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Experimental and Numerical Study on Behavior of Externally Bonded RC T-Beams using GFRP Composites

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Abstract: 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. In this study, an experimental investigation on the flexural behavior of RC T-beams strengthened using glass fiber reinforced polymer (GFRP) sheets are carried out.

Reinforced concrete T beams externally bonded with GFRP sheets were tested to failure using a symmetrical two point static loading system. Seven RC T-beams were casted for this experimental test. All of them were weak in flexure and were having same reinforcement detailing. One beam was used as a control beam and six beams were strengthened using different configurations of glass fiber reinforced polymer (GFRP) sheets. Experimental data on load, deflection and failure modes of each of the beams were obtained. The effect of different amount and configuration of GFRP on ultimate load carrying capacity and failure mode of the beams were investigated.

The experimental results show that externally bonded GFRP can increase the flexural capacity of the beam significantly. In addition, the results indicated that the most effective configuration was the U-wrap GFRP.A series of comparative studies on deflection between the present experimental data and results from finite element method and IS code method were made. A future area of research are being outlined.

INTRODUCTION

Deterioration in concrete structures is a major challenge faced by the infrastructure and bridge industries worldwide. The deterioration is mainly due to environmental effects, which includes corrosion of steel, gradual loss of strength with ageing, repeated high intensity loading, variation in temperature, freeze-thaw cycles, contact with chemicals and saline water and exposure to ultra-violet radiations. This problem, coupled with revisions in structural codes needed to account for the natural phenomena like earthquakes or environmental deteriorating forces, demands development of successful structural retrofit technologies. The structural retrofit problem has two options, repair/retrofit or demolition/reconstruction.

FRP repair is a simple way to increase both the strength and design life of a structure. Because of its high strength to weight ratio and resistance to corrosion, this repair method is ideal for deteriorated concrete structure due to exposure to de-icing salts and other environmental factors by encasing concrete members.FRP protects from existing salts and other environmental factors

It increases the capacity with the minimal addition of dead load to the structure. Materials are easy to transport and handle no lifting gear required. It is easy to use at height. It increases the ability to work in confined areas and in situations with difficult access (e.g. tunnel and basements). This technique is relatively quick with reduced disturbance and installation time.

ADVANTAGESAND DISADVANTAGES OF FRP

ADVANTAGES

FRP materials have the higher ultimate strength and lower density as compared to steel. When these properties are taken together they lead to fiber composites having a strength/weight ratio higher than steel plate in some cases. The lower weight of FRP makes installation and handling significantly easier than steel. These properties are particularly important when installation is done in cramped locations. The availability of long lengths and the flexibility of the material also simplify installation.

1. Laps and joints are not required
2. The material can take up irregularities in the shape of the concrete surface
3. The material can follow a curved profile; steel plate would have to be pre-bent to the required radius.
4. The material can be readily installed behind existing services
5. Overlapping, required when strengthening in two directions, is not a problem because the material is thin.

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.

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.

REVIEW OF LITERATURE

Development of FRP materials in various forms and configurations offers an alternative design approach for construction of new structures and rehabilitation of the existing structures. Research on FRP material for use in concrete structures began in Europe in the mid 1950's [Rubinsky and Rubinsky, 1954; Wines, J. C. et al., 1966]. The pioneering work of bonded FRP system can be credited to Meier [Meier 1987]; this work led to the first on-site repair by bonded FRP in Switzerland [Meier and Kaiser 1991].Japan developed its first FRP applications for repair of concrete chimneys in the early 1980s [ACI 440 1996].By 1997 more than 1500 concrete structures worldwide had been strengthened with externally bonded FRP materials. Thereafter, many FRP materials with different types of fibers have been developed. FRP products can take the form of bars, cables, 2-D and 3-D grids, sheet materials and laminates.

Nanni et al. (1997) made an analytical & experimental study of the retrofitting effect of CFRP sheets applied on the tension side & web of the damaged R.C. beams due to loading beyond cracking strength of concrete. Besides, the effect of CFRP sheets on stiffening effect is studied with various orientations of fibers with respect to the beam axis. Results showed a substantial enhancement in the strength of the retrofitted damaged beams varying from 20% to 60%. Malek et al. (1998) also carried out an experimental investigation to predict the failure load of RC beams strengthened with FRP plates. Their experimental study showed the local failure of the concrete cover along the longitudinal reinforcement in the retrofitted beams due to stress concentration of the plate end. Grace et al. (1999) investigated the behaviour of RC beams strengthened with CFRP and GFRP sheets and laminates. They studied the influence of the number of layers, epoxy types, and strengthening pattern on the response of the beams. It is observed that all beams experienced brittle failure, with appreciable enhancement in strength, thus requiring a higher factor of safety in design.

Several possible test methods have evolved to measure the bond strength between adhesive and concrete substrates, mainly for applications in concrete repair (Franke, 1986; Naderi et al., 1986). The Réunion Internationale des Laboratoires d'Essais et de Recherches sur les Matériaux et les Constructions (RILEM) Technical Committee 52-RAC lists some currently used laboratory and field test methods for assessing the bond between resin and concrete (Sasse and Friebrich, 1983). Procedures are mentioned on the strength of adhesion in tension, shear, and bending, as well as shrinkage and thermal compatibility in the context of coatings, concrete repair, concrete/ concrete and steel/concrete bonds. Variations of the slant shear test (Kreigh, 1976), in which two portions of a standard cylinder or prism are joined by a diagonal bond line and then tested in compression, have been found to produce discriminating and consistent results (Kreigh, 1976; Naderi, 1985; Wall et al., 1986).

OBJECTIVE AND SCOPE OF THE PRESENT WORK

The objectives of this work are to carry out the experimental investigation of externally bonded R.C. T- Beams using GFRP sheets and study the enhancement of the strength.And compare its results numerically to know the suitability of the FRP composites as retrofit materials for deteriorated R. C. Structures.

In the present work the behavior of T-section reinforced concrete beams, retrofitted with GFRP is observed to know the practical feasibility in the construction industry. Seven number of T-section concrete beams are casted. All these beams except one beam are bonded with GFRP sheets using epoxy in different size and layers. These beams are subjected to flexure by applying two points loading to evaluate the excess of flexural strength due to retrofitting of GFRP. And the results are validated numerically.

EXPERIMENTAL STUDY

MATERIALS

CONCRETE

It is composed of Portland cement and water combined with sand, gravel, crushed stone, or other inert material such as expanded slag or vermiculite. A strong stone-like mass is formed from a chemical reaction of cement and water. The concrete paste is plastic and can be easily molded into any form or trowelled to produce a smooth surface. Hardening starts immediately after mixing, 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. Excess of 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.

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 cement, but these are classified as adhesives, and the term cement alone means a construction material. The most widely used of the construction cement is Portland cement. It is a bluish-gray powder.

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.

COURSE AGGREGATE

Coarse aggregate is 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 lager sizes may be used for massive concrete aggregate. Machine chorused granite broken stone angular in shape is used as coarse aggregate.

MATERIAL TESTING OF CONCRETE

The testing of the ingredient materials of concrete such as cement, fine aggregate, and coarse aggregate is carried out and results are presented below.

Testing Of Cement

	Type: Konark Portland Slag Cement.	
i	Specific gravity	2.96
ii	Normal Consistency	32%
iii	Setting Times	initial :105 minutes
		Final :535 minutes
iv	Soundness	2 mm expansion
v	Fineness	1gm retained in 90micron sieve

TESTING OF FINE AGGREGATE

Sieve Analysis

i. The results of sieve analysis for fine aggregate are furnished in table Grading Zone = III.

ii. Specific gravity: 2.67

iii. Water absorption: 0.8

OF SIEVE ANALYSIS FOR FINE AGGREGATE

Sl. No.	Sieve size (in mm)	Mass retained (in gm)	Mass passing (in gm)	% passing	Remarks
1.	4.75	20	1980	99	90-100
2.	2.36	44	1936	96.8	85-100
3.	1.18	132	1804	90.2	75-100
4.	600µ	346	1458	72.9	60-79
5.	300µ	1216	242	12.1	12-40
6.	150µ	202	40	2	0-10
7.	Pan	40	0	0	-

Given Sand Confirms To Zone - III

TESTING OF COURSE AGGREGATE

Sieve Analysis

i. The results of sieve analysis for coarse aggregate are furnished in table Grading Zone = III.

ii. Specific gravity: 2.72

iii. Water absorption: 0.5

Results of Sieve Analysis for Coarse Aggregate (20mm)

Sl.No.	Sieve size (in mm)	Mass retained (in gm)	Mass passing (in gm)	% passing	Remarks
1	80	0	5000	100	-
2	40	0	5000	100	-
3	20	436	4564	91.28	95-100
4	10	3027	1537	30.74	25-55
5	4.75	1478	59	1.18	0-10
6	Pan	59	0	0	0

Mix Design of M20 Grade Concrete

1	**Design Stipulations**	
a)	Characteristics strength	20N/mm^2
b)	Degree of quality control	Good
c)	Degree of exposure	Mild
d)	Workability	62

Results of Sieve Analysis for Course Aggregate (10mm)

2.	Materials Supplied	
a)	Cement	Konark Portland Slag Cement
b)	Course aggregate	20mm down
c)	Fine aggregate	Sand conforming to grading zone III

Description	Cement	Sand (Fine Aggregate)	Course Aggregate	Water
Mix proportion (by weight)	1	1.56	3.30	0.5
Quantities of materials (in Kg/m^3)	372	580	1228	186

REINFORCEMENT

High-Yield Strength Deformed bars of 20 mm diameter is used for the longitudinal reinforcement and 8 mm diameter high-yield strength deformed bars are used as stirrups. The yield strength of steel reinforcements used in this experimental program is determined by performing the standard tensile test on the three specimens of each bar. The average proof stress at 0.2 % strain of 20 mm φ bars is 378 N/mm^2.

DETAILING OF REINFORCEMENT IN R.C. T- BEAMS

For all the seven reinforced concrete T beams, the same arrangement for flexure and shear reinforcement is made. The tension reinforcement consists of 2 nos of 20 mm diameter HYSD bar. Four bars of 8 mm of HYSD bars are also provided as hang up bars.The shear reinforcement consists of 8 mm diameter 2-legged vertical stirrups of HYSD bars @100mm c/c. The detailing of reinforcement of the beam is shown in fig.

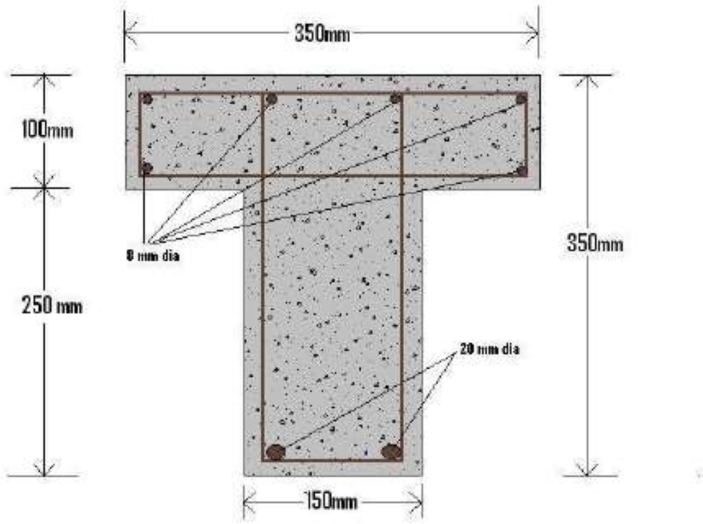
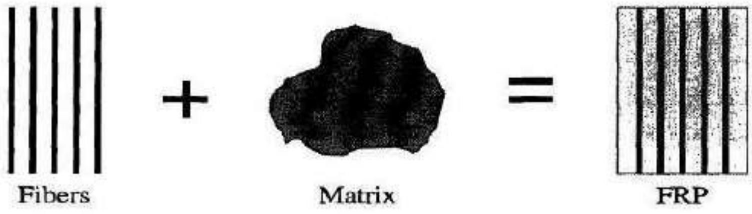


Fig: Reinforcement Detailing of T- Beam

FIBERREINFORCED 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.

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 the micro level.



Formation of Fiber Reinforced Polymer Composite

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.

PROPERTIES OF DIFFERENT FIBERS

Material	Density (g/cm^3)	Tensile Modulus (E) (GPa)	Tensile Strength (σ) (GPa)	Specific Modulus (E/σ)	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

Types of fibers used in fiber reinforced polymer composites:
i) Glass fibers ii) Carbon fibers
iii) Aramid fibers iv) Glass fibers

These are fibers commonly used in the naval and industrial fields to produce composites of medium-high performance. Their peculiar characteristic is their high strength. Glass is mainly made of silicon ($SiO2$) with a tetrahedral structure ($SiO4$). Some aluminum oxides and other metallic ions are then added in various proportions to either ease the working operations or modify some properties (e.g., S-glass fibers exhibit a higher tensile strength than E-glass).

TYPICAL COMPOSITION OF FIBERGLASS (% IN WEIGHT)

	E-glass	S-glass
Silicon oxide	54.3	64.20
Aluminium oxide	15.2	24.80
Iron oxide	-	0.21
Calcium oxide	17.2	0.01
Magnesium oxide	4.7	10.27
Sodium oxide	0.6	0.27
Boron oxide	8.0	0.01
Barium oxide	-	0.20
Various	-	0.03

The production technology of fiberglass is essentially based on spinning a batch made of sand, alumina, and limestone. The constituents are dry mixed and brought to melting (about 1260 °C) in a tank. The melted glass is carried directly on platinum bushings and, by gravity, passes through ad hoc holes located on the bottom.

EXPERIMENTAL STUDY

The experimental study consists of the casting of seven reinforced concrete T beams. All the seven beams weak in flexure are casted, out of which one is taken as the controlled beam and other six beams are strengthened using continuous glass fiber reinforced polymer (GFRP) sheets in flexure. 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 are obtained.

CASTING OF SPECIMEN

For conducting an experiment, seven reinforced concrete T beam specimen of size as shown in the fig (Length = 2m, flange width = 0.35m, web width = 0.15 m, depth of the flange = .10m, overall depth=.35m) and all having the same reinforcement detailing are casted. The proportion of **0.5: 1: 1.56: 3.30** for water, cement, fine aggregate and course aggregate is taken. The mixing is done by using a concrete mixture. The beams are cured for 28 days. For each beam, three cubes are casted to determine the compressive strength of concrete for 28 days.

MATERIALS FOR CASTING

REINFORCING STEEL

HYSD bars of 20 mm φ is used as main reinforcement. 8 mm φ HYSD steel bars are used for shear reinforcement.

FORM WORK

STRENGTHENING OF BEAMS

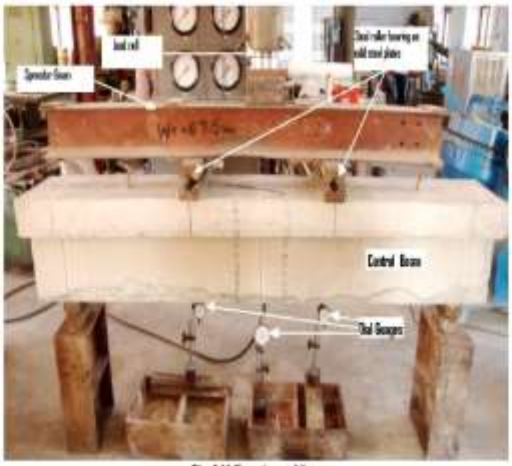
At the time of bonding of fiber, the concrete surface is made rough using a coarse sand paper texture and then cleaned with an air blower to remove all dirt and debris. After that, the epoxy resin is mixed in accordance with manufacturer's instructions. The mixing is carried out in a plastic container (100 parts by weight of Araldite LY 556 to 10 parts by weight of Hardener HY 951). After their uniform mixing, the fabrics are cut according to the size then the epoxy resin is applied to the concrete surface. Then the GFRP sheet is placed on top of epoxy resin coating and the resin is squeezed through the roving of the fabric with the roller.Air bubbles entrapped at the epoxy/concrete or epoxy/fabric interface are eliminated.

APPLICATION OF EPOXY AND HARDENER ON THE BEAM

FIXING OF GFRP SHEETS ON THE BEAM

EXPERIMENTAL SETUP

The T-beams are tested in the loading frame of the "Structural Engineering" Laboratory of National Institute of Technology, Rourkela. The testing procedure for the all the specimen is same. First, the beams are cured for a period of 28 days then its surface is cleaned with the help of sand paper for clear visibility of cracks. The two-point loading arrangement is used for testing of beams. This has the advantage of a substantial region of nearly uniform moment coupled with very small shears, enabling the bending capacity of the central portion to be assessed. Two-point loading is conveniently provided by the arrangement shown in Figure.



EXPERIMENTAL SETUP

TESTING OF BEAMS All The seven are tested one by one.Six with FRP and one without FRP which is taken as the control Beam.All of them are tested in the above arrangement. The gradual increase in load and the deformation in the strain gauge reading are taken throughout the test. The dial gauge reading shows the deformation. The load at which the first visible crack is developed is recorded as cracking load. Then the load is applied till the ultimate failure of the beam.

Experimental Setup of the Control Beam 1

Control Beam after Cracking

(a) (b)

a) Crack Pattern at 2l/3 (Near Right Support)
b) Crack Pattern at L/2(At Center)

Table: Deflection Values of Control Beam1

Load (in KN)	At point L/3(in mm)	At point L/2(in mm)	Remarks
0	0	0	
20	0.36	0.44	
30	0.53	0.63	
40	0.64	0.76	
50	0.75	0.89	
60	0.86	1.02	
70	1.00	1.20	
80	1.16	1.33	
90	1.29	1.54	
100	1.46	1.74	
110	1.58	1.88	
120	1.78	2.10	Hair line crack started appearing
130	1.91	2.23	
140	2.06	2.40	
150	2.19	2.52	
160	2.34	2.73	
170	2.54	2.95	
180	2.73	3.16	
190	2.87	3.32	
200	3.01	3.48	
210	3.14	3.63	
225	3.38	3.88	
240	3.63	4.17	Ultimate load

Single Layered GFRP bonded at Bottom of Web from end to end

Fig: Deboning is around 21 cm and cracks occurred near the centre and under the loads

(a) **(b)**

(a) Cracks under the load at L/2
(b) Cracks under the load at 2L/3

Table: Deflection Values of Beam 2

Load (in KN)	At point L/3(in mm)	At point L/2(in mm)	Remarks
0	0	0	
20	0.26	0.31	
30	0.36	0.44	
40	0.45	0.55	
50	0.56	0.67	
60	0.72	0.87	
70	0.82	0.99	
80	0.97	1.17	
90	1.12	1.33	
100	1.28	1.51	
110	1.40	1.65	
120	1.57	1.85	
130	1.70	1.99	
140	1.84	2.15	
150	2.00	2.32	
160	2.16	2.49	
170	2.32	2.66	
180	2.45	2.81	Debonding of fiber
190	2.61	2.98	
200	2.74	3.10	
210	2.84	3.23	
220	3.00	3.39	
230	3.10	3.54	
240	3.25	3.68	

250	3.38	3.82	
260	3.50	3.98	
270	3.65	4.14	
276	4.07	4.68	Tearing of fiber
290	4.53	5.40	
308			Tearing and Debonding
310			Ultimate load

RESULTS AND DISCUSSIONS

In this, the experimental results of all the beams with different types of layering of GFRP are interpreted. Their behavior throughout the test 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. All the beams are tested for their ultimate strengths.Beams-1 is taken as the control beam. It is observed that the control beam had less load carrying capacity and high deflection values compared to that of the externally strengthened beams using GFRP sheets.

All the beams except the control beam are strengthened with GFRP sheets in different patterns.Beam-2 is strengthened only at the soffit from end to end. Beam-3 is also strengthened only at the soffit but for the length L/3 to 2L/3. In Beam-4 the web part is strengthened throughout its length with U-Jacketed single layered GFRP. Beam-5 is also strengthened in the web but for 1 m length in the middle portion where most of the cracks are occurring. Beam-6 is first loaded till hairline cracks are formed then it is retrofitted in a similar pattern as is done for Beam-5. Beam-7 is also loaded till hairline cracks are formed then it is retrofitted in a similar pattern as is done for Beam-4.Deflection behavior and the ultimate load carrying capacity of the beams are noted. The ultimate load carrying capacity of all the beams along with the nature of the failure is given in Table.

The GFRP strengthened beam and the control beams are tested to find out their ultimate load carrying capacity. It is found that all the failed in flexure. Beam-2 failed due to fracture of GFRP sheet and then the flexural failure of the beam took place. Beam-3 failed due to debonding of the GFRP sheet and then the flexural failure of the beam. Beam-4 failed due to fracture of GFRP at the center followed by debonding and finally flexural failure of the beam.Beam-5 failed in the manner as in Beam-4. Beam-6 failed due to debonding of GFRP and then the flexural failure of the beam. In Beam-7 first fracture of GFRP took place at the center followed by debonding of the top portion in the center.

LOAD DEFLECTION ANALYSIS

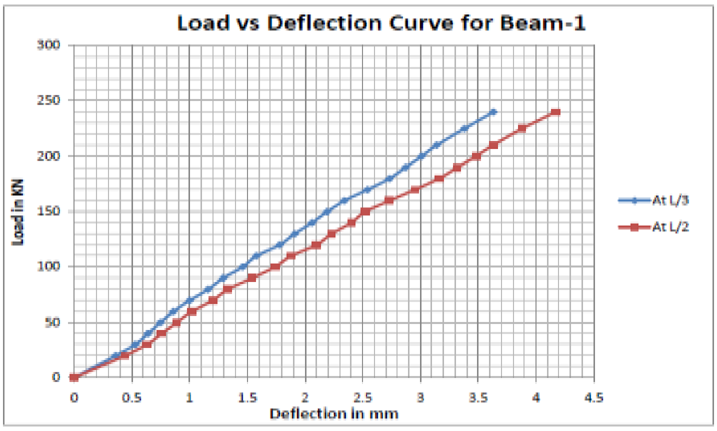


Fig: Load vs. Deflection Curve for Control Beam 1

Beam 1 is taken as the control beam which is weak in flexure. In Beam1 no strengthening is done. Two point static loading is applied to the beam and at each increment of the load, deflection at L/3, L/2 and 2L/3 are taken with the help of dial gauges. Using this load and deflection data, load vs. deflection curve is plotted. At the load of 120 KN, initial hairline cracks appeared. Later with the increase in loading values, the crack propagated further. The Beam1 failed completely in flexure.

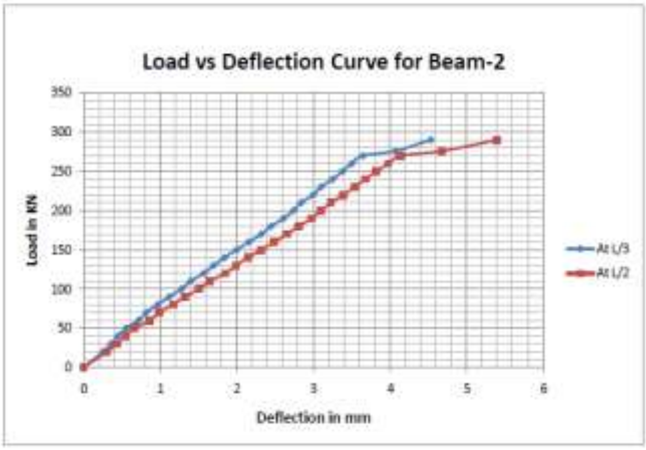


Fig: Load vs. Deflection Curve for Control Beam 2

Beam-2 is strengthened only at the soffit from end to end.Two point static loading is applied to the beam and at each increment of the load, deflection at L/3, L/2 and 2L/3 are taken with the help of dial gauges. Using this load and deflection data, load vs. deflection curve is plotted. At the load of 130 KN, initial hairline cracks appeared. Later with the increase in loading values, the crack propagated further. Beam-2 failed due to fracture of GFRP sheet and then the flexural failure of the beam took place.

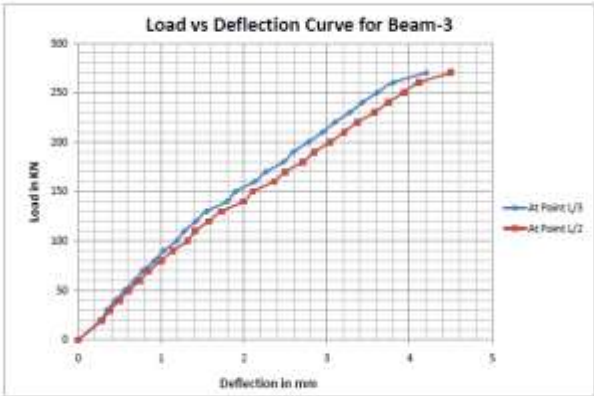


Fig: Load vs. Deflection Curve for Control Beam

Beam-3 is also strengthened only at the soffit but for the length L/3 to 2L/3. Two point static loading is applied to the beam and at each increment of the load, deflection at L/3, L/2 and 2L/3 are taken with the help of dial gauges. Using this load and deflection data, load vs. deflection curve is plotted. At the load of 125 KN, initial hairline cracks appeared. Later with the increase in loading values, the crack propagated further. Beam-3 failed due to debonding of the GFRP sheet and then the flexural failure of the beam.

ULTIMATE LOAD CARRING CAPACITY

The load carrying capacity of the control beams and the strengthen beam are plotted below. It is observed that beam 4 is having the max load carrying capacity.

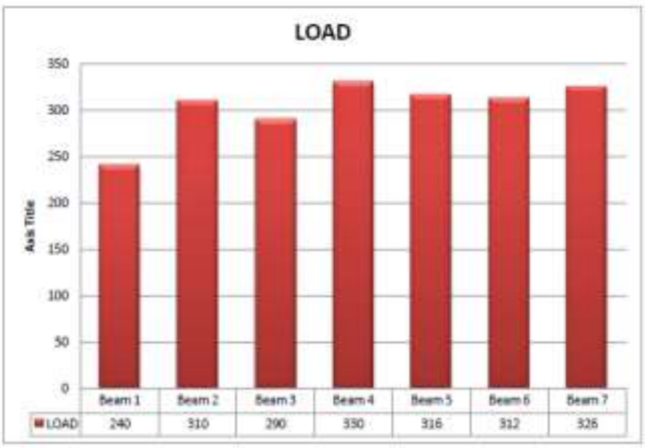
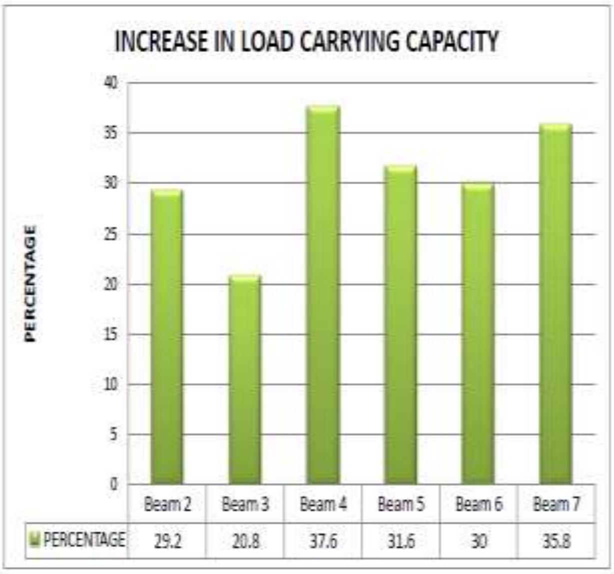


Fig: Ultimate Load Carrying Capacity



From the above figure, we can observe the amount of increase in the flexural strength for each strengthened beam with respect to the Control Beam 1

CONCLUSIONS

The present experimental study is done on the flexural behavior of reinforced concrete T-beams strengthened by GFRP sheets. Seven reinforced concrete (RC) T-beams weak in flexure having same reinforcement detailing are casted and tested. From the test results and calculated strength values, the following conclusions are drawn:

1. The ultimate load carrying capacity of all the strengthen beams were enhanced as compared to the Control Beam1.

2. Initial flexural cracks appear for higher loads in case of strengthened beams.

3. The load carrying capacity of the strengthened Beam 4 was found to be maximum of all the beams. It increased up to 37.5 % more than the control beam 1, 6.5% more than strengthened beam 2 and 4.4 % more than the strengthened beam 5.

4. Beam 6 which was retrofitted in the web part only for 1 m length in the center showed minimum deflection values on same loads as compared to other strengthened beams and the control beam.

5. Beam 4 and Beam 7 were giving the best results in terms of load carrying capacity and deflection respectively. And both are having same wrapping pattern of GFRP which is bonded to the web part throughout its length.

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