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Enhancing the Strength of Reinforced Concrete Beams With Glass Fiber Reinforced Polymer Composite Strengthening

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Abstract

Extensive research is underway globally on the application of fiber-reinforced polymer (FRP) wraps, laminates, and sheets for the repair and strengthening of reinforced concrete structures. Fiber-reinforced polymer (FRP) systems offer a highly effective and economically viable alternative to traditional repair methods for enhancing the structural performance of weakened concrete members.

This study focuses on the experimental investigation of the flexural and shear behavior of reinforced concrete (RC) beams strengthened with continuous glass fiber reinforced polymer (GFRP) sheets. Concrete beams externally reinforced with epoxy-bonded GFRP sheets were tested to failure under a symmetrical two-point concentrated static loading system. Two experimental sets were utilized: SET I involved three beams deficient in flexure, including one control beam and two beams strengthened with GFRP sheets in flexure; SET II involved three beams deficient in shear, including one control beam and two beams strengthened with GFRP sheets in shear. The strengthening was performed with varying amounts and configurations of GFRP sheets.

Key experimental data, including load, deflection, and failure modes, were recorded for each beam. The study details the procedure for applying GFRP sheets and investigates the impact of the number of GFRP layers and their orientation on the ultimate load-carrying capacity and failure modes of the beams.

Keywords: Reinforced Concrete Beams, Glass Fiber Reinforced Polymer (GFRP), Flexural Strengthening, Shear Strengthening, Experimental Investigation, Load Carrying Capacity, Failure Modes.

1. Introduction

The maintenance, rehabilitation, and upgrading of structural members are critical challenges in civil engineering. Many older structures, built to outdated design codes, are now deemed unsafe according to current standards. Replacing these elements is expensive and time-consuming, making strengthening a preferable method to enhance load-carrying capacity and extend service life. Infrastructure decay, often due to deterioration or damage, has prompted the development of various repair and strengthening techniques.

Structural strengthening is needed for:

- Increased Load Requirements: Changes in use or additional loads demand enhanced capacity.
- Unanticipated Loads: Structures must resist new loads from wind, seismic forces, or blasts.
- Deficiencies in Design: Issues like corrosion, damage, or design errors necessitate strengthening.

Each project presents unique challenges, including space, constructability, and budget constraints. Strengthening typically involves addressing flexural, shear, axial, and torsional forces, and can be achieved through techniques such as section enlargement, externally bonded reinforcement, post-tensioning, and supplemental supports.

Strengthening systems can be:

- Passive: Activated only when additional loads are applied, such as bonding steel plates or FRP composites.
- Active: Engage the structure immediately by introducing external forces, like external post-tensioning.
- Choosing the best method requires considering:
- Strength Increase: Desired improvement in load capacity.
- Member Stiffness Changes: Impact on structural performance.
- Project Size and Cost: Cost-effectiveness of methods for various project scales.
- Environmental Conditions: Suitability of methods in different environments.
- Concrete Strength and Integrity: Effectiveness of bonding methods.
- Dimensional Constraints: Limitations on space for section enlargement.
- Accessibility and Operational Constraints: Impact on construction time and access.
- Material and Contractor Availability: Access to necessary resources.
- Lifecycle Costs: Total cost, including maintenance and construction.

Replacing steel reinforcement with fiber-reinforced polymers (FRPs) addresses corrosion issues, which compromise both steel and concrete integrity. FRPs prevent the deterioration associated with traditional steel reinforcement, which leads to reduced cross-sectional strength and concrete damage due to corrosion.

Various techniques, including the external bonding of steel plates using epoxy adhesives, have been employed to strengthen concrete structures. Although effective, this method has drawbacks such as high weight, difficulty in handling, vulnerability to corrosion, and limited plate lengths requiring joints.

2. Literature Review

The utilization of pre-stressed composite plates, at the time of bonding, for strengthening concrete members has been studied only relatively recently in comparison with investigations of non-prestressed plates, although the benefits of external prestressing with plate materials have been recognized for many years. For example, Peterson (1965) considered the external prestressing of timber beams using prestressed steel sheets and found significant improvements in bending stiffness and ultimate capacity. External prestressing with composite plates also provides these benefits as well as cost savings. Triantafillou and Deskovic (1991) noted that this method of prestressing is a more economical alternative to conventional prestressing methods used in new construction. Initial research on the strengthening of reinforced concrete beams by external plate prestressing at EMPA in Switzerland has been widely reported (Meier and Kaiser, 1991; Meier et al., 1993; Deuring, 1994). This work included the cyclic loading of a beam whose plate was prestressed to 50% of its strength. Although this prestress ensures the mean stress level in the cyclic loading was high, there was no evidence of damage to the plate after 30×10^7 cycles and the cracking of the concrete was well controlled.

The non-prestressed beam loading tests reported by Deuring (1993) revealed failures by the initiation of plate separation from the base of a shear crack. It was found that the compression transfer into the concrete by the plate prestress could delay or even prevent this type of failure, thereby allowing the plate to reach its ultimate tensile strain so that the beam failed in flexure rather than by premature plate separation (Deuring, 1993). The ability of the plate to alter the failure mode from premature plate separation to flexure is influenced by the pre-stressing force and the cross-sectional area of the plate. One of the conclusions of the work was that the greatest flexural resistance of a strengthened section is reached when the plate fractures in tension, either after or at the same time as yield of the internal steel rebars.

Triantafillou et al. (1992) tested reinforced concrete beams in three point bending with various quantities of internal reinforcement and magnitudes of CFRP plate prestress. Improved control of concrete cracking was brought about not only by a greater internal reinforcement provision, but also by higher plate prestress, indicating the serviceability advantage gained by prestressing the composite. It was noted that prestressed composite plates can potentially act as the sole tensile reinforcement in new concrete construction and prefabrication is also possible due to the simplicity with which composites may be handled and applied. The confinement imposed by the initial compressive stress at the base of the beam was thought to be capable of improving the shear resistance of the member. Also, an advantage from a cost point of view is that the same strengthening to failure may be achieved with a prestressed plate of relatively small cross section, like that achieved with a larger non-prestressed plate (Triantafillou et al., 1992).

2.1 Objectives of the Study

- To study the flexural behavior of reinforced concrete beams.
- To examine the effect of GFRP strengthening on the ultimate load-carrying capacity and failure pattern of reinforced concrete beams.
- To analyze the shear behavior of reinforced concrete beams.
- To evaluate the impact of GFRP strengthening on the shear behavior of reinforced concrete beams.

3. Materials and Method

3.1 Materials

3.1.1 Concrete

Concrete is a construction material made from Portland cement, water, and aggregates such as sand, gravel, or crushed stone. The cement and water form a paste that hardens through a chemical reaction, binding the aggregates into a strong, stone-like mass. The amount of cement paste is minimized to coat aggregate surfaces and fill voids, ensuring economy and strength. Proper water content is crucial; too much water weakens the concrete, while too little prevents proper curing. Concrete mixtures are designed for specific compressive strengths, typically 15 to 35 MPa. Mixture proportions vary: a rich mixture for columns might be 1 part cement, 1 part sand, and 3 parts stone, while a lean mixture for foundations could be 1:3:6. Concrete can be dense or porous, with additives to enhance properties like waterproofing or light weight. Full hardening takes at least 7 days, with strength increasing as tricalcium aluminates and silicates hydrate.

3.1.2 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.

3.1.3 Fine Aggregate

Fine aggregate, or sand, is composed of mineral grains derived from rock disintegration. It is distinguished from gravel by grain size and from clays by the absence of organic materials. Sands are typically uniform in grain size when sorted by water or wind, with commercial sand often sourced from riverbeds or sand dunes. Most sands are quartz and other siliceous materials, with commercially valuable silica sands being over 98% pure. Beach sands, formed by wave and tide abrasion, have smooth particles and are usually free of organic matter. These white sands, primarily silica, may also contain minerals like zircon, monazite, and garnet, used for extracting elements.

3.1.4 Fiber Reinforced Polymer (FRP)

Continuous fiber-reinforced materials with a polymeric matrix (FRP) are composite, heterogeneous, and anisotropic materials that exhibit a linear elastic behavior up to failure. They are extensively used for strengthening civil structures due to their numerous advantages, including lightweight, excellent mechanical properties, and corrosion resistance. FRPs come in various forms, such as laminates for regular surfaces and bi-directional fabrics that adapt to the member's shape. These composites are ideal for preserving the aesthetics of historical buildings or for situations where traditional strengthening techniques are ineffective.

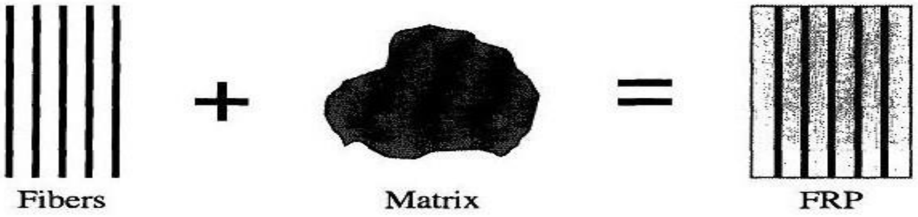

Fig. 3.1 Formation of Fiber Reinforced Polymer Composite

Table 3.1 Properties of Different Fibers

Material	Density (g/cm^3)	Tensile Modulus (E) (Gpa)	Tensile Strength (σ) (Gpa)	Specific Modulus	Specific Strength	Relative Cost
E-Glass	2.54	70	3.45	27	1.35	Low
S-Glass	2.50	86	4.50	34.5	1.8	Moderate
Graphite, High Modulus	1.9	400	1.8	200	0.9	High
Graphite, High Strength	1.7	240	2.6	140	1.5	High
Boron	2.6	400	3.5	155	1.3	High
Kevlar 29	1.45	80	2.8	55.5	1.9	Moderate
Kevlar 49	1.45	130	2.8	89.5	1.9	Moderate

Table 3.2 Typical properties of Carbon Fiber

Typical Properties	Density (g/cm^3)	Young's Modulus (Gpa)	Tensile Strength (Gpa)	Tensile Elongation (%)
High Strength	1.8	230	2.48	1.1
High Modulus	1.9	370	1.79	0.5
Ultra-High Modulus	2.0-2.1	520-620	1.03-1.31	0.2

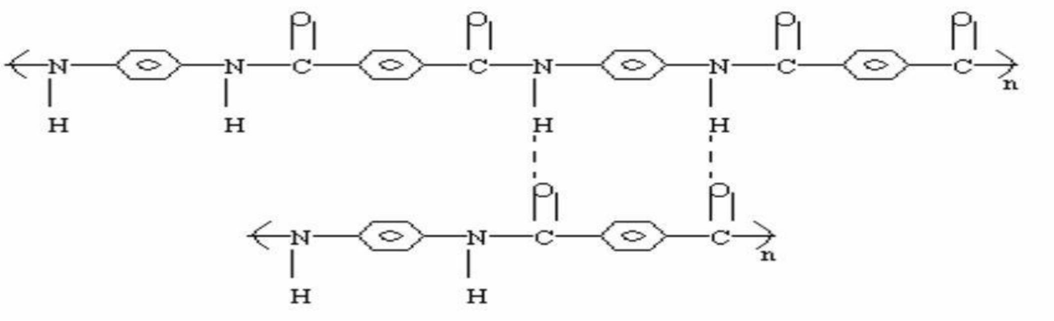

Fig. 3.3 Structure of Aramid fiber

Table 3.3 Properties of Epoxy Resin

Property	
Density, Density (g/cm^3)	1.2-1.3
Tensile Modulus, Mpa	55-130
Tensile Modulus, Gpa	2.75-4.10
Thermal Expansion, 10^{-6}/C	45-65
Water Absorption % in 24 h	0.08-0.15

The success of the strengthening technique critically depends on the performance of the epoxy resin used. Numerous types of epoxy resins with a wide range of mechanical properties are commercially available. These epoxy resins are generally two part systems, a resin and a hardener. The resin and hardener are used in this study is Araldite LY 556 and Hardener HY 951, respectively. Araldite LY-556, an unmodified epoxy resin based on Bisphenol-A and the hardener (Ciba-Geig, India) HY 951 (8% of total Epoxy taken) analiphatic primary amine, were mixed properly.

Table 3.4 Properties of Epoxy Resin and Hardener

Properties	**Araldite LY 556**	**Hardener HY 951**
Color	Clear	Colorless
Odor	Slight	Ammonia
Physical State	Liquid	Liquid
Solubility in water	Insoluble	Miscible
Vapor Pressure	< 0.01 Pa at 20^{0}C	<0.01 mm Hg at 20^{0}C
Specific Gravity	1.15 – 1.2 at 25^{0}C	1 at 20^{0}C
Boiling Point	>200^{0}C	>200^{0}C
Decomposition Temperature	>200^{0}C	>200^{0}C

3.2 Experimental Study

The experimental study consists of casting of two sets of reinforced concrete (RC) beams. 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. The strengthening of the beams is done with varying configuration and layers of GFRP sheets. Experimental data on load, deflection and failure modes of each of the beams were obtained. The change in load carrying capacity and failure mode of the beams are investigated as the amount and configuration of GFRP sheets are altered. The following chapter describes in detail the experimental study.

3.3 Casting of Beams

Two sets of beams were casted for this experimental test program. In SET I three beams (F1, F2 and F3) weak in flexure were casted using same grade of concrete and reinforcement detailing. In SET II three beams (S1, S2 and S3) weak in shear were casted using same grade of concrete and reinforcement detailing. The dimensions of all the specimens are identical. The cross sectional dimensions of the both the set of beams is 250 mm by 200 mm and length is 2300 mm. In SET I beams 2, 12 mm bars are provided as themain longitudinal reinforcement and 6 mm bars as stirrups at a spacing of 75 mm center to center where as in SET II beams 3, 12 mm bars are provided as the main longitudinal reinforcement and without any stirrups.

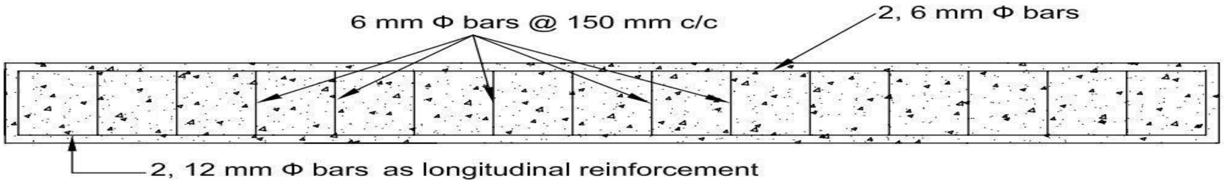

Fig. 3.6 Reinforcement details of SET I beam

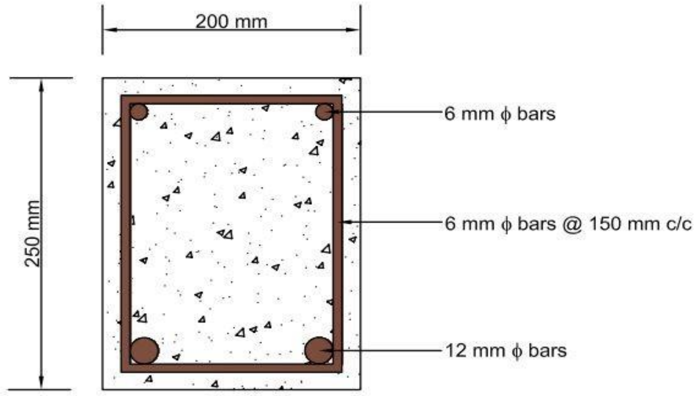

Fig. 3.7 Section of SET I beam

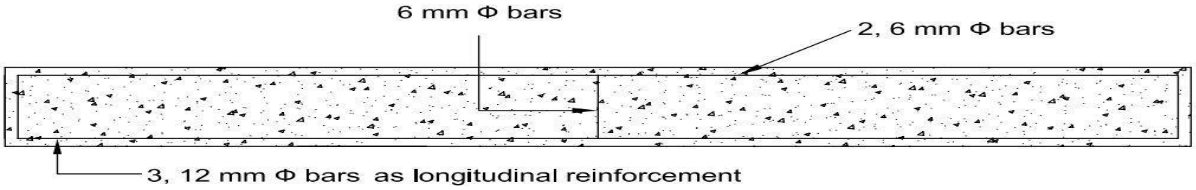

Fig. 3.8 Reinforcement details of SET II beams

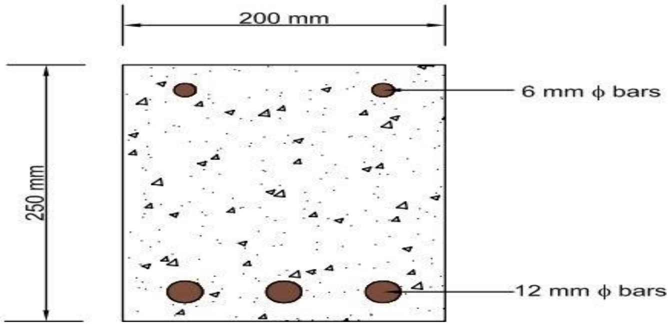

Fig. 3.9 Section of SET II beams

3.4 Strengthening of Beams

Before bonding composite fabric to the concrete, the surface was roughened with coarse sandpaper and cleaned with an air blower to remove dirt and debris. The epoxy resin was mixed as per the manufacturer's instructions (100 parts by weight Araldite LY 556 and 8 parts by weight Hardener HY 951) until it achieved a uniform color. After cutting the fabric to size, the epoxy resin was applied to the concrete surface. The composite fabric was then placed on the epoxy, and the resin was worked through the fabric using a roller to remove air bubbles. A second layer of epoxy resin was applied, and a GFRP sheet was placed on top, with the process repeated. Uniform pressure was applied during epoxy curing to ensure good contact and remove excess resin. Concrete beams with glass fiber fabric were cured at room temperature for 24 hours before testing.

Fig. 3.10 Application of Epoxy and Hardener on the Beam

Fig. 3.11 Fixing of GFRP sheet on the beam

Fig. 3.12 Roller used for Removal of Air Bubbles

3.5 Experimental Setup

All specimens were tested in the “Structural Engineering” Laboratory at National Institute of Technology, Raipur. After a 28-day curing period, the beams were washed and cleaned for crack visibility. Testing involved a two-point loading arrangement to assess the bending capacity of the central portion while minimizing shear effects.The setup included a load cell and spherical seating on a spreader beam supported by rollers on steel plates. The test member was supported on roller bearings with similar spreader plates. The loading frame was designed to handle expected loads without significant distortion, with considerations for crack observation, deflection readings, and safety.

Each specimen was positioned on two steel rollers, 150 mm from each end, with a 2000 mm span divided into three 667 mm sections. Loading was applied using a 100 kN hydraulic jack. Three dial gauges recorded deflections: one at the center of the beam and two beneath the point loads.

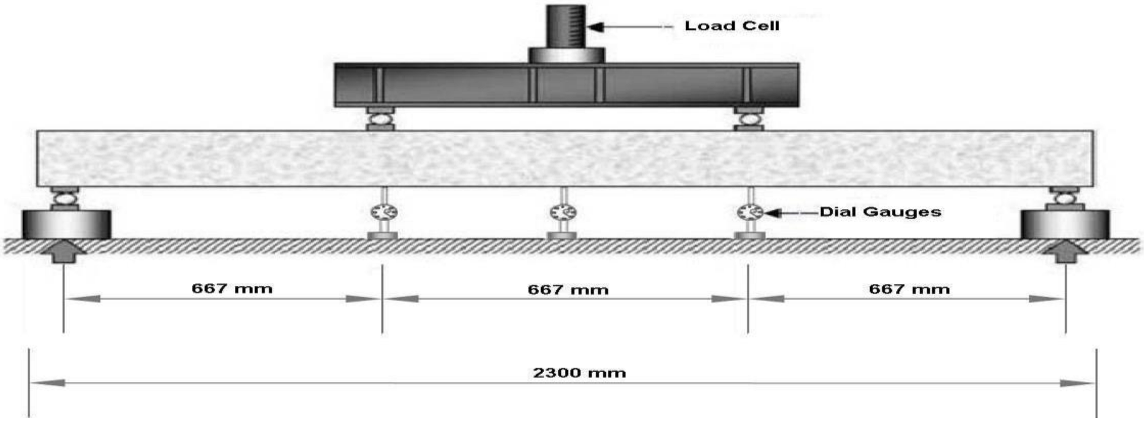

Fig. 3.13 Two Point Loading Experimental Setup

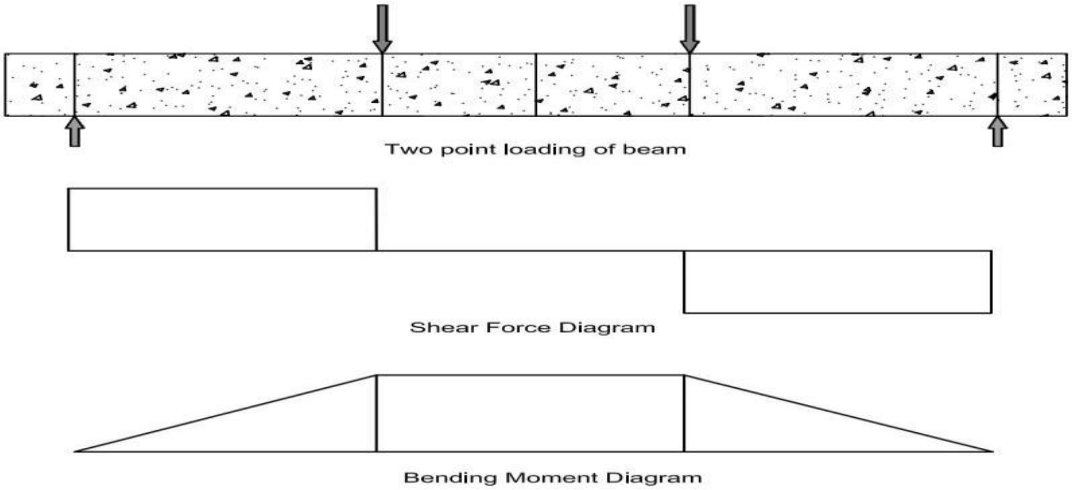

Fig. 3.14 Shear Force and Bending Moment Diagram for Two Point Loading

5. Results and Discussions

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 ofthe 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.

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

Sr. No.	Type of Beam	Beam Designation	Load AtInitial Crack (KN)	UltimateLoad (Kn)	Nature of Failure
1	Beams weak inflexure (SET I)	F1	30	78	Flexural failure
		F2	34	104	GFRP rupture + Flexure-shearfailure
		F3	Not visible	112	GFRP rupture +Flexure-shear failure
2	Beams weak inshear (SET II)	S1	35	82	Shear failure
		S2	39	108	Flexural failure + Crushing ofconcrete
		S3	40	122	Flexural failure + Crushing of concrete

5.1 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 whenbonded with GFRP sheets were better than their corresponding control beams. The mid-spandeflections 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 ofthe beam.

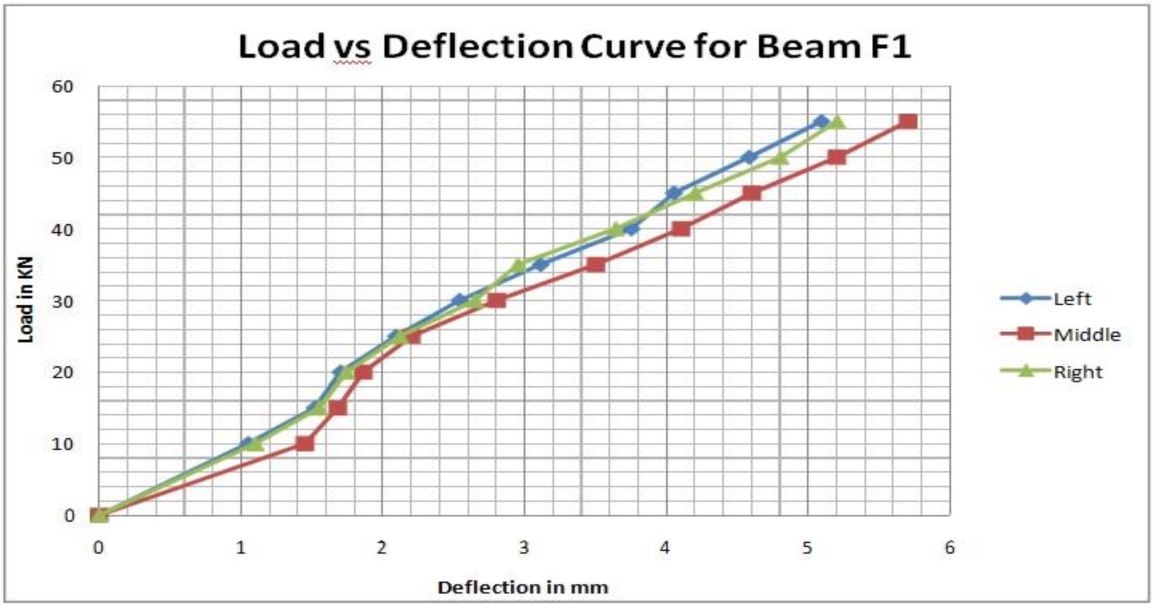

Fig. 5.1 Load vs Deflection Curve for Beam F1

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 plotted. 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.

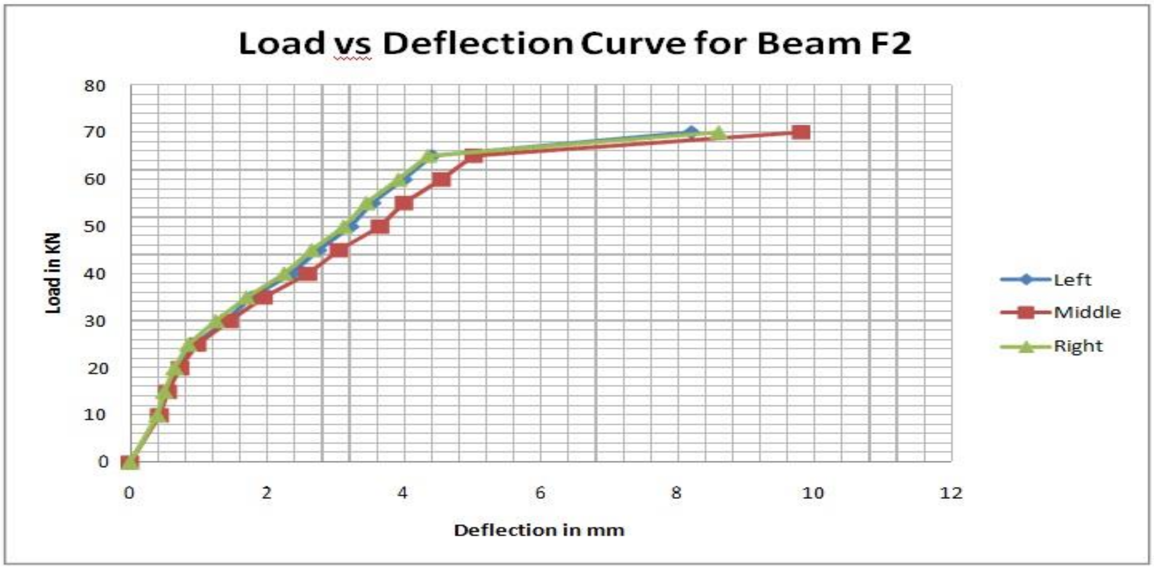

Fig. 5.2 Load vs Deflection Curve for Beam F2

5.7 Comparison 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 has not allowed developing 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.

Table 5.2 Comparison of M_u Value Obtained From Analytical and Experimental Study

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

6. Conclusion

The experimental investigation into the flexural and shear behavior of reinforced concrete (RC) beams strengthened with Glass Fiber Reinforced Polymer (GFRP) sheets has yielded several key findings:

1. **Flexural Strengthening (SET I)**

- **Beam Strengthening Results:** Strengthening beams at the soffit and extending up to the neutral axis significantly enhances the ultimate load-carrying capacity. Beam F2, strengthened only at the soffit, showed a 33% increase, while Beam F3, strengthened at both the soffit and the sides up to the neutral axis, demonstrated a 43% increase over the control beam F1. The additional strengthening at the neutral axis led to a 7% improvement over F2.

- **Failure Modes:** Control beams failed in flexure, while strengthened beams exhibited flexure-shear failure, which is more critical as it provides less warning before failure. Therefore, shear strengthening should be considered alongside flexural strengthening.

- **Cost and Effectiveness:** Strengthening up to the neutral axis, while improving load capacity, incurs significantly higher costs (approximately three times more) than strengthening only at the soffit. The increase in load-carrying capacity is not proportionate to the cost, suggesting that targeted strengthening may be more cost-effective.

2. **Shear Strengthening (SET II)**

- **Beam Strengthening Results:** The control beam S1, intentionally made weak in shear, failed as expected. Strengthened beams S2 and S3 showed improvements in load-carrying capacity and crack behavior. Beam S2, with GFRP sheets applied only to the vertical sides, showed a 31% increase in ultimate load capacity compared to S1. Beam S3, strengthened by U-wrapping in the shear zone, and demonstrated a 48% increase over S1 and a 13% improvement over S2.

- **Failure Modes:** Strengthened beams primarily experienced flexural failure rather than shear failure, indicating that GFRP sheets effectively increase shear strength while delaying the onset of flexural failure. The bonding between GFRP sheets and concrete remained intact until failure, emphasizing the effective composite action.

- **Shear Strength Restoration:** The use of GFRP sheets effectively restores or upgrades the shear strength of beams, resulting in increased shear strength and stiffness with minimal visible shear cracks.

6.1 Scope of the Work

This research provides a comprehensive analysis of the impact of GFRP sheet strengthening on the flexural and shear behavior of RC beams. Future research could focus on:

a) **Long-Term Performance:** Assessing the long-term durability and performance of GFRP-strengthened beams under various environmental conditions and load scenarios.

b) **Different GFRP Configurations:** Investigating other configurations and application methods of GFRP sheets to optimize strengthening techniques for different types of structural deficiencies.

c) **Cost-Benefit Analysis:** Performing a detailed cost-benefit analysis to evaluate the economic feasibility of various GFRP strengthening methods compared to traditional reinforcement techniques.

d) **Field Studies:** Conducting field studies on existing structures to validate laboratory findings and understand the practical challenges of implementing GFRP strengthening in real-world conditions.

e) **Hybrid Systems:** Exploring the combination of GFRP with other strengthening materials and techniques to enhance overall structural performance and cost efficiency.

This work lays the foundation for further exploration into the application of GFRP in structural engineering, offering valuable insights into its effectiveness in improving the strength and safety of reinforced concrete structures.

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