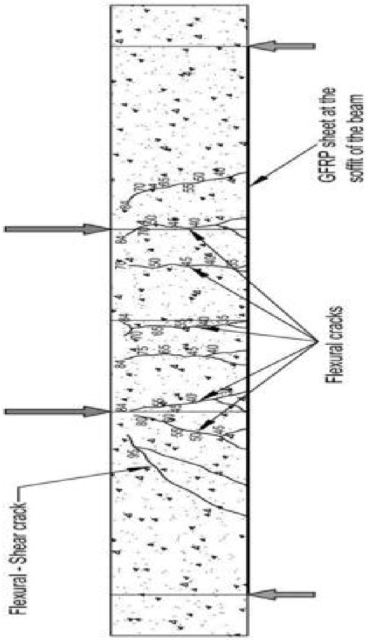


Fig. 5.14 Crack pattern of Beam F2

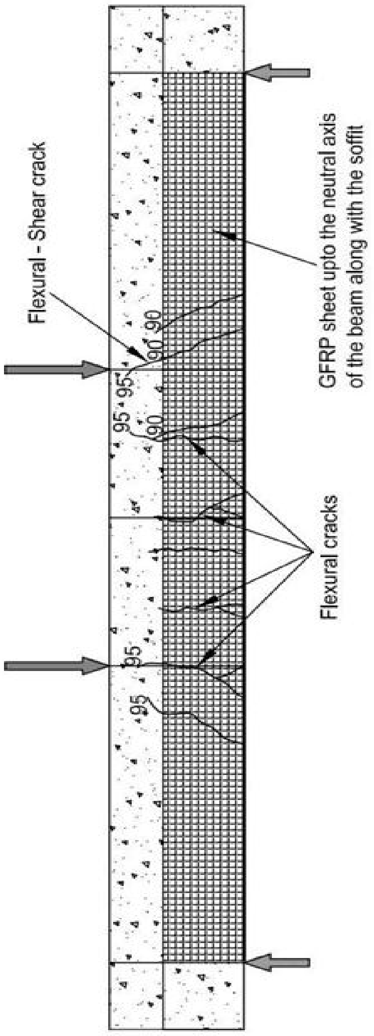


Fig. 5.15 Crack pattern of Beam F3

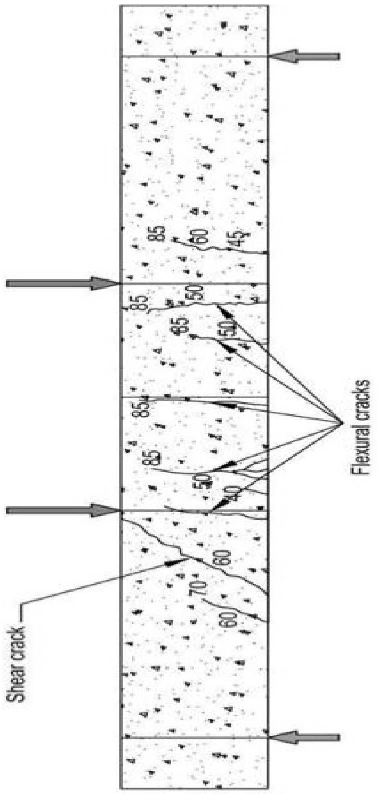


Fig. 5.16 Crack pattern of Beam S1

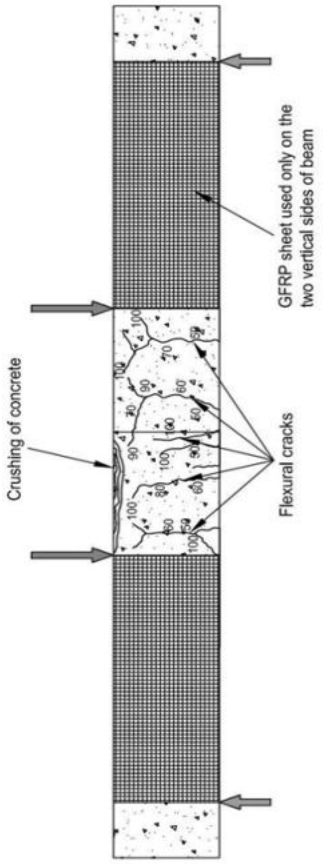


Fig. 5.17 Crack pattern of Beam S2

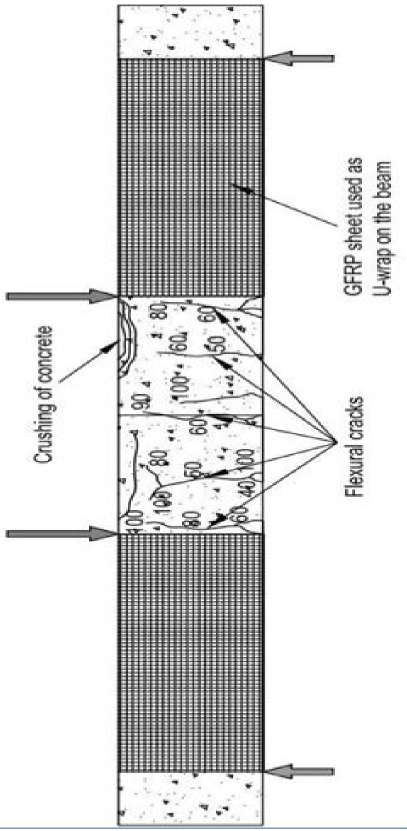
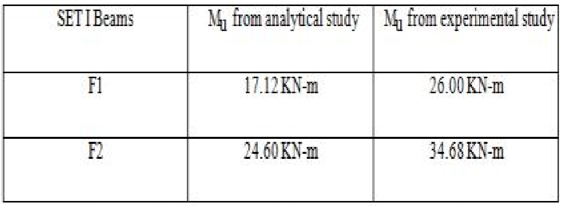


Fig. 5.18 Crack pattern of Beam B3

COMPARISION OF RESULTS

The results of the two set of beams tested are shown in Table 5.1. The failure mode, load at initial crack and ultimate load of the control beams without strengthening and the beams strengthen with two layers GFRP sheet are presented. The difficulties inherent to the understanding of strengthen structural member behavior subjected to flexure and shear have not allowed to develop a rigorous theoretical design approach. The complexity of the problem has then made necessary an extensive experimental research. Moment of resistance of the SET I beams was calculated analytically and was compared with the obtained experimental results.



SET I Beams	M_u from analytical study	M_u from experimental study
F1	17.12 KN-m	26.00 KN-m
F2	24.60 KN-m	34.68 KN-m

Table 5.2 Comparision of M_u value obtained from analytical and experimental s

Conclusion

In this experimental investigation the flexural and shear behaviour of reinforced concrete beams strengthened by GFRP sheets are studied. Two sets of reinforced concrete (RC) beams, in SET I three beams weak in flexure and in SET II three beams weak in shear were casted and tested. From the test results and calculated strength values, the following conclusions are drawn:

1. Initial flexural cracks appear at a higher load by strengthening the beam at soffit. The ultimate load carrying capacity of the strengthen beam F2 is 33 % more than the controlled beam F1.
2. Load at initial cracks is further increased by strengthening the beam at the soffit as well as on the two sides of the beam up to the neutral axis from the soffit. The ultimate load carrying capacity of the strengthen beam F3 is 43 % more than the controlled beam F1 and 7 % more than the strengthen beam F2.
3. Analytical analysis is also carried out to find the ultimate moment carrying capacity and compared with the experimental results. It was found that analytical analysis predicts lower value than the experimental findings.
4. When the beam is not strengthen, it failed in flexure but after strengthening the beam in flexure, then flexure-shear failure of the beam takes place which is more dangerous than the flexural failure of the beam as it does not give much warning before

failure. Therefore it is recommended to check the shear strength of the beam and carry out shear strengthening along with flexural strengthening if required.

5. Flexural strengthening up to the neutral axis of the beam increases the ultimate load carrying capacity, but the cracks developed were not visible up to a higher load. Due to invisibility of the initial cracks, it gives less warning compared to the beams strengthen only at the soffit of the beam.
6. By strengthening up to the neutral axis of the beam, increase in the ultimate load carrying capacity of the beam is not significant and cost involvement is almost three times compared to the beam strengthen by GFRP sheet at the soffit only.

B) SET II Beams (S1, S2 and S3)

1. The control beam S1 failed in shear as it was made intentionally weak in shear.
2. The initial cracks in the strengthen beams S2 and S3 appears at higher load compared to the un-strengthen beam S1.
3. After strengthening the shear zone of the beam the initial cracks appears at the flexural zone of the beam and the crack widens and propagates towards the neutral axis with increase of the load. The final failure is flexural failure which indicates that the GFRP sheets increase the shear strength of the beam. The ultimate load carrying capacity of the strengthen beam S2 is 31 % more than the controlled beam S1.
4. When the beam is strengthen by U-wrapping in the shear zone, the ultimate load carrying capacity is increased by 48 % compared to the control beam S1 and by 13% compared the beam S2 strengthen by bonding the GFRP sheets on the vertical sides alone in the shear zone of the beam.
5. When the beam is strengthen in shear, then only flexural failure takes place which gives sufficient warning compared to the brittle shear failure which is catastrophic failure of beams.
6. The bonding between GFRP sheet and the concrete is intact up to the failure of the beam which clearly indicates the composite action due to GFRP sheet.
7. Restoring or upgrading the shear strength of beams using GFRP sheet can result in increased shear strength and stiffness with no visible shear cracks. Restoring the shear strength of beams using GFRP is a highly effective technique.

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